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Techno-Economic Optimization of Molten Salt Solar Tower Plants

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Abstract. In this paper the results of a techno-economic analysis of improved and optimized molten salt solar tower plants (MSSTP plants) are presented. The potential improvements that were analyzed include different receiver designs, different designs of the HTF-system and plant control, increased molten salt temperatures (up to 640°C) and multi-tower systems. Detailed technological and economic models of the solar field, solar receiver and high temperature fluid system (HTF-system) were developed and used to find potential improvements compared to a reference plant based on Solar Two technology and up-to-date cost estimations. The annual yield model calculates the annual outputs and the LCOE of all variants. An improved external tubular receiver and improved HTF-system achieves a significant decrease of LCOE compared to the reference. This is caused by lower receiver cost as well as improvements of the HTF-system and plant operation strategy, significantly reducing the plant own consumption. A novel star receiver shows potential for further cost decrease. The cavity receiver concepts result in higher LCOE due to their high investment cost, despite achieving higher efficiencies. Increased molten salt temperatures seem possible with an adapted, closed loop HTF-system and achieve comparable results to the original improved system (with 565°C) under the given boundary conditions. In this analysis all multi tower systems show lower economic viability compared to single tower systems, caused by high additional cost for piping connections and higher cost of the receivers.

INTRODUCTION

In recent years the growth and success of renewable power generation on a worldwide scale is a continuous development. Concentrated solar power technologies (CSP) also contribute to that trend, with various operating plants. Compared to other renewable power technologies, concentrated solar power offers the advantage to include a thermal storage system, which allows dispatchable or even base load power generation.

The main characteristic of a molten salt solar tower plant (MSSTP) is the use of a molten salt mixture as heat transfer and storage medium. The salt is a mixture of roughly 60 % NaNO₃ and 40 % KNO₃ and is commonly referred to as solar salt. Most MSSTP operate within a temperature range of 290°C to 565°C and use an external tubular receiver similar to the Solar Two experimental plant [1], [2], [3], [4]. Using molten salt for thermal energy storage is very cost efficient. This gives the technology an advantage compared to other regenerative energy sources (wind, photovoltaics), where large scale storage is still not economically or technologically viable. However, a further cost reduction is necessary to remain competitive in the future.

OVERVIEW OF VARIANTS AND BOUNDARY CONDITIONS

There are various options to improve the performance and economic feasibility of molten salt tower plants. In the HPMS project the focus was put on improvements of the high temperature fluid system (HTF-system) and the receiver system along four different paths. An overview of all the considered variants is given in Table 1.

- Receiver concept and design
- High temperature fluid system (HTF-system) design and plant operation
- Increased upper fluid temperature
- Multi tower systems

To investigate the findings of the research project, a hypothetical 125 MW_{el} MSSTP located in Postmasburg, South Africa with a solar multiple of 2.4 and 12 hours of storage capacity is defined as a base for the comparison. This results in a power plant with approximately 700 MW_{th} thermal power at design conditions. The receiver and HTF-system are designed for a single 700 MW_{th} receiver as well as a multi-tower system with five 140 MW_{th} receivers. A 121m² heliostat based on Abengoa's Sanlucar 120 is chosen for all solar fields. The power block remains the same for all variants with 565 °C salt temperature. It includes dry-cooling and achieves a gross efficiency of 43.1% with steam parameters of 125 bar / 550°C. The meteorological data were obtained from Meteororm software [5]. For the annual calculations a solar-only operational strategy of the plant was deployed, operating at full load during sunshine hours and while sufficient heat can be discharged from the storage tanks. A reference case model was created for both receiver dimensions. The reference case is based on an upscaled version of the Solar Two plant according to the literature [1], [2], [3], [4]. It inherits the same receiver design, the same HTF-system design (with adaptations of the piping dimensions for higher mass flows) and the same plant operation logic. The cost assumptions of the reference case are from various recent publications with contemporary and short term future cost data of MSSTP [6], [7], [8].

One possible approach to reduce generation costs of MSSTP is to increase the efficiency of the receiver. By constructing a cavity structure around the receiver panels, it is expected to minimize convective and radiative heat losses, consequently increasing the receiver efficiency. Two different types of cavity receivers have been analyzed for the study. The aperture plane of the Facedown cavity receiver is directed in normal direction to the ground, whereas the aperture area of the Heliotower receiver [9] is inclined at 65° from horizontal towards the ground. The novel so-called Star receiver consists of receiver panels similar to an external receiver, but due to the star-shaped arrangement allows to apply solar irradiation to both sides of some of its panels. All concepts are shown in Fig. 1.

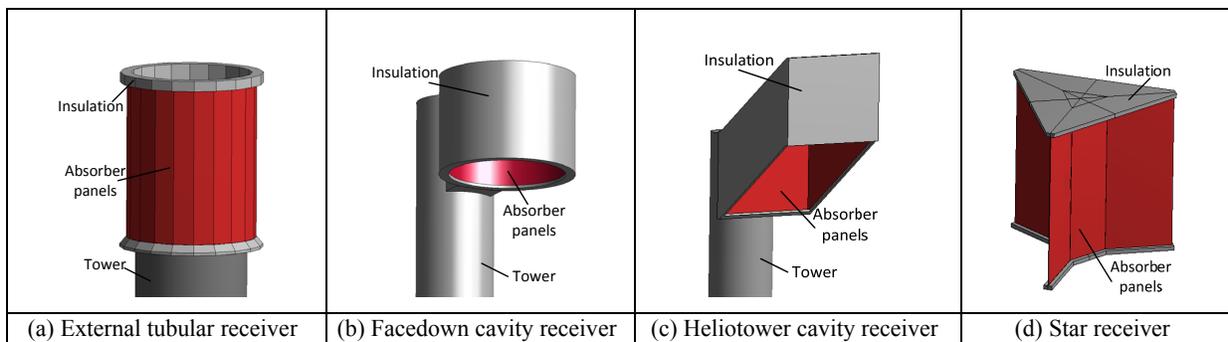


FIGURE 1. Overview of the receiver concepts that were analyzed in the study: (a) External Receiver as reference, (b) + (c) cavity receivers, (d) Star-receiver

Another route for improvement of MSST plants is to increase the power block efficiency by using higher steam parameters. Two external tubular receiver concepts were designed to achieve increased outlet temperatures of 600°C and 640°C, respectively. An optimized high temperature fluid cycle (HTF-cycle) including appropriate materials was designed to consider the increased thermal stresses as well as increased corrosion effects of the solar salt.

