Experience of operating a solar parabolic trough direct steam generation power plant with superheating

Authors:

Lisa Willwerth[a], Jan Fabian Feldhoff[b1], Dirk Krüger[a], Lothar Keller[c], Martin Eickhoff[c], Joachim Krüger[d], Yuvaraj Pandian[d], Jörg Tiedemann[e], Manuel Succo[e], Abdallah Khenissi[b2]

[a] German Aerospace Center, Linder Höhe, 51147 Köln, Germany, lisa.willwerth@dlr.de
[b] German Aerospace Center, Wankelstrasse 5, 70563 Stuttgart, Germany
[c] German Aerospace Center, Plataforma Solar de Almería, Ctra. De Senés s/n, km 4, 04200 Tabernas, Spain
[d] Solarlite CSP Technology GmbH, Schloss Duckwitz, 17179 Duckwitz, Germany
[e] Tiede- & Niemann Ingenieurgesellschaft mbH, Harburger Schloßstraße 6-12, 21079 Hamburg, Germany

Abstract

TSE1 is the first solar thermal power plant operating in Southeast Asia. It was planned by Solarlite GmbH with support of Tiede- & Niemann GmbH, both German based. It is the first power plant with direct steam generation (DSG) concept and superheating in parabolic troughs. The solar field has a nominal power of 19 MW_{th} driving a 5 MW_{el} turbine by superheated steam at 30 bar and 330 °C. During 2010/2011 Solarlite built the solar field, while the later owner and operator Thai Solar Energy (TSE) from Bangkok built the power block, in Kanchanaburi, Thailand. TSE1 is being operated by TSE since January 2012 (Krüger et al., 2012).

This publication is based on a study within the KanDis project, funded by the German Federal Ministry for Economic Affairs and Energy, in which an extensive database of records of almost 500 sensors installed in the power plant (solar field and power block) has been investigated. The data have been provided by Solarlite with a time resolution of about 1 minute.

Within the KanDis project, a stable operation could be demonstrated (Khenissi et al., 2015, Krüger et al., 2016). Even under the fluctuating irradiance conditions in the rainy season of Thailand, the turbine could be operated well and generate electricity. Evaluation of the operation data has helped to learn more about DSG behaviour. The TSE1 layout and the implemented control strategies were evaluated and strategies for improvement of TSE1 are suggested within this paper. From the experiences with the TSE1 power plant, conclusions could be drawn to improve the layout and control of future DSG plants.

Keywords: CSP, concentrated solar power, DSG, direct steam generation, evaporator control, superheater control

[1] SWU Stadtwerke Ulm/Neu-Ulm GmbH, Karlstraße 1-3, 89073 Ulm, Germany
[2] BP 71 Poste Hessi Jerbi, 4174 Zarzis, Tunisia

1. Introduction

The process of pre-heating, evaporating and superheating water directly in the collector absorbers is called direct steam generation (DSG[3]) (Hirsch et al., 2013). It is a promising option in solar thermal power plants to reduce costs and to increase the efficiency in comparison to conventional solar thermal power plants using oils as heat transfer fluid (Eck et al., 2008, Feldhoff et al., 2009). While common oils can only be used up to a temperature of 395 °C (new silicon-based oils promise temperatures up to 420°C), water/steam can be superheated to higher temperatures. Upper temperatures of 500 °C to 550 °C seem reasonable with current line focus technologies. The steam parameters are not bound by the fluid, but by component design limitations such as receiver coating and material costs, as well as by heat losses and concentration factors.

DSG is a perfect match as fuel-saver for co-fired plants, e.g. with coal or biomass, but it can also be used for stand-alone plants. Integration to the live steam of high pressure turbines of existing plants is possible as well. DSG also can have the benefit of directly providing steam without additional heat exchangers, for example as process heat or for enhanced oil recovery. Furthermore, there is no risk of environmental pollution or extra investment costs due to environmental safety.

Figure 1: Aerial view of TSE1, Kanchanaburi, Thailand, Source: Solarlite

---

[3] Abbreviations

ANI = irradiance normal to aperture area
DNI = direct normal irradiance
CSP = concentrated solar power
DSG = direct steam generation
NMP = non-minimum phase
PI = proportional-integral controller
PSA = Plataforma Solar de Almería
SD = Steam Drum
TSE = Thai solar energy (company name, operator)
TSE1 = name of the appointed power plant in Kanchanaburi, Thailand

The feasibility of DSG in parabolic troughs has been proven within the European DISS project (Eck et al., 2003) in a single test loop at the Plataforma Solar de Almería (PSA[3]). Within the Spanish-German REAL-DISS project, the experiences from the DISS project were used to implement a DSG collector in a conventional power plant in Carboneras, Spain (Eck et al., 2011). Components, especially the receiver tubes and flexible joints, were designed to withstand higher temperatures. Operation of the DSG solar field with temperatures up to 500 °C has been demonstrated successfully. Thereafter, the DISS loop was altered and operated to validate the benefits of the once-through concept within the German DUKE project (Feldhoff and Meyer-Grünefeld, 2016). Since 2009 DSG was commercially applied by the first linear Fresnel plant in Puerto Errado, Spain, PE1 and in 2011 a superheating collector was installed there to gain first experience. A stable operation was demonstrated (Morin et al., 2012). In 2012, DSG was commercially applied by the PE2 linear Fresnel plant and the TSE1 parabolic trough plant in Kanchanaburi, Thailand. At PE2, the stable operation of parallel evaporation loops for a 30 MW_{el} DSG plant with saturated steam was demonstrated (Mertins et al., 2012). This paper presents the results of the KanDis project (Krüger et al., 2016), namely the operation of the 5 MW_{el} TSE1[3] plant with recirculation mode and superheating.
The KanDis project aimed at investigating the operational behaviour of a commercial-sized DSG plant with evaporation and superheating in parallel loops, to estimate the stability of the process and to improve the layout, components and the control strategy for TSE1 and future DSG plants. Therefore operational data from 2012 to 2013 were analysed. This Paper offers unique and detailed insight into the experiences with control of a DSG evaporator and superheater field. It is not the aim of this paper to offer an analysis of the performance of the TSE1 plant over the two years period, which would not be representative, because it spans over the commissioning period and scientific test periods.

2. Description of the TSE1 power plant

The TSE1 solar field was built by Solarlite with the contribution of Tiede & Niemann in 2010 and 2011 whereas the power block was built by the owner Thai Solar Energy. Its design was described in (Krüger et al., 2010). It consists of a solar evaporator and a solar superheater, both with SL4600 parabolic trough collectors. It is a DSG plant operating in recirculation mode. Water is preheated and partially evaporated within the evaporator. This two-phase flow of liquid and steam flows to the steam drum, where it is separated (Willwerth et al., 2016). The saturated steam moves on to the superheater field, where it is superheated. Therefore, the live steam mass flow depends on the evaporator field and the steam temperature depends on the superheater field. The superheated steam drives the turbine and is condensed. The condensate from the turbine, as well as the liquid phase from the steam drum, mix and re-enter the evaporator field. To optimise the flexibility of the 5 MW_{el} turbine, MAN adapted it to accept low partial load pressures during commissioning. The turbine is normally operated in fixed pressure mode where the control valves at the inlet of the turbine control the pressure in the solar field. The solar field output has to match or exceed the turbine swallowing capacity to reach the turbine's maximum rated power in normal operation. On the contrary, Sliding pressure control is achieved when the control valves at the turbine inlet are always fully open and the live steam pressure is therefore an indirect result of the mass flow delivered by the solar field. Fixed pressure control was adopted during regular operations and sliding pressure control was used during transient operation to prolong the turbine operation as long as possible.