Another possibility for improvement of MSST plants is to use multiple smaller solar fields instead of one big solar field, feeding the same storage system and power block. Due to the smaller size, higher solar field efficiencies can be expected but also additional cost for piping connections between the smaller subfields. In a previous case study based on heat generation costs, a multi-tower system with 5 towers and approximately 140 MW_{th} receivers showed the most potential, and was chosen for this analysis. An overview of all variants included in this analysis is shown in Table 1.

TABLE 1. Overview of variants

Group	Abbreviation	SM	Atmosphere	Salt temp. [°C]	Nr. of towers	Receiver power [MW _{th}]	Receiver type	HTF system
Reference system (based on Solar Two)	EXT-ST-Ref	2.4	clear	290 - 565	1	696.2	External	Reference (SolarTwo)
	EXT-MT-Ref	2.4	clear	290 - 565	5	5 x 139.2	External	Reference (SolarTwo)
HPMS 565°C HTF system (open)	EXT-ST-565	2.4	clear	290 - 565	1	696.2	External	Improved, 565°C, open
	EXT-MT-565	2.4	clear	290 - 565	5	5 x 139.2	External	Improved, 565°C, open
	FD-ST-565	2.4	clear	290 - 565	1	696.2	Face Down Cavity	Improved, 565°C, open
	FD-MT-565	2.4	clear	290 - 565	5	5 x 139.2	Face Down Cavity	Improved, 565°C, open
	HEL-ST-565	2.4	clear	290 - 565	1	696.2	Heliotower Cavity	Improved, 565°C, open
	HEL-MT-565	2.4	clear	290 - 565	5	5 x 139.2	Heliotower Cavity	Improved, 565°C, open
	STN-ST-565	2.4	clear	290 - 565	1	696.2	Star	Improved, 565°C, open
	STN-MT-565	2.4	clear	290 - 565	5	5 x 139.2	Star	Improved, 565°C, open
HPMS 600°C HTF system (closed)	EXT-ST-600	2.4	clear	290 - 600	1	696.2	External 600°	Improved, 600°C, closed loop
	EXT-MT-600	2.4	clear	290 - 600	5	5 x 139.2	External 600°	Improved, 600°C, closed loop
HPMS 640°C HTF system (closed)	EXT-ST-640	2.4	clear	290 - 640	1	696.2	External 640°	Improved, 640°C, closed loop
	EXT-MT-640	2.4	clear	290 - 640	5	5 x 139.2	External 640°	Improved, 640°C, closed loop

MOLTEN SALT SOLAR TOWER MODEL FOR ANNUAL YIELD CALCULATION

The evaluation of the concepts is conducted primarily by annual yields, annual efficiencies and levelized cost of electricity (LCOE). In this chapter a conclusion of the modelling work of the subsystems is given, as well as a detailed description of the annual yield calculation model. A general overview of the workflow of the annual yield calculation model is depicted in Fig. 2.

The software HFLCAL [10] was used for the layout of the cost optimized solar fields on annual basis: heliostat positioning, solar tower height, receiver aperture areas and positioning. The thermal receiver output is calculated based on hourly meteorological data, the solar position, a characteristic map of the heliostat field efficiency and receiver efficiency. An Epsilon Professional [11] model of the MSSTP is used to calculate energy flows in each time step. An excel tool is used to combine all the necessary inputs, to control the annual calculations and to collect results. With the energy yields and the cost input data, the LCOE are calculated according to a simplified LCOE method with 100 % debt finance and no tax and construction time consideration. A 20 % surcharge for EPC and owners cost was added to the total investment cost.

Primary inputs for the annual yield calculation model are the receiver performance, the heliostat field performance, the dynamic behavior of the HTF-system for startup, standby and regular operation, the power block behavior and the cost data. To keep the calculation time and complexity of the annual yield model limited, specialist models have been used to create the input data in the form of simplified relations or characteristic curves. Specialized models were used for sub-systems of the MSSTP such as receiver design, piping design, dynamic simulation of the HTF-cycle, and heliostat field design.