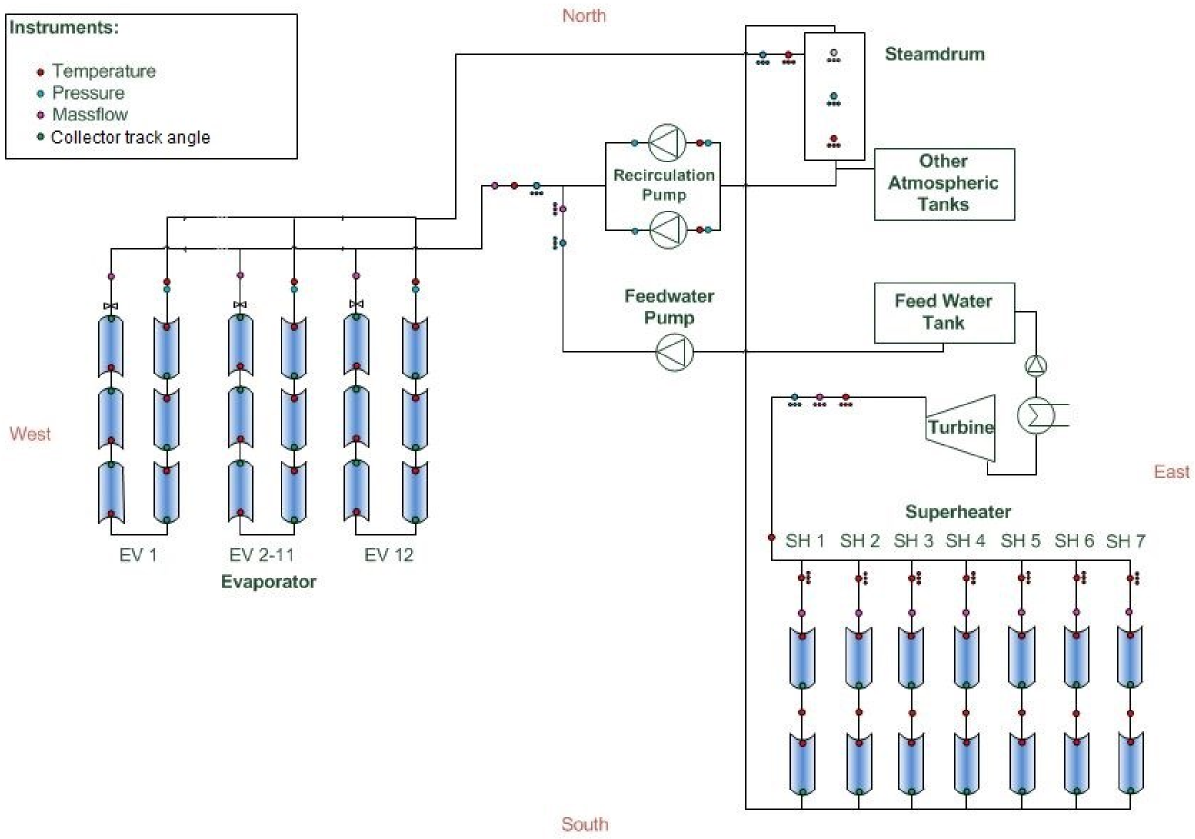

Figure 2: Schematic P&ID of TSE1 with selected sensors

Some technical parameters of the TSE1 plant are collected in table1.

Table 1: technical parameters of the TSE1 plant

term	value	unit
Nominal thermal power P_{th}	19,5	MW
Nominal electrical power P_{el}	5	MW
Nominal live steam pressure	30	bar
Nominal live steam temperature	330	°C
SL4600 collector segment length	12	m
SL4600 collector aperture width	4,6	m
PTR70 receiver diameter	70	mm
Steam drum volume	25	m^3
Steam drum max pressure	43	bar

3. Data

A thorough analysis of the TSE1 operation was possible due to an extensive database of about 500 sensors from the solar field, from which data were transmitted about every minute from January 2012 to July 2013. The most interesting sensors are schematically drawn in Figure 2. There are temperature measurements at the outlet of each single collector as well as in the steam drum and header lines. The tracking angle of each collector is also transmitted. Pressures are measured at the outlets of each evaporator loop, within the steam drum and in the header lines. Similarly, the water mass flows are measured at the inlet of each evaporation loop as well as at the outlet of the feed water pump. The steam mass flows are measured in each superheating loop as well as in the main steam line at the outlet of the

solar field. The water content in the steam drum can be calculated by data from a level sensor. At the entry of the turbine, temperature, pressure and mass flow of the live steam are detected. The electrical power output measurement is only available from January 2012 to August 2012. Besides the sensors symbolised in the picture, there is also a weather station with sensors for direct normal irradiance (DNI[3]), wind speed and wind direction. For the data analysis instead of DNI the irradiance normal to aperture area (ANI[3]) is used, which is the DNI multiplied by the cosine of the incidence angle.
The uncertainty of each measurement is not elaborated upon here, since only qualitative conclusions shall be drawn.

4. Results from Operation

Live steam output and the control of evaporator as well as superheater are evaluated in the following.

4.1 Live steam output

The TSE1 turbine has a nominal power of 5 MW_{el} at a nominal live steam pressure of 30 bar and a temperature of 330 °C. The TSE1 demonstrated that reaching and maintaining these live steam parameters is possible with DSG without co-firing.
Live steam parameters have a strong influence on the life span of steam turbines. Unlike in plants supplied by steam from fossil sources, steam supply from solar thermal plants varies depending on the irradiation. In general, storage and co-firing can reduce fluctuations in live steam. Co-firing is not installed in TSE1 and storage is only inherent by the limited buffer of the steam drum. Changes in live steam parameters are better tolerated by smaller turbines with lower pressures and temperatures, as they have less wall thickness resulting in lower tensions caused by temperature changes (Agora_Energiewende, 2017). Therefore, the 5 MW_{el} MAN turbine is more robust than larger turbines.
To improve operation, the strict operating restrictions of the turbine were adapted by MAN to the fluctuating energy supply and its part load characteristics were improved. Originally, the turbine operation was coupled to a minimum pressure of 15 bar. Within the commissioning, changes were implemented and since the 3rd of May in 2012 the turbine can still be operated at a steam pressure of down to 11 bar and switches off at 10 bar. This allows the bridging of longer ANI disturbances and the longer operation at sunset. Especially, a shutdown of the turbine due to long dips in the ANI is often prevented. Thus, the turbine does not need to start-up again when the radiation is back. The start-up of the turbine entails a time delay. Thus, avoiding the shut-down and start-up process allows for a continuous electricity generation even with significant gaps in the ANI.
The solar field in TSE1 could meet the desired live steam conditions for absolute values and transients in pressure, temperature and mass flow well. In Figure 3 live steam pressure and temperature are displayed for a sunny day. The plant runs in fixed pressure mode, the live steam pressure is kept constant and the temperature remains well within the limits.
On days with long drops in ANI, which occur fairly often within the rainy season of Kanchanaburi, temperature and pressure vary as depicted in the period around 10 o’clock in Figure 4. Nevertheless, the required steam conditions are reached and the turbine keeps running in part load. The lower main steam pressure allows for a lower temperature. Only superheating must be ensured in order to maintain steam dryness for the turbine.

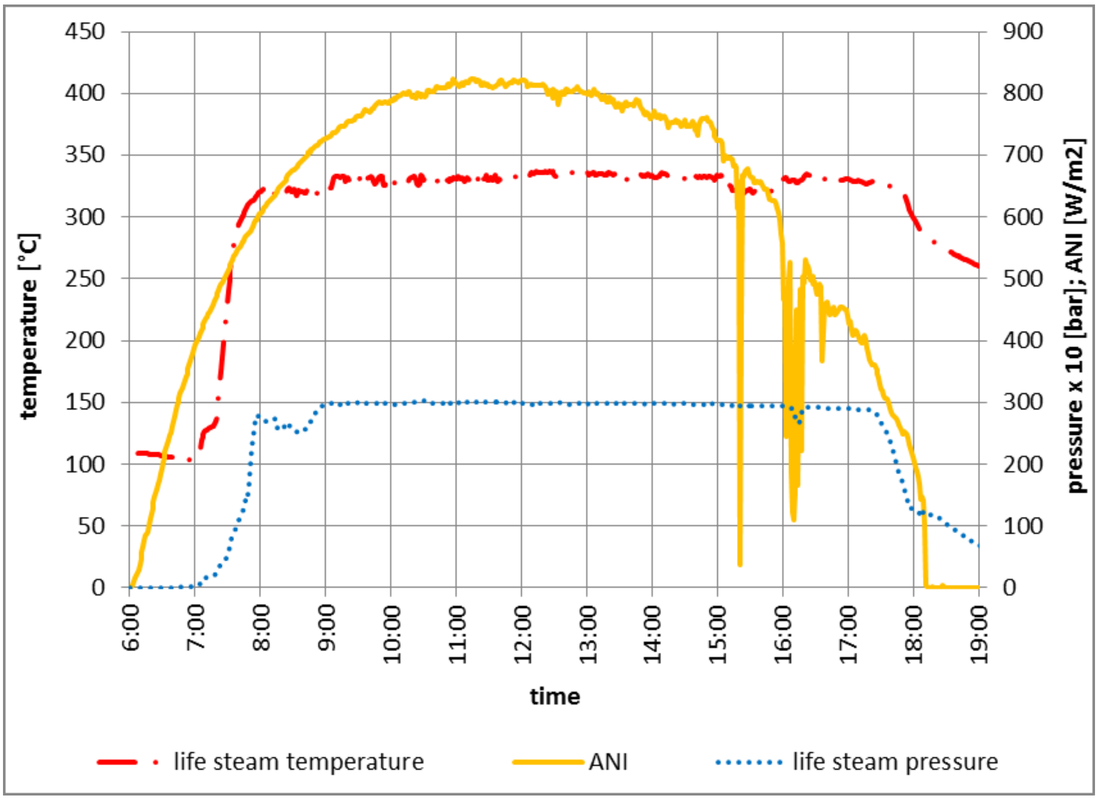

Figure 3: Live steam parameters on an exemplary day of high and constant ANI (11th May 2012)