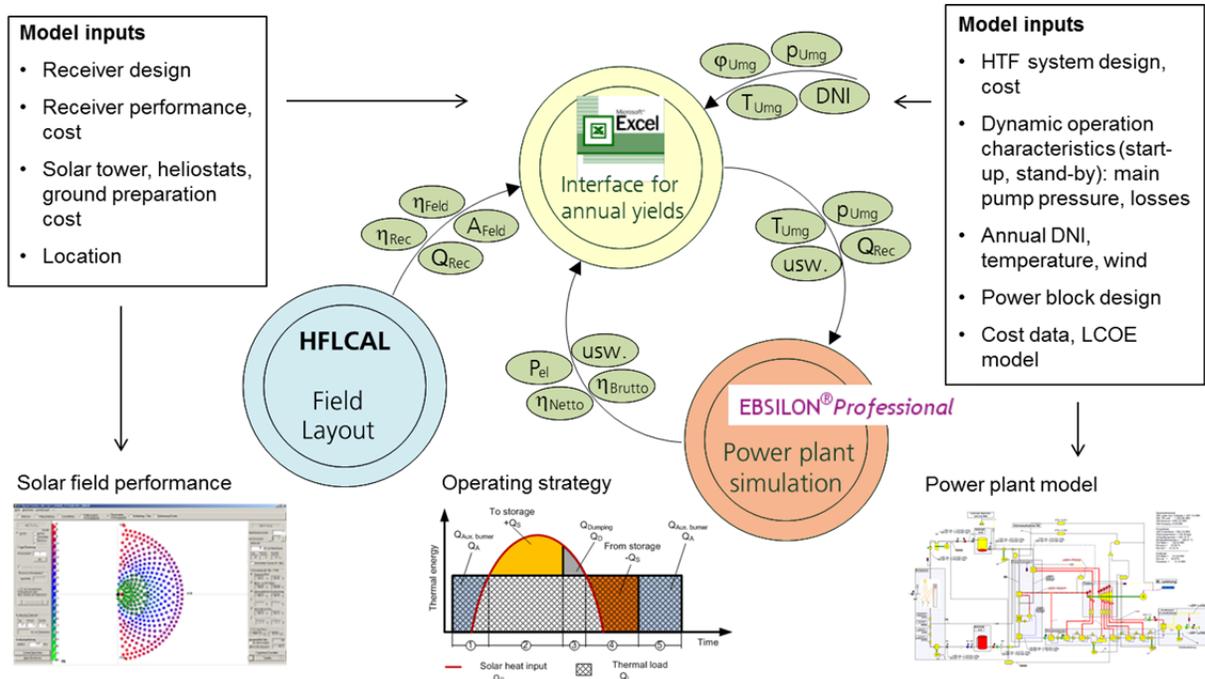


FIGURE 2. Overview of the annual yield model

Receiver Modelling

The design of a tubular solar receiver is a complex and iterative process, with the goal to find an ideal compromise between optical and thermo-hydraulic efficiency, material loads from thermal stresses, and cost. The design parameters are the average peak flux density, the tube diameter, the absorber panel interconnection (serial or parallel), as well as the geometric arrangement of the heliostat field and the aiming points. All receivers were designed using DLR's ASTRID code [12]. At first a fast lower-detail modelling process is used. For this a heliostat field for the desired design thermal power and irradiance is generated with the HFLCAL [10] software, using an estimated receiver efficiency for a given geometry. A suitable aimpoint strategy is applied on the receiver aperture to limit the flux density and absorber surface temperatures at a given time. With this the flux density distribution on the aperture is fed into the more detailed FEM model of the ASTRID code for the thermal analysis, which delivers a precise local temperature simulation. A CFD model is used to determine natural and forced convection losses for typical wind velocities at the given location. With the resulting surface temperatures and heat transferred to the salt, receiver efficiency maps can be calculated as a function of relative thermal load and wind velocity.

After the thermo-hydraulic receiver design a support structure constructional drawing as well as a complete set of piping connections and auxiliary equipment was designed by the industry partners for each receiver variant. A mechanical analysis of the receiver models as well as the support structures was concluded for various test cases taking into account the filled receiver weight, the operating pressure, operating temperature distributions and maximum wind velocity. The material and manufacturing cost of the receivers was determined by the industry partners.

Furthermore, a dynamic receiver model using the Dymola software was created and validated as part of this research project [13]. The model allows to simulate the dynamic behavior of the receiver as a reaction to changes of the flux density on the surface. In conjunction with the raytracing software STRAL, single heliostats can be deactivated to simulate the passing of clouds over the heliostat field. Other simulated scenarios include safety relevant events such as pump malfunctions or an electric blackout.

As a result the receiver efficiency as a function of thermal load and wind speed and the receiver cost were obtained for each receiver model variation and used as an input for the annual yield calculations. An example of the receiver efficiency of the External receiver is given in Fig. 3.

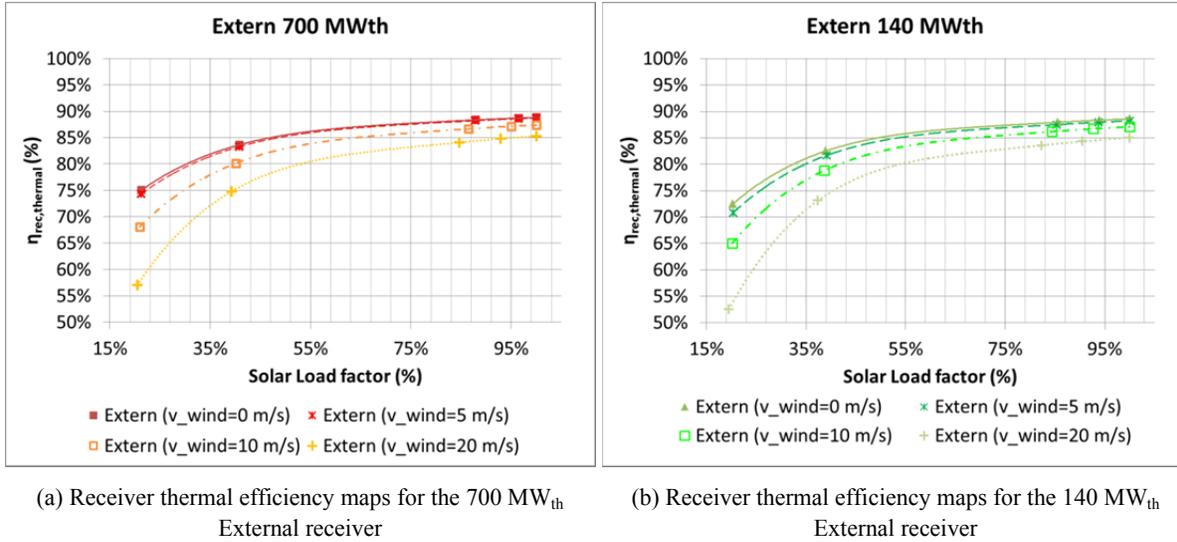


FIGURE 3. External receiver thermal efficiency including aimpoint strategy as a function of solar load: (a) 700 MW for single tower, (b) 140 MW for multi-tower

HTF System Modelling

Detailed HTF system models were created for the analysis. The main components that were analyzed as part of the HTF system are the molten salt pump, riser and downcomer pipes, inlet vessel and outlet vessel, other pipe connections such as a the receiver bypass, vessels, instrumentation and the heat tracing system. The storage was not analyzed in the scope of this research project. The HTF system design includes the development of the process P&IDs (Fig. 4), suitable material selection, piping design, constructional design of connectors and instrumentation. The pressure drop of the HTF system was calculated using the Sinetz [14] software for the single tower and multi tower configuration. The heat tracing system was created and used to estimate the electric consumption and cost of the system.

To investigate the dynamic behavior of the plant, the dynamic receiver model was integrated in a model of the whole HTF-system. The model was created using Dymola, while using interfaces with the raytracing software STRAL [15] and MATLAB Simulink to include solar irradiation data and to provide a process control algorithm, respectively. The inputs created from the dynamic HTF-system model are in the form of start-up times and thermal and electric energy consumption for predefined start-up and standby procedures. Startup requires a slow preheating of the empty pipes by the heat tracing system and of the receiver by the heliostat field. While the pipe preheating can start before the scheduled operation, the preheating process of the receiver leads to a timespan in which the available DNI cannot be used. The main electricity consumption is caused by the heat tracing system and the molten salt pump during bypass operation.

Detailed investigations of the receiver and HTF-system behavior caused from partial and full cloud coverage of the heliostat field were made. In the cloud-standby operation mode from Solar Two the salt mass flow to the receiver is increased by the control system to achieve 510°C receiver outlet temperature at (theoretical) clear sky radiation. This is to prevent a too rapid increase of the receiver temperature when the clouds recede, which could cause structural damage. A result of the investigations is that the receiver behavior is strongly influenced by the location of a local flux density decrease on the receiver surface, and thus the distribution of shaded area on the heliostat field. There were no annual data for this available for this project, so the cloud-standby behavior is simplified in the annual yield model. To be able to achieve the increased mass flow in cloud-standby, the pressure in the inlet vessel must be high enough to sustain the mass flow through the receiver for 60 seconds as a safety measure (to prevent receiver damage in case of a blackout). As a result, the pressure in the inlet vessel is increased and dependent of the clear sky radiation, leading to a higher electricity consumption of the molten salt pump. This is represented in the annual yield model in the form of characteristic curves of the inlet pressure for each variant.

As a reference case, an upscaled version of the HTF system of the Solar Two plant was created according to the literature [1], [2], [3]. Next an improved version with adaptations and developments from the research project was designed. Third, a closed loop HTF-system to allow higher solar salt operating temperatures of 600°C and 640°C was designed. With higher operating temperatures, a closed molten salt loop is recommended, to prevent an increase of corrosion of the molten salt caused by the constant oxygen exchange with the environment.

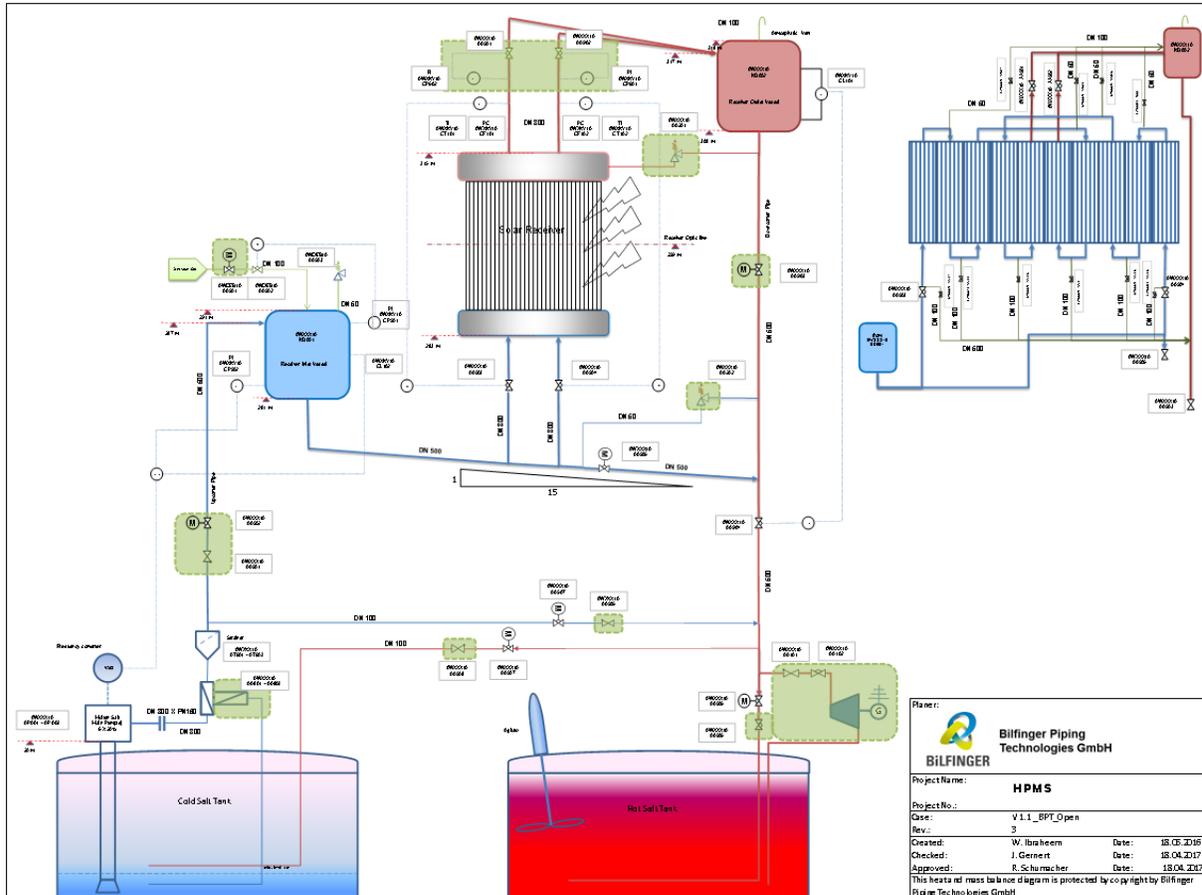


FIGURE 4. HTF-system of the improved HTF system for the 700 MW_{th} External receiver (EXT-ST-565)