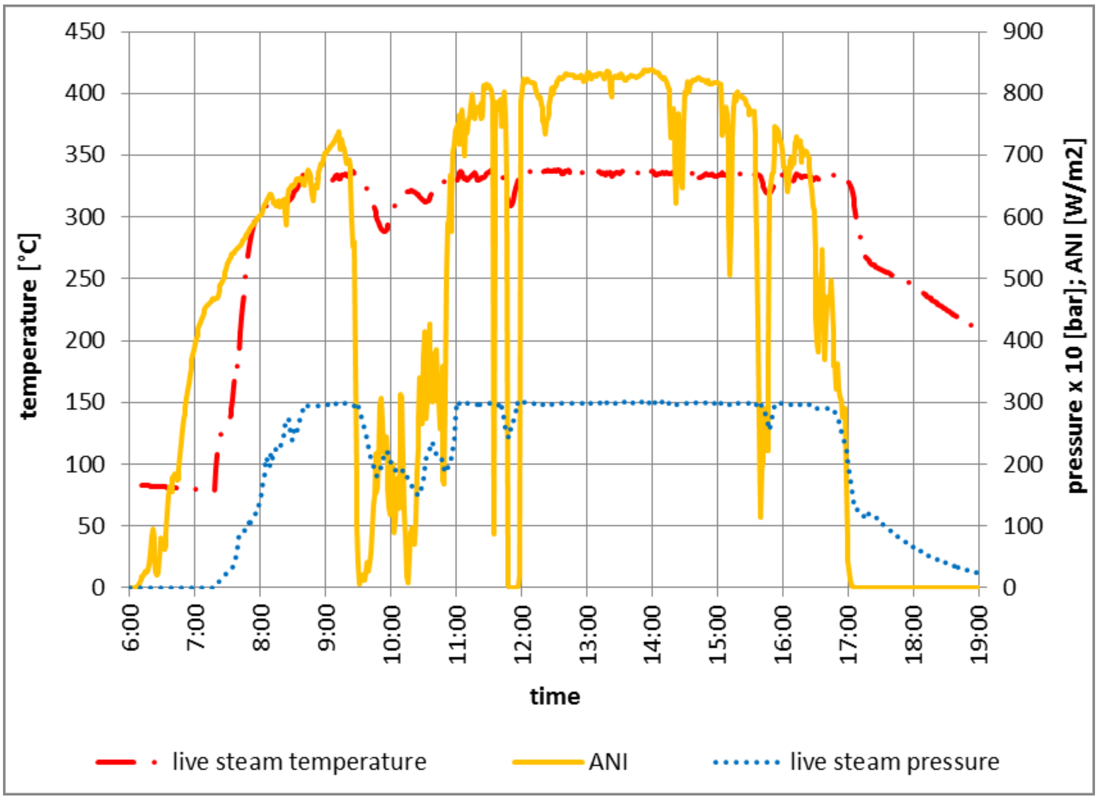

Figure 4: Live steam parameters on an exemplary day of high and fluctuating ANI (4th May 2012)

The steam drum (SD[3]) acts as a steam accumulator (Ruths storage (Tamme et al., 2008)) in the case of interruptions of irradiation: when the pressure is reduced, the saturated water in the SD evaporates. The steam continues to flow into the superheater field and from there to the turbine. The thermal capacity of the superheater field can superheat that steam for a short period even without irradiation. Thus, the turbine can still be operated without harsh temperature gradients for the turbine.

The evaporator and the superheater influence two different live steam values. In the evaporator, a part of the water is evaporated. This steam is separated in the SD and flows via the superheater to the turbine. Hence, the live steam mass flow is determined by the evaporator including the SD. In the superheater, the saturated steam is then superheated. The superheater thus influences the temperature of the live steam (see also (Birnbaum et al., 2011)). Both the evaporator power and the superheater power are directly dependent on the ANI. Therefore, the live steam mass flow and the live steam temperature in the stationary case are also functions of the ANI.

In fact, it can be seen in the measured values in Figure 5 that a change in the ANI (yellow line) always entails a change in the steam mass flow (green line). For example, at around 9:30 the ANI drops from almost 750 W/m² to 0 W/m². A few minutes later, the live steam mass flow also drops from roughly 6 kg/s to 2 kg/s.

Nevertheless, the measured data shows that the live steam mass flow does not only refer to the ANI. A drop of the ANI also leads to a pressure drop in the evaporator and the steam drum, as a result of which it is possible to evaporate for a considerable time. Although the ANI drops to 0 W/m² and stays beneath 400 W/m² for more than one hour, the mass flow does not break down completely, but is only reduced to 2 kg/s. The likewise steep slump in the steam drum level shows that there is flash evaporation. The live steam pressure drops from 30 bar to 15 bar. Thus, the turbine can continue to generate electricity. The electrical power is reduced from about 4 MW to 0.5 MW due to the reduced live steam mass flow.

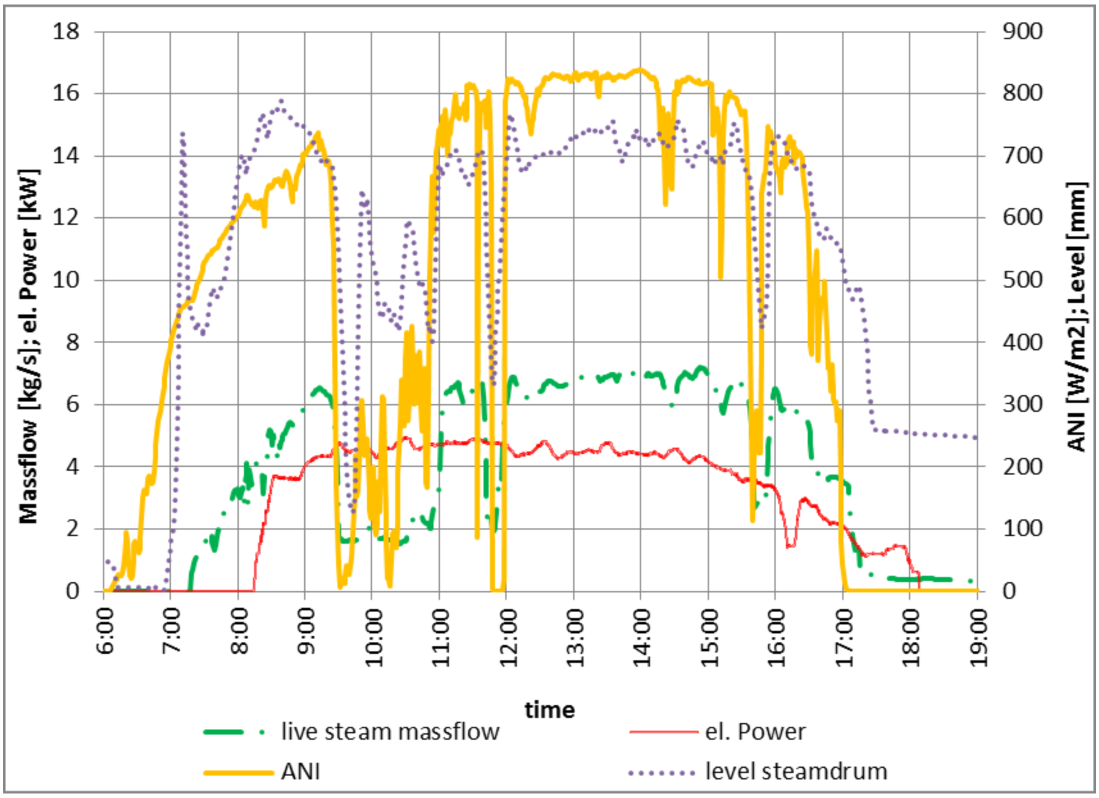

Figure 5: Live steam mass flow in dependence of fluctuating ANI and steam drum level (4th May 2012)

The live steam temperature reacts quite slowly to changes in the irradiation. On the slump of the ANI on the same day around 15:45, the live steam temperature does not react with a major drop (Figure 4). The live steam temperature can be kept relatively constant at 330 °C, with a short minimum at around 320 °C and peak temperature gradients well below 3 K/min. The Superheater is dimensioned large enough to reduce fluctuations in live steam temperature. During the long radiation dip at 09:30, the live steam temperature drops from 330 °C to 290 °C by about 40 K. Due to the pressure drop in the SD, the temperature drop in the SD is also approximately 40 K. In consequence, the live steam temperature can be maintained throughout the day at about 80 K above the SD temperature by the superheater field (Figure 6).