The improvements from the reference case (EXT-ST-Ref) to the open cycle improved HTF-system (EXT-ST-565) include amongst others two main points. In the reference case the receiver including all pipe connections on the tower, the downcomer and the riser pipes are drained into the storage tanks every night. The 140 MW_{th} or 700 MW_{th} receivers in this study comprise significantly increased pipe diameters of the downcomer and riser pipes compared to Solar Two. As a result it is more viable to keep them filled during the night and conduct a periodical circulation of the molten salt. Simulations with the dynamic model showed that 30 minutes of circulation and heating the salt in the pipes to 300°C every 4 hours is sufficient to keep the salt temperature above 260°C at all times. The pump electricity consumption is significantly decreased.

A salt turbine to use the potential energy of the molten salt in the downcomer pipe is used. Technical data and a price offer from a potential deliverer were obtained. Instead of three pumps with each 50 % design power in the reference system, 6 pumps with 20 % are used and the lower plant operation limit is decreased from 30 % to 12 %. Furthermore, improvements of the cloud-standby control system lead to a lower pressure in the inlet vessel and lower electricity consumption.

Power Block Modelling for Increased Molten Salt Temperature

An external receiver and heliostat field was designed for a single and multi tower system for increased upper salt temperatures of 600°C and 640°C using the method outlined in the paper (EXT-ST-600, EXT-MT-600, EXT-ST-640, EXT-MT-640). The HTF-system was adapted as a closed-loop cycle. The cost the 600°C system was determined, and also used for the 640°C system. The increased salt temperature allows a higher steam temperature for the power block turbine, however the same steam pressure is used. This leads to a moderate increase of the power block efficiency and reduces the size of the heliostat field (Table 2).

The main difference of the closed system for increased salt temperatures is an additional connection for air transfer between the storage tanks during charge and discharge operation. Furthermore an additional pressurized air tank is connected with the inlet and outlet vessel in the tower, which is not anymore vented to the atmosphere. While there are added costs for the additional connections and the air tank, the inlet and outlet vessels can be smaller, leading to a minor cost increase of the HTF-system.

TABLE 2. Overview of system parameters for increased salt temperatures (@DP means at design point)

	Unit	565°C system	600°C system	640°C system
Molten salt temperatures	[°C]	290-565	290-600	290-640
Live steam parameters	[bar / °C]	125 / 550	125 / 580	125 / 620
Powerblock gross efficiency @DP	[%]	43.1	43.7	44.4
Powerblock net efficiency @DP	[%]	41.6	42.2	43.0
Thermal power receiver @DP	[MW]	696.2	677.1	666.6

Plant Operation Modelling

An overview of the dynamic plant behavior in the annual yield model is given in Figure 5. If a start-up of the plant is required, the necessary electric energy for the pumps and heat tracing system are deducted from the electric production. During the time of the start-up procedure, the incoming DNI is not used to generate thermal heat in the receiver. The start-up time is typically a fraction of an hour. A linear interpolation of the DNI from the start of the start-up process to the end of the start-up process is used, to determine the unusable DNI at exactly that time period within one data point. The start-up time is longer at sunrise, because the solar irradiation on the receiver at low elevation angles is not sufficient to preheat the receiver at its intended rate. Due to thermal convection losses it is also a function of the wind velocity, and is interpolated with the wind velocity at receiver height. If the irradiation falls below the minimum plant operation limit during plant operation (typically by a clouded sky), the system goes into standby mode for up to three hours. During standby the electricity consumption for salt circulation through the bypass and parts of the heat tracing system (receiver connections) is deducted. If the system goes back to operation from standby, only the second phase of the preheat process is necessary, with significantly lower losses.

When the available thermal energy for electricity production is determined, the Ebsilon model of the power plant is started with the corresponding receiver pressure drop. The model chooses the suitable operating state (charge, full discharge, partial discharge) according to the storage status.

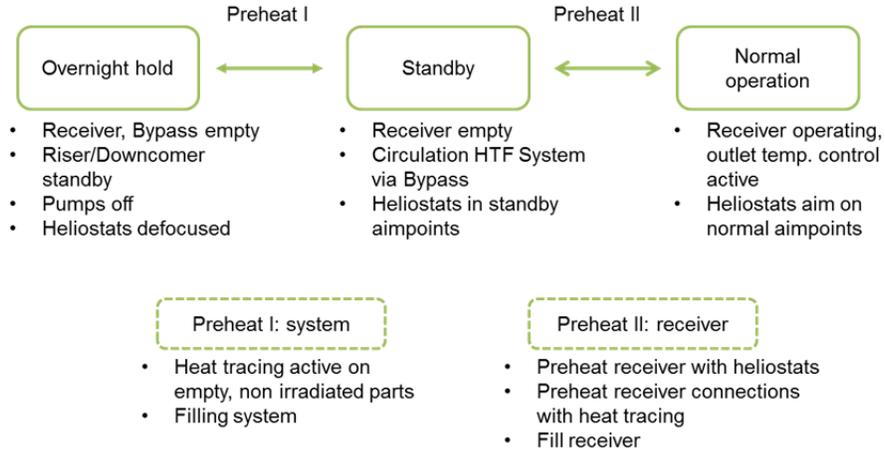


FIGURE 5. Plant operation in annual yield model

ANNUAL YIELD AND ECONOMIC RESULTS

External receivers are the current state-of-the-art technology for MSSTP. The external receiver with improved HTF-cycle (EXT-ST-565) achieves lower LCOE than the reference case system (EXT-ST-Ref) by 11.7 % (Fig. 6). It also shows a significant increase of total annual efficiency (Fig. 7). Main reasons are a reduction of losses from the lower operating limit of the salt pumps and a lower electrical own consumption. In terms of cost, the main improvement is achieved by the significantly lower cost of the receiver (~56 % of the reference system) (Fig. 9b). A sensitivity analysis shows that about half of the total LCOE improvement is caused by investment cost reductions and the other half by the increased efficiency of the HTF system and less own consumption. The additional investment of the molten salt turbine at the bottom of the downcomer pipe contributes positively to the LCOE in all variants, despite its relatively low conversion efficiency of ~50 %: e.g. for the EXT-ST-565 0.6 %-point lower LCOE coming from the molten salt turbine.

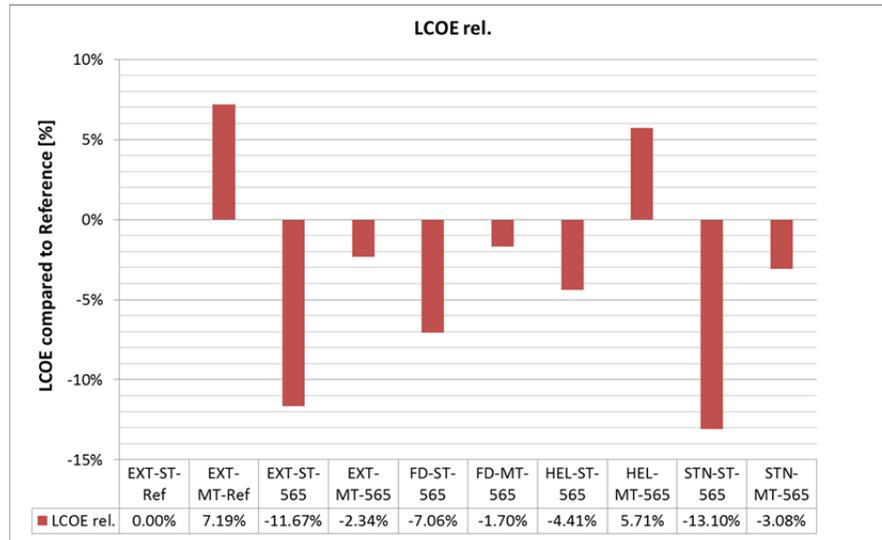


FIGURE 6. LCOE results of the receiver concepts with improved HTF system and the reference case

A comparison of the proposed receiver designs shows that the single tower variants of the external receiver (EXT-ST-565) and the star receiver (STN-ST-565) achieve the lowest LCOE with an improvement of 11.7 % and 13.1 % respectively. The Facedown cavity receiver (FD-ST-565) and the Heliotower cavity receiver (HEL-ST-565)

have 4 % to 7 % lower LCOE than the reference case, but significantly higher than the aforementioned concepts (Fig. 6).

Fig. 7 shows the annual efficiencies¹ of all receiver concepts. To better compare the receiver technologies, the combined receiver and aiming efficiency is displayed in this analysis ($\eta_{rec} \cdot \eta_{aiming}$). The aiming efficiency includes the losses caused by an aim point strategy to avoid too high flux densities on the aperture area of the receiver. For Cavity receivers such an aim point strategy is not necessary.

Cavity receiver systems achieve higher annual combined receiver efficiencies at the cost of a lower solar field efficiency caused by limited aperture angles. For the Heliotower system, this also translates to higher total efficiency of the overall plant (Fig.7). However the increased cost of those receivers outweighs the performance gain significantly. The Facedown receiver has increased cost as well as a lower total efficiency.

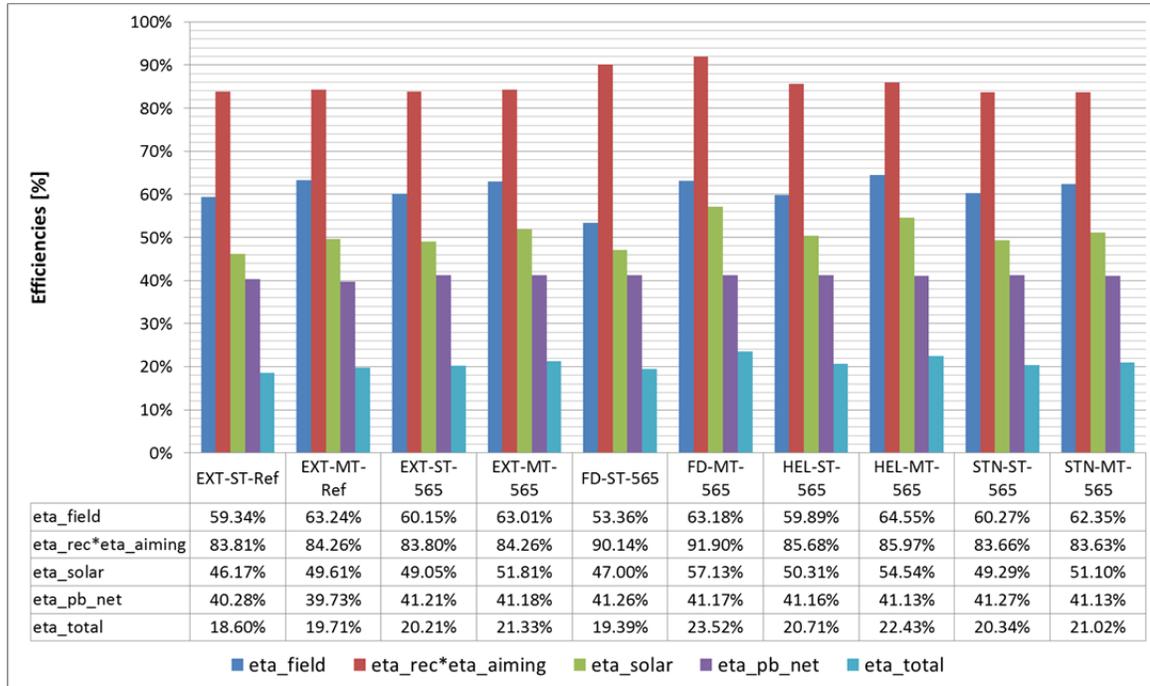


FIGURE 7. Annual efficiencies of the receiver concepts with improved HTF system and the reference case

The LCOE of systems with increased molten salt temperature are both about 1 % higher than the improved external receiver system (and therefore ~11 % lower than the reference case). An analysis of the annual efficiencies shows that the increased power block efficiency is mostly countered by decreased receiver efficiency, caused by increased thermal losses of the receiver (Fig. 8). The receiver and HTF-system with higher temperatures are more expensive than the 565°C external receiver system (EXT-ST-565). The 600°C and 640°C system (EXT-ST-600, EXT-ST-640) surprisingly have lower total investment cost due to the smaller heliostat field, but also a lower total electricity production.