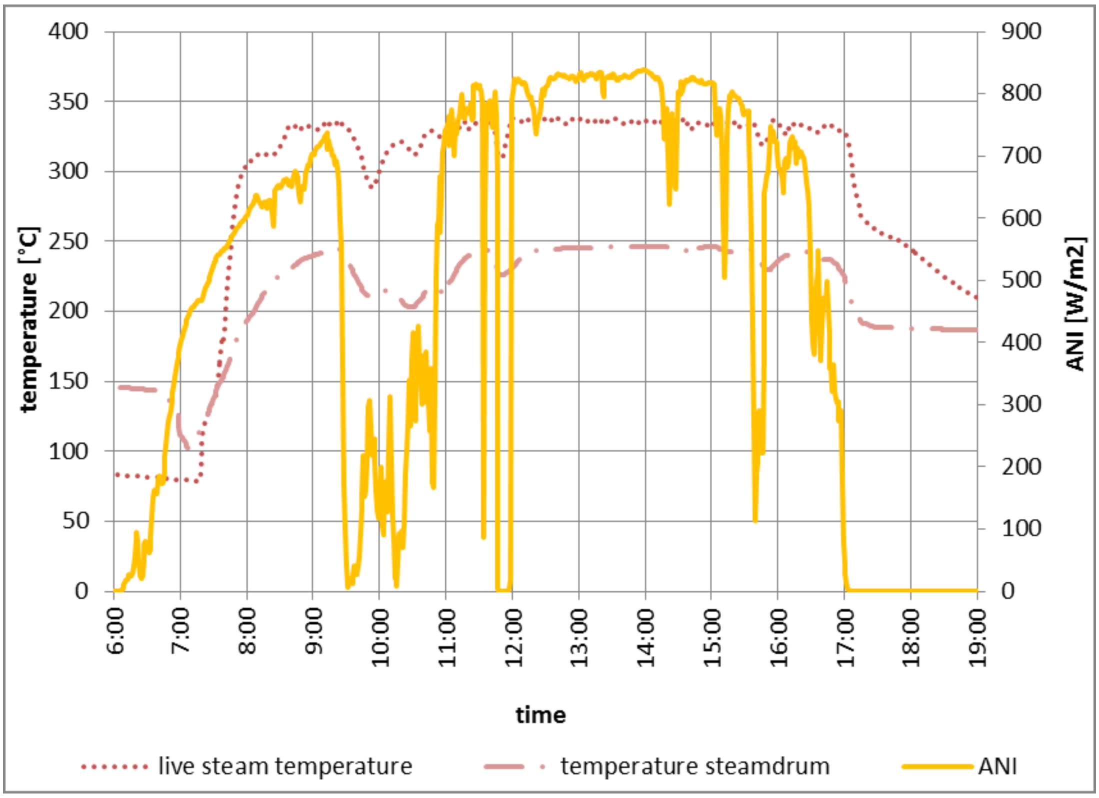

Figure 6: Live steam temperature in dependence of fluctuating ANI and comparison to the steam drum temperature (4th May 2012)

4.2 Evaporator

The recirculation pump moves water from the steam drum through the evaporator field. The pump can ensure a minimum mass flow and can control a desired steam quality at the outlet of the loops. The control valves at the inlet of the evaporator loops divide the flow equally into the parallel loops. One of the main concerns for DSG in parallel loops before the project was that the flow could not be distributed equally and that the parallel loops would influence each other, causing instabilities in control. Operation of the TSE1 eliminated these concerns. A stable parallel flow was demonstrated. As in conventional steam generators, this stability is increased by increasing the pressure level before the inlet valves in order to provide a higher working range for the valves and, thereby, buffer for pressure drop transients in a loop. During normal operation the pressure and temperature levels at the outlet of the loops can be kept fairly stable.

Within an evaporator loop four parameters are controlled independently.

- A Minimum mass flow at the loop inlet
- B Maximum pressure of the steam drum for power limitation
- C Over temperature protection of the entire loop
- D Over temperature protection of every single collector

A) The minimum mass flow of each loop depends on the desired flow pattern within the loop and the desired steam fraction at the outlet of the loop. Annular flow is desired for an optimal heat transfer and moderate temperature gradients within a receiver's cross-section. Annular flow completely wets the inner wall surface and encloses the steam flow. Thereby, the inner wall is cooled uniformly. This is achieved by maintaining a certain minimum mass flow, which can be estimated by a flow regime map. These maps are usually valid only for adiabatic conditions, i.e. without irradiation. A common flow regime map is the one of (Taitel and Dukler, 1976), although others or extended ones for the adiabatic case exist. An overview for the DSG application is provided in (Hirsch et al., 2013). The mass flow to maintain annular flow at adiabatic conditions is increased by a safety factor for irradiation and serves as a minimum mass flow of the evaporation loop.
Furthermore, the steam quality depends on the balance between power input (respectively ANI) and power output. The dissipated heat is mainly controlled by the mass flow. To maintain a stable steam mass fraction at the outlet of the evaporator, the mass flow must increase with rising ANI. Thus, an almost linear dependence of design mass flow on ANI results from a constant steam quality assumption. This dependence should be used as a second mass flow condition to control the inlet mass flow to the evaporation loops. For each ANI, the maximum of the constant value from the flow map and the ANI-dependent value from steam quality design is chosen as recommended mass flow.
The minimum mass flow for the boundary conditions of TSE1 was calculated by DLR with (Taitel and Dukler, 1976). Additionally a minimum mass flow curve in dependence of the ANI was calculated with a heat balance and recommended to Solarlite during the design phase of TSE1. The minimum mass flow has to be calculated anew for every solar field layout and location, more precisely, ANI profile. The control system of the TSE1 was supposed to allow a focusing of the mirrors only when the minimum mass flow in the corresponding loop is reached. Evaluation of the operational data of the TSE1 shows that the minimum mass flow has not been kept in all situations. The respective control was either removed or the minimum mass flow implemented was reduced by the operator. In addition, the collectors were sometimes focused, although the mass flow was not yet established sufficiently. Both situations may lead to superheating in the evaporator, which is explained below.

B) If the power input is too high and the turbine cannot take more steam mass flow, the excess power input will lead to an increase in the pressure level of the steam drum and the evaporation section. In order to limit the power input, a limit to the pressure level can be established. If the pressure is too high, collectors must be defocused. Furthermore, steam drum pressure and saturation temperature are strictly related within the evaporation section. Thus, a pressure limit can be reformulated as a temperature limit. As a result, in order to automatically limit the incoming power and protect the system from overpressure, the temperature at the collectors may not exceed a certain maximum temperature. Otherwise, the collector will be defocused until the temperature is below the limit again. This defocus temperature can be changed by the operator, which should not be the case.

Evaluation of the TSE1 data showed that the operator changed the defocus temperatures of the collectors during the year. When they were chosen too low, the collectors defocused too often. Especially, when all collectors in one loop had the same defocus temperature, the collectors at the beginning of the loop defocused first, which led to non-minimum phase (NMP[3]) behaviour and, in the worst case, caused superheating events (both described below).

C) To protect the components in the evaporator from temperatures higher than their design temperature, all collectors of one loop will defocus as soon as the temperature at the outlet of the evaporator exceeds a maximum temperature. This temperature should not be allowed to be manipulated by the operator.