¹ The definition of the efficiencies are given in Table 4 in the Appendix.

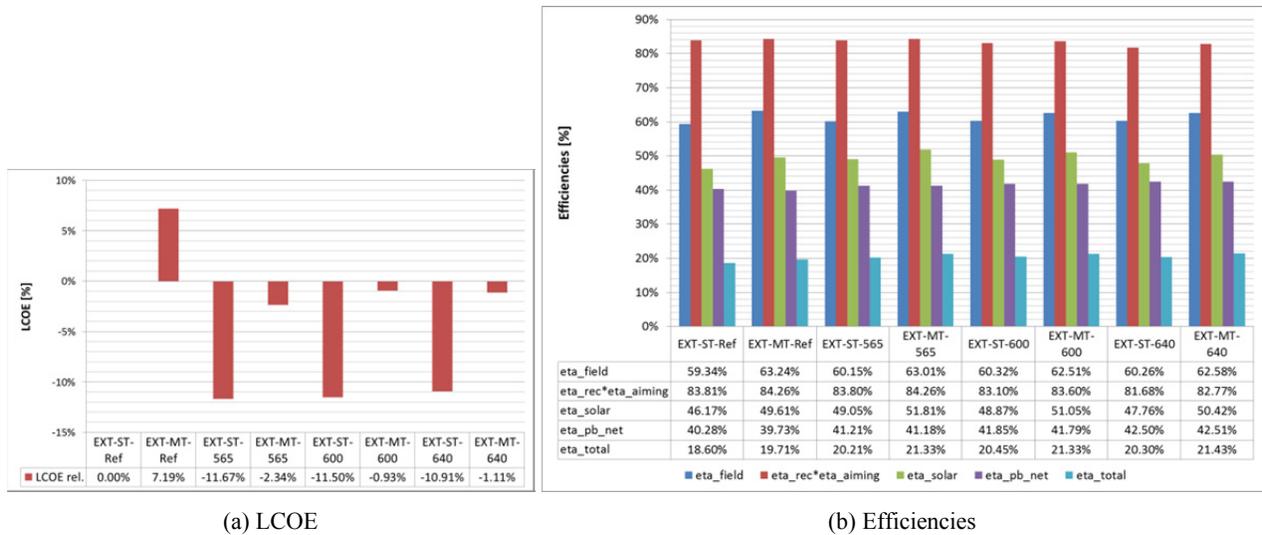


FIGURE 8. LCOE and annual efficiencies of the systems with external receiver and increased temperature of 600°C and 640°C: (a) LCOE, (b) Efficiencies

In all cases so far, the multi tower systems (XXX-MT-XXX) lead to distinctly higher LCOE than their single tower counterparts (XXX-ST-XXX) (Fig 6-8) despite achieving a higher efficiency. The main reason for that can be seen in the investment cost breakdown, which shows much higher cost for the receiver and the HTF-system (Fig 9). Main contributors to the cost increase of the HTF-system are the connecting pipes of the 5 heliostat fields to the central power block and storage systems. The total length of connecting pipes is estimated to ~ 11.5 km with varying diameters. The pipes are built on elevated structures, to enable an incline so that the pipes can be drained into the storage tanks by gravity. This adds significant extra cost for the support structures. However, even with the additional cost of the HTF-system set to zero, the multi tower LCOE are still higher than the single tower variants due to the receiver cost increase. Another case study was conducted with higher atmospheric attenuation, which gives an advantage to multiple smaller heliostat fields. For each variant heliostat fields were designed with increased attenuation, which means a higher total amount of heliostat is necessary. Also in this case the single tower variants achieve lower LCOE, even though only by ~5 % points.

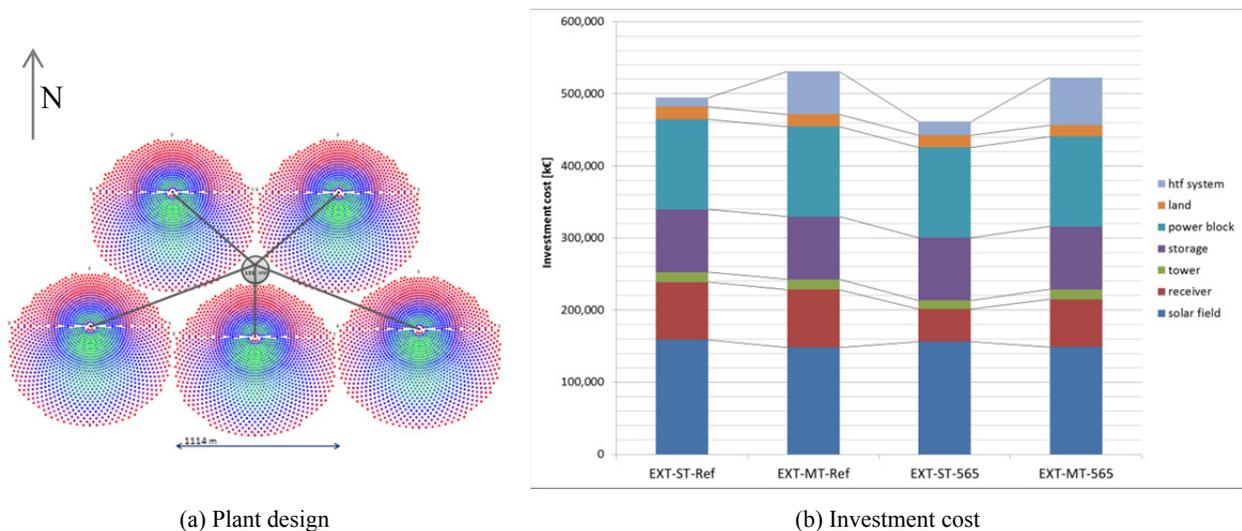


FIGURE 9. (a) Plant layout of a multi tower system, (b) Investment cost overview of single and multi tower 565°C systems with External receivers