D) To prevent every single collector from superheating, each collector can be defocused once it reaches a certain individual temperature. This temperature can be changed by the operator. If the plant is run at low pressure, the related superheating temperature limit is reduced. In general, it should be some degrees above the current saturation temperature.
To summarize, rule A guarantees a minimum mass flow, while rules B, C and D limit the temperature. In TSE1, the temperature limits of B to D seem to be implemented or used as one rule, although having different intentions. Data of TSE1 suggests that the four basic rules could sometimes be ignored by the operators. The suggested steam quality at the outlet of the evaporator loops seemed to be ignored as well. By combinations of those operational mistakes, superheating events were observed in the TSE1 evaporator.
Superheating events in the evaporator can be critical for the absorber tubes and can lead to a decrease in life time expectancy. Superheating occurs when all water within a pipe section is evaporated and all additional energy input leads to an increase in temperature. This may lead to exceeding the receivers' design temperature, which might be lower than the design temperature in the superheating section. A rapidly increasing steam temperature also means a high temperature gradient from the inlet of the receiver tube to the outlet of the receiver tube. The most relevant problem however arises from the temperature gradients around a receiver's cross-section (Eck et al., 2004, Eck and Steinmann, 2005, Steinmann and Eck, 2000). These gradients can lead to increased tension in the material and can therefore decrease the life time expectancy significantly. The main problem does not lie in the section with the superheating, but already in the section before with a low liquid share. The ideal annular flow requires a sufficiently fast flow and a sufficiently high liquid ratio. Otherwise, a stratified flow with water at the bottom and steam on top can develop, which leads to a higher gradient in the cross-section than with superheated steam only. This phenomenon is amplified, if the irradiation is incident from the side rather than from the bottom. Analysis with an FEM (finite element method) model for the once-through mode, for which a direct transition from evaporation to superheating is unavoidable, showed that such short stratifications are not necessarily critical (Feldhoff, 2016, Rosselló Robert, 2015). However, the evaporation section of a recirculation mode plant as TSE1 is usually not designed for such conditions. Vice versa, it is designed to have a large excess of liquid available even at the outlet of the loop. Therefore, superheating events indicate a potentially critical off-design case, which shall and can be avoided.
Nevertheless, the complexity of the system suggests analysing the reasons for superheating events in the evaporation section in the following. Data analysis resulted in three main circumstances that increase the likeliness of superheating events. Those circumstances are

(1) a decrease in the temperature at the entrance of the evaporator, which is usually caused by an increase in the feed water flow,
(2) a simultaneous focusing of all collectors in one loop at once as well as
(3) a too low or disturbed mass flow through the loop.

1. Decrease of the temperature at the entrance of the evaporator

A decrease of the inlet temperature results in a disturbance of the enthalpy at the entrance of the evaporation section. The system reaction at the loop outlet shows an initial counter-reaction in the opposite direction. At first, the enthalpy decrease at the inlet results in a strong enthalpy increase at the outlet. Only after that, the outlet enthalpy converges to a final state lower than the initial one. This phenomenon is called “non-minimum phase” (NMP) behaviour in control theory. This behaviour is already theoretically and experimentally proven from once-through DSG systems(Feldhoff et al., 2015, Lippke, 1996).
The decrease in enthalpy at the beginning of the loop or evaporation section, respectively, results in a disturbance in the specific volume and pressure drop profile along the loop, which in turn reduces the steam flow rate especially at the loop outlet. This temporarily leads to a longer residence time of the steam, a higher solar energy input and a higher enthalpy at the outlet of the loop. In recirculation mode plants, this behaviour is ideally not visible, since a higher enthalpy only leads to a higher steam quality at the evaporation loop outlet. Only if the resulting enthalpy exceeds the saturation enthalpy, the behaviour is visible by an increase in temperature.
The decrease of the temperature at the entrance of the loop can be triggered by different events, e.g. 1) by an increase in the feed water mass flow, since it has a lower temperature than the water from the steam drum and the mixed flow is led to the inlet; 2) by a defocusing of one of the first collectors in a loop; as well as 3) by a cloud that shades only the section close to the entrance of the loop.
The intensity of the NMP reaction depends on the location of the disturbance. It is the most intense close to the initial location of boiling and decreases with the local disturbance acting further downstream.
A dynamic simulation with the boundary conditions of a TSE1 evaporator loop shows the influence of an exemplary temperature drop on the steam quality for exemplary inlet temperatures (Figure 7). The nominal initial conditions of the simulation (“nom.”) are assumed to be an inlet mass flow $m_{in,nom}$ = 1.4 kg/s, constant *ANI* = 620 W/m², inlet temperature $T_{in,0,nom}$ = 200 °C. The resulting nominal steam quality is $x_{out,0,nom}$ = 41 %. The result of a temperature disturbance depends on the mass flow, the initial temperature, the amplitude of the temperature disturbance (all three exemplified in Figure 7) as well as the temporal gradient of the inlet temperature disturbance (exemplified in (Feldhoff, 2016) for a different loop). Figure 7 shows four variations of an inlet temperature step disturbance. All steps of the temperature are performed within one minute (left graph). The resulting temporal behaviour of the steam quality at the outlet of the evaporation loop is depicted in the graph on the right hand side. A drop of T_{in} by 20 K results in an intermediate peak at 56 %, before it reaches the final steam quality at around 36 %. A drop of T_{in} by 40 K shows a peak at about 70 %. Such changes are not visible in the real plant, since the saturation temperature is not exceeded and remains constant during the whole time. Steam quality cannot easily be measured in a real plant. The simulated temporal behaviour of the nominal case does not reveal critical peaks, although a particular analysis on flow conditions with 70 % steam quality may be reasonable. A higher initial inlet temperature $T_{in,0}$ = 230 °C (“highTin”) corresponds to a higher initial steam quality ($x_{out,0}$ = 49 %), as the same heat input is

assumed for all loops here. The inlet temperature disturbance now results in a peak at about 94 % steam quality. The liquid share is already very low and disadvantageous temperature gradients might already appear in a cross-section. The fourth variation considers a lower initial inlet mass flow m_{in} = 1.0 kg/s ("lowM"). The initial resulting steam quality is 63 %. The inlet disturbance then leads to an outlet steam quality peak > 1, which is superheating, about 11 minutes after the disturbance. Only then, the disturbance is measurable at the outlet and the collectors may defocus for safety. As a conclusion, a high mass flow in the evaporation zone, equivalent to a high recirculation rate, has significant advantageous for the transient behaviour of a DSG system.

The resulting temperature gradients within a cross-section can either be modelled by an FEM model (Feldhoff et al., 2016, Roldán et al., 2013) or they can be measured by special receivers equipped with thermocouples around the circumference, as in the DISS (Zarza, 2002) and the DUKE (Feldhoff et al., 2012) projects.

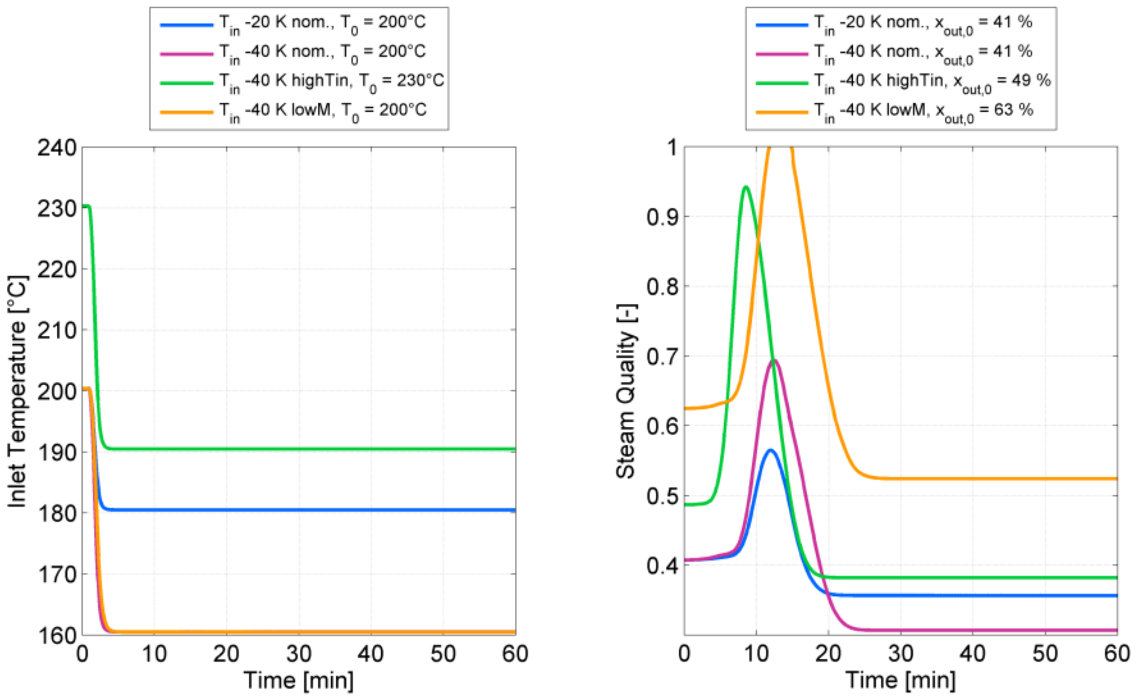

Figure 7: Variation of inlet temperatures and step response of the outlet temperature of a 696 m evaporator loop, simulation by DLR's Dymola tool; nominal conditions: inlet mass flow m_in = 1,4 kg/s at 620 W/m² ANI and initial inlet temperature T_in,0 = 200°C; highTin with T_in,0=230°C; lowM with m_in=1,0 kg/s; Temperature change within 1 min.

2. Simultaneous focusing of all collectors in one loop

Simultaneous focusing of all collectors of one loop at once is one reason for overheating during start-up. Prior to focusing, water at low pressure flows through the evaporator loops. When all mirrors focus simultaneously, a sudden increase in energy input occurs. This may lead to a situation, at which the first steam bubbles do not only appear at the beginning of the loop, but at the same time further downstream. The pressure drop profile gets locally disturbed. As a result, the flow through the collector loop may be blocked and strong overheating within the loop, not necessarily at the outlet, can be evoked.

This phenomenon cannot be analysed by TSE1 data because of a lack of pressure sensors within the loop. It would be interesting to research this subject, for example at the DISS-test loop. A simple solution exists though. Instead of focusing all the collectors at the same time, the collectors should be focused one after the other, from inlet to outlet. Thereby, the power gradient is lower. This keeps the desired pressure gradient towards the steam drum and safely avoids superheating.

3. Too low or disturbed mass flow through the receiver tube

The energy introduced into the absorber tubes by the solar radiation is carried away as heat from the water and steam. While some of the water evaporates, the excess water serves as a coolant to prevent overheating in the evaporator. It is therefore always necessary to ensure sufficient excess of water in each evaporator loop.
The operating data shows that on days of very high solar irradiation lower mass flows were often used instead of the recommended mass flow for operation, which increased the steam quality at the outlet and sometimes led to superheating during certain transient situations.
A simulation in Dymola shows the impact that a change in inlet mass flow has on the steam mass flow and the ratio between the differences in specific enthalpies [x=(h_steam-h_satuation,liquid)/(h_satuaton,steam-h_satuation,liquid)] as an indicator of the steam quality at the loop outlet (Figure 8). This ratio is introduced to be able to show the steam quality of wet steam and the transition to superheated steam in one diagram. A ratio x<1 represents the steam quality of wet steam, x=1 indicates saturated steam while a ration x>1 indicates superheating.

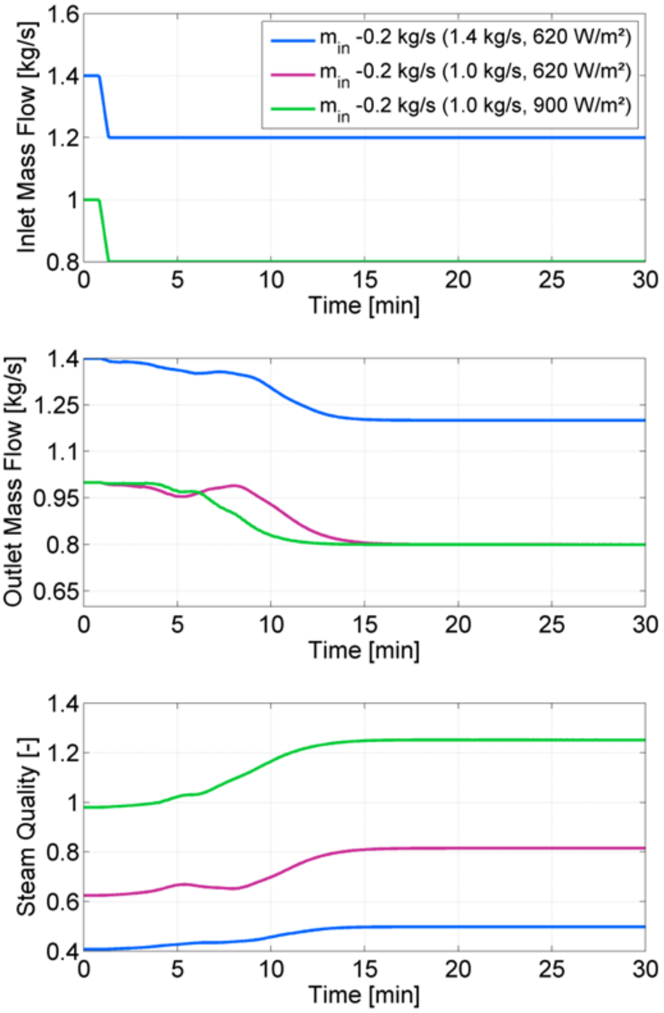

Figure 8: Simulation of the total outlet mass flow and the ratio of the differences in specific enthalpies

Every drop in inlet mass flow leads to an increase in outlet steam fraction. A mass flow of 1.4 kg/s offers a buffer for all irradiation conditions. A mass flow of 1.0 kg/s seems reasonable for ANI values of 620 W/m², but results in almost saturation for steady-state conditions at 900 W/m² (time 0 in the graphs). If another disturbance occurs, superheating occurs very quickly. Such a disturbance can be a focus/defocus of a collector, a short valve fluctuation or a short lower mass flow set point. In general, the greater the inlet mass flow is, the lower is the outlet steam fraction and, therefore, the higher is the robustness against a drop in mass flow or other transients, as for example a local disturbance in mass flow caused by a small sudden shading or defocussing of only one collector (Krüger et al., 2016, Lobón et al., 2014). This benefit of a higher mass flow has to be balanced against the higher investment costs and the higher energy consumption of the pump. The simulations show that a change in inlet mass flow takes about 10 to 15 min until the final steam quality is reached at the outlet. In addition, this transient is not smooth, but can show a stepwise behaviour, e.g. the transition of 1.0 kg/s at 620 W/m² in Figure 8. In a real plant, not only the inlet mass flow changes, but usually it is evoked by a change in irradiation. For example, a drop of ANI evokes a controlled reduction of the inlet mass flow. If the irradiation then increases again, the inlet mass flow is re-established as well. However, due to the time delay of the reaction, the high ANI can coincide with a low steam mass flow at the loop outlet. If the steam quality was chosen with very low buffer, a short superheating could occur –even though the single instantaneous values of inlet mass flow and ANI correspond well to each other. A reasonable buffer in steam quality and a good control strategy can avoid potential superheating events safely.

4.3 Superheater

Each superheater loop independently increases the temperature of its flow from saturation to the desired outlet steam temperature. Two collectors are connected in series to form one loop. The distribution of the mass flows onto the parallel loops is not controlled, but provided by the geometry of the piping and a hand valve at the inlet of the loop, which is a well working solution. The hand valves must only be adjusted once during commissioning and checked regularly, which is similar to solar fields with oil. The pressure drop over the superheater is defined by the pressure of the turbine and the pressure of the evaporator. The steam mass flow varies according to the pressure levels.

The main control of the superheater concerns the steam temperature. The target value of the steam temperature at the outlet of the superheater should be slightly above the live steam temperature in order to compensate for the heat losses of the header. This value is manually adjustable by the operator.
In TSE1, two possibilities to control the live steam temperature are implemented. A two-step-control with hysteresis for defocussing the collectors is regularly used. Additionally, a temperature control with injection coolers was tested. This control mechanism was probed at the DISS-instalation before (Valenzuela et al., 2006).
With both strategies, supported by a high thermal capacity of the live steam header, the desired live steam temperature and pressure can be maintained well within acceptable boundaries for the turbine.

1. Control of the superheated steam temperature by defocussing

In regular operation of TSE1, defocusing of the superheating collectors is used to regulate the steam temperature. A simple on-off feedback control with hysteresis is used for each

collector. The measurement is carried out in the steam downstream the collector. If the measured value exceeds the upper setpoint, the collector defocusses to reduce the energy input. As soon as the temperature gets below the lower temperature setpoint, the collector is turned back into the focus again to provide more energy to the system. This results in a frequently varying temperature.
Since the superheater field of TSE1 was oversized by one loop as a precaution and to allow for injection control, the steam mass flow from the evaporator could be distributed to more superheater loops than needed. This results in low mass flows per loop and leads to a frequent defocussing and refocusing. This frequency can be reduced by not operating one or two of the superheater loops.
Dynamically, the on-off control is unfavourable, since the temperature drops quickly below the refocus value during the process of defocusing. However, a refocusing is only possible when the defocusing has been completed. The resulting amplitude of the temperature hysteresis is correspondingly high, at maximum in the range of the collector's steady-state temperature difference between inlet and outlet. The temperature variation at the outlet of the loop is smoothened by the thermal capacity of the header piping and by the mixing of the parallel steam flows. Nevertheless, the dynamic behaviour becomes worse, if the first collector of the superheating loop is also working with permanent on-off-control. This situation occurs, if the upper setpoint for defocusing is below the steady-state temperature at the outlet of the first collector. This steady-state temperature arises from the steam mass flow and the ANI conditions. If the steady-state temperature at the outlet is below the upper limit, the first collector can remain in focus and does not impose additional transients to the following collector.
The operational data was statistically analysed for the on-off defocus control. Statistically, the first collector of each superheating loop is defocused 53 times a day on average. The second collector of a loop is defocused 71 times on average. In average, 45 % of the superheater area is not used. With regard to the evaporator, 76 % of the collector area is focused on average, which means a loss of about 24 % of the power irradiated onto the evaporator area. This unavailability was mainly caused by a lightning strike within the period of the data, which kept two evaporation loops out of work for a long period. A reduction in energy input to the evaporator also causes a loss of the same share in the superheater. In consequence, about 24 % of the superheater defocus times are due to evaporator defocusing and the remaining 21 % are attributable to the defocus control. The later corresponds to 3.6 % of the total area.
A simple proportional-integral (PI[3]) controller would already improve the defocus control significantly. Furthermore, no feedforward action is used so far, which would also contribute significantly to controller performance. Such control can be foreseen for future plants, but could not be implemented for TSE1.

2. Control of the superheated steam temperature with injection coolers

The use of the injection coolers replaces the above-described on-off control of the collectors. The upper setpoint values of both collectors are chosen such that they remain focused until a critical value is reached. The desired outlet temperature is then only influenced and controlled by the mass flow of the injection cooler. The goal is to always keep the collectors in focus to generate as much steam as possible. The corresponding control is state of the art and has already been developed and tested in the DISS project (Eck et al., 2003). There are different ways of implementation, from simple to advanced. A basic control system with a good control quality was designed as part of the DUKE project for the once-through concept (Feldhoff et al., 2016, Feldhoff and Meyer-Grünefeld, 2016). The control strategy used for the

injection in the superheater section can also be applied for the recirculation concept. The temperature before the injection is measured and the injection mass flow is adapted by a feedforward control. When the first collector is defocussed, the resulting temperature wave is already significantly compensated for. The fine adjustment of the outlet temperature is achieved by means of an adaptive PI controller. Details can be found in (Feldhoff, 2016).
The operating behaviour at TSE1 during tests with injection cooling is appropriate. The injection rate is dependent on the focused collector areas. On the 3rd of April in 2012, for example, all collectors were in operation. The injection rate averaged to 6.6 % of the live steam mass flow due to the relatively higher superheater area. The oversizing can thus be exploited for higher steam production, as originally foreseen during the design phase of TSE1. With defocusing control, steam production takes place solely in the evaporator and no additional yield from excess superheater area can be gained. About 6.6 % of energy is additionally gained at TSE1 by using the injections. In combination with the 3.6 % lost due to the simple implementation of on-off defocus control the yield of TSE1 could be increased by about 10 % in total when using a good PI injection control with feedforward in the superheater.
Furthermore, when the injection coolers are used, temperature gradients in the superheater are significantly reduced, whereas high undesirable gradients can occur without injection coolers. This control strategy is therefore recommended from an operational point of view for future power plants with recirculation concept and superheating. On a financial project basis, the benefit of additional yield and operational stability must be traded off against the additional initial cost of injection coolers.

5. Lessons learned and recommendations for future DSG plants

Operation of TSE1 demonstrates that DSG with superheating is a reliable option to provide live steam with stable parameters to a steam turbine. Even during highly fluctuating ANI, TSE1 can reliably generate electricity due to the buffer function of the steam drum, the high thermal capacity of the live steam header and the flexible steam turbine.
The basic layout of TSE1 proved to be functional. Sufficiently high pressure drops over the inlet valves of the evaporator loops guarantee a stable and parallel flow, ensure controllability and prevented static instabilities (Ledinegg, 1938).
It could be confirmed that the setting of manual throttle valves at the superheater loop inlet ensures a uniform distribution of the mass flow in the parallel loops. The distribution remains equally even during partial load and start-up. No active mass flow control is required at the entrance to the superheater loops. This design concept for the superheater field was confirmed and should therefore also be retained for future power plants.
The analyses showed that various parameters and control strategies recommended in the design phase were not adhered to. Also thresholds and values implemented during commissioning seem to have been changed later on. The reasons for those changes and the exact implementation cannot be retraced from the data. Nevertheless, an obvious statement is that well trained staff is essential for a safe and stable operation. An extensive and restrictive automatic control is necessary to make the operation more independent from the individual skills of the operators.
From experience with the operation of TSE1, the following advices can be given regarding the control of the evaporator and the superheater field:

Evaporator control:

- The minimum mass flow should be fixed in the control system and must not be skipped or modified.
- The minimum mass flow should be extended by a radiation component. On days with a high ANI, a higher evaporator mass flow should be set to ensure a low steam content and to prevent overheating. A corresponding control is easily possible in a recirculation solar field. It is sensible that the loop mass flow is linked to the maximum possible (clear sky) ANI and not only to the measured value. As a result, a maximum buffering effect is achieved and strong fluctuations in the drum filling level are avoided or reduced.
- Defocusing and refocusing should be slow to avoid gradients and mass flow oscillations. Otherwise, control valves must work very hard and can influence each other.
- Focusing of a loop should start with the first collector and continue downstream. Defocusing should start with the last collector and continue upstream. Never focus all collectors simultaneously or from back to front!
- The maximum temperature for defocusing of collectors in an evaporator loop should be descending (for inlet collector higher than for outlet collector) to prevent non-minimum phase deflections.
- The special dynamics of a solar evaporator are very complex. At the same time, the state at the exit of an evaporator loop is neither measurable nor observable. The condition at the exit of the loop should therefore be estimated and, ideally, predicted in order to be able to guarantee safe operation. In addition, state estimation provides better prediction of the steam drum level, which can be very helpful for reducing the drum's size (and cost). The development of good non-linear state estimators therefore appears to be a very relevant research subject.
- In order to better evaluate the behaviour of the flow at the loop outlet, a velocity measurement of the medium would be desirable at this point (for example by means of a Prandtl probe). Because of the two-phase mixture of the medium, no statement can be obtained about the mass flow; however, a measurement of the velocity changes can give a hint about the relative behaviour of the flow during particular events. This could be tried in a test loop (DISS plant, new power station) and used as a supplement to a state estimator.

Superheater control:

- An on-off defocusing temperature control results in a hysteresis with high temperature amplitude at the loop outlet. Instead, a PI control seems more reasonable, ideally accompanied by a feedforward action and adaptive features.
- In TSE1, a permanent energy gain of about 6-7 % would result from the use of the installed injection coolers compared to a perfectly adopted defocus control. This gain would be due to the oversizing of the superheater field to allow for reasonable injection control, as was foreseen during the design phase. In any case, the ratio of superheating to evaporation area is one of the most important design parameters of a recirculation mode plant.
- In particular days with active injection coolers and good ANI conditions showed uniform temperature behaviour and no significant fluctuations during commissioning. The control strategy and design procedure for an injection cooler in the recirculation

concept can directly be taken from the once-through concept, which has been developed within the project (Feldhoff and Meyer-Grünefeld, 2016).

The data analysis has further confirmed the confidence in DLR's detailed transient simulation tools. Complex situations can be represented well and modelling of a whole plant can be used for the optimisation of future plants, e.g. regarding steam drum sizing or control strategy improvements.

6. Conclusions

The TSE1 plant is the first commercial power station with DSG in parabolic troughs.
A stable operation was demonstrated. Even in the highly fluctuating weather conditions of Kanchanaburi province, the plant could operate and generate electricity reliably. The experience shows that DSG is a feasible alternative to the conventional parabolic trough plants with thermal oil. The turbine of TSE1 operates at 330 °C, but solar field operation at higher temperatures up to 550 °C has been demonstrated (Alguacil et al., 2014, Eck et al., 2011). With the experience of TSE1, a larger DSG power plant with a higher rated power and higher live steam temperatures is conceivable.

7. Funding:

This work was supported by the German Federal Ministry for Economic Affairs and Energy [grant number 0325483A].

8. References:

Agora_Energiewende, 2017. Flexibility in thermal power plants - With a focus on existing coalfired power plants. Prognos AG and Fichtner GmbH & Co. KG Report, 115/04-S-2017/EN.

Alguacil, M., Prieto, C., Rodriguez, A., Lohr, J., 2014. Direct Steam Generation in Parabolic Trough Collectors. Energy Procedia, 49, 21-29.

Birnbaum, J., Feldhoff, J.F., Fichtner, M., Hirsch, T., Jöcker, M., Pitz-Paal, R., Zimmermann, G., 2011. Steam temperature stability in a direct steam generation solar power plant. Solar Energy, 85, 4, 660-668.

Eck, M., Zarza, E., Eickhoff, M., Rheinländer, J., Valenzuela, L., 2003. Applied research concerning the direct steam generation in parabolic troughs. Solar Energy, 74, 4, 341 - 351.

Eck, M., Steinmann, W.-D., Rheinländer, J., 2004. Maximum temperature difference in horizontal and tilted absorber pipes with direct steam generation. Energy, 29, 5-6, 633-659.

Eck, M., Steinmann, W.-D., 2005. Modelling and Design of Direct Solar Steam Generating Collector Fields. Journal of Solar Energy Engineering, 127, 371-380.

Eck, M., Benz, N., Feldhoff, J.F., Gilon, Y., Hacker, Z., Müller, T., Riffelmann, K.-J., Silmy, K., Tislaric, D., 2008. The Potential of Direct Steam Generation in Parabolic Troughs - Results of the German Project DIVA. Proceedings of the 14th SolarPACES Symposium, Las Vegas, USA.

Eck, M., Eickhoff, M., Feldhoff, J.F., Fontela, P., Gathmann, N., Meyer-Grünefeldt, M., Hillebrand, S., Schulte-Fischedick, J., 2011. Direct Steam Generation in parabolic troughs at 500°C - First results of the REAL-DISS project. Proceedings of the 17th SolarPACES Conference, Granada, Spain.

Feldhoff, J.F., Benitez, D., Eck, M., Riffelmann, K.-J., 2009. Economic Potential of Solar Thermal Power Plants with Direct Steam Generation compared to HTF Plants. Proceedings of the ASME 2009 3rd International Conference of Energy Sustainability, San Fransisco, CA, USA.

Feldhoff, J.F., Eickhoff, M., Karthikeyan, R., Krüger, J., León Alonso, J., Meyer-Grünefeldt, M., Müller, M., Valenzuela Gutierrez, L., 2012. Concept comparison and test facility design for the analysis of direct steam generation in once-through mode. Proceedings of the 18th SolarPACES Conference, Marrakech, Morocco.

Feldhoff, J.F., Hirsch, T., Pitz-Paal, R., Valenzuela, L., 2015. Transient Models and Characteristics of Once-through Line Focus Systems. Energy Procedia, 69, 0, 626-637.

Feldhoff, J.F., 2016. Analysis of Once-Through Boiler Concepts in Parabolic Troughs. Shaker Verlag.

Feldhoff, J.F., Hirsch, T., Pitz-Paal, R., Valenzuela, L., 2016. Analysis and potential of once-through steam generators in line focus systems – Final results of the DUKE project. AIP Conference Proceedings, 1734, 1, 100006.

Feldhoff, J.F., Meyer-Grünefeld, M., 2016. DUKE Abschlussbericht - Entwicklung und Erprobung des Durchlaufkonzepts in Parabolrinnen-Kraftwerken mit solarer Direktverdampfung. DLR Report, 3005406.

Hirsch, T., Feldhoff, J.F., Hennecke, K., Pitz-Paal, R., 2013. Advancements in the Field of Direct Steam Generation in Linear Solar Concentrators—A Review. Heat Transfer Engineering, 35, 3, 258-271.

Khenissi, A., Krüger, D.R., Hirsch, T., Hennecke, K., 2015. Return of Experience on Transient Behavior at the DSG Solar Thermal Power Plant in Kanchanaburi, Thailand. Energy Procedia, 69, Proceedings of the SolarPACES 2014 Conference, 1603-1612.

Krüger, D., Krüger, J., Pandian, Y., Feldhoff, J.F., Eck, M., Eickhoff, M., Hennecke, K., 2010. Kanchanaburi Solar Thermal Power Plant with Direct Steam Generation – Layout. Proceedings of the 16th SolarPACES Conference, Perpignan, France.

Krüger, D., Krüger, J., Pandian, Y., O'Connell, B., Feldhoff, J.F., Karthikeyan, R., Hempel, S., Muniasamy, K., Hirsch, T., Eickhoff, M., Hennecke, K., 2012. Experiences with Direct Steam Generation at the Kanchanaburi Solar Thermal Power Plant. Proceedings of the 18th SolarPACES Conference, Marrakech, Morocco.

Krüger, D., Willwerth, L., Feldhoff, J.F., Khenissi, A., Eickhoff, M., Keller, L., 2016. KanDis: Wissenschaftliche Begleitung der Direktverdampfung im Kanchanaburi Kraftwerk - Schlussbericht. German Aerospace Center (DLR) Institute of Solar Research Report, Köln.

Ledinegg, M., 1938. Instability of flow during natural and forced circulation. Die Wärme, 61, 8, 891-898.

Lippke, F., 1996. Direct Steam Generation in Parabolic Trough Solar Power Plants: Numerical Investigation of the Transients and the Control of a Once-Through System. Journal of Solar Energy Engineering, 118, 1, 9-14.

Lobón, D.H., Valenzuela, L., Baglietto, E., 2014. Modeling the dynamics of the multiphase fluid in the parabolic-trough solar steam generating systems. Energy Conversion and Management, 78, 0, 393-404.

Mertins, M., Link, E., Tscheche, M., Leuckel, H., 2012. Expericences of operation of 30 MW solarthermal power station based on Fresnel collector technology. Proceedings of the 18th SolarPACES Conference, Marrakech, Morocco.

Morin, G., Kirchberger, J., Lemmertz, N., Mertins, M., 2012. Operational results and simulation of a superheating Fresnel collector. Proceedings of the 18th SolarPACES Conference, Marrakech, Morocco.

Roldán, M.I., Valenzuela, L., Zarza, E., 2013. Thermal analysis of solar receiver pipes with superheated steam. Applied Energy, 103, 0, 73-84.

Rosselló Robert, A., 2015. Charakterisierung der thermo-mechanischen Belastungen eines Parabolrinnen-Solarkraftwerks, in, TU Munich and DLR Stuttgart.

Steinmann, W.-D., Eck, M., 2000. Direct Solar Steam Generation in Parabolic Troughs: Thermal Stress due to Variations in Irradiation. Proceedings of the 10th SolarPACES Symposium, Sydney.

Taitel, Y., Dukler, A.E., 1976. A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow. AIChE Journal, 22, 1, 47-55.

Tamme, R., Bauer, T., Buschle, J., Laing, D., Müller-Steinhagen, H., Steinmann, W.-D., 2008. Latent heat storage above 120°C for applications in the industrial process heat sector and solar power generation. International Journal of Energy Research, 32, 3, 264-271.

Valenzuela, L., Zarza, E., Berenguel, M., Camacho, E.F., 2006. Control scheme for direct steam generation in parabolic troughs under recirculation operation mode. Solar Energy, 80, 1, 1-17.

Willwerth, L., Müller, S., Krüger, J., Succo, M., Feldhoff, J.F., Tiedemann, J., Pandian, Y., Krüger, D., Hennecke, K., 2016. Steam Drum Design for Direct Steam Generation, in: SolarPACES Conference, Abu Dhabi, United Arab Emirates.

Zarza, E., 2002. DISS Phase II Project - Final Project Report. Report, EU Contract No. JOR3-CT98-0277; DISS Document DISS-MQ-QA-48, Almeria, Spain.