An extensive overview of the input data and results of the annual yield calculations is given in Table 3 in the appendix.

CONCLUSIONS

A variety of modelling and simulation tools were used in this research project to design a state-of-the-art external tubular receiver as well as cavity receivers and a star receiver for a molten salt solar tower plant. The external receiver system achieves roughly 12 % lower LCOE than the reference system based on Solar Two technology and contemporary cost estimations. The improvements are caused by lower receiver investment costs as well as improvements of the HTF-system and plant operation strategy, significantly reducing the plant own consumption. A promising star receiver concept achieves even lower LCOE of 13 % below the reference in an early stage of maturity. While cavity receivers show higher efficiencies, they don't appear economically competitive in the plant scale of this analysis. An increase of the higher salt temperatures leads to similar results than the 565°C system. Multi tower systems did not achieve an economic improvement under the given boundary conditions due to the significantly higher investment costs. Further work is recommended to investigate other configurations of the multitower system, investigate uncertainties of key cost assumptions and to investigate the influence of a staggered construction of subfields of a multitower system, which can lead to improved financing conditions.

ACKNOWLEDGEMENTS

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APPENDIX

TABLE 3. Variants specifications and results

	Unit	EXT-ST-Ref	EXT-MT-Ref	EXT-ST-565	EXT-MT-565	FD-ST-565	FD-MT-565	HEL-ST-565	HEL-MT-565	STN-ST-565	STN-MT-565	EXT-ST-600	EXT-MT-600	EXT-ST-640	EXT-MT-640
System layout (@design point)															
Number of heliostats (total)	[-]	10097	9435	9946	9460	10346	8600	9263	8770	9971	9590	9686	9270	9637	9195
Heliostat reflective area	[m ²]	121	121	121	121	121	121	121	121	121	121	121	121	121	121
Tower height	[m]	310.3	155.1	335.1	157.9	365.5	184.2	364.7	178.0	338.4	153.4	327.3	148.7	333.1	154.6
Receiver thermal power	[MW]	696.2	5*139.2	696.2	5*139.2	696.2	5*139.2	696.2	5*139.2	696.2	5*139.2	677.1	5*134.4	666.6	5*133.3
Receiver aperture area	[m ²]	1412.9	284.7	1412.9	284.7	1032.3	137.6	1124.9	218.5	1362.2	266	1338.1	265.6	1317.4	263.5
Total pressure drop salt pump	[bar]	83.6	58.8	88.5	60.5	89.9	69.8	94.9	69.7	83.9	61.1	56.0	25.1	57.1	26.1
Powerblock gross power	[MW]	125	125	125	125	125	125	125	125	125	125	125	125	125	125
Powerblock gross efficiency	[%]	43.1	43.1	43.1	43.1	43.1	43.1	43.1	43.1	43.1	43.1	43.7	43.7	44.4	44.4
Plant net efficiency	[%]	38.1	39.2	38.9	39.5	38.9	39.2	38.7	39.2	39.1	39.5	39.9	40.5	40.9	41.4
Annual Heat															
Q solar (DNI to field)	[GWh]	3269.1	3054.8	3220.2	3062.9	3349.7	2784.4	2999.1	2839.5	3228.3	3105.0	3136.0	3001.4	3120.2	2977.1
Q field (optical)	[GWh]	1940.0	1931.9	1936.8	1930.0	1787.3	1759.1	1796.2	1832.8	1945.8	1935.9	1891.6	1876.2	1880.1	1863.0
Q rec* (Q rec * eta _{int,aim})	[GWh]	1625.9	1627.9	1623.1	1626.1	1611.1	1616.7	1538.9	1575.6	1627.9	1619.0	1571.9	1568.5	1535.6	1542.0
Q loss operational limit (pumps)	[GWh]	86.7	88.5	9.2	9.6	11.0	9.7	13.4	10.9	9.5	9.7	9.9	9.7	11.2	10.3
Q dumping (field)	[GWh]	16.8	11.0	17.3	13.0	11.0	1.5	2.6	0.5	19.2	14.8	9.8	6.9	10.8	7.4
Q loss storage	[GWh]	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.5	13.5	13.3	13.3
Q PB total (used for electricity production)	[GWh]	1509.3	1515.4	1579.5	1586.7	1574.4	1590.8	1508.8	1548.6	1591.2	1586.6	1532.6	1532.1	1490.1	1501.1
Annual Electricity															
W auxiliary consumption rec. & storage pumps	[GWh]	25.1	17.9	20.9	15.5	20.6	17.5	20.9	17.0	19.8	15.6	17.9	12.9	15.7	11.8
W auxiliary EHTS	[GWh]	6.5	19.4	3.1	3.2	3.1	3.2	3.2	3.3	3.0	3.2	3.2	3.6	4.0	4.1
W auxiliary PB (water pumps)	[GWh]	22.0	22.0	23.1	23.0	23.1	23.1	22.2	22.6	23.3	23.0	22.2	22.0	21.1	21.2
W auxiliary startup & standby (pumps & EHTS)	[GWh]	6.6	19.5	1.8	2.1	1.8	2.1	2.1	2.3	1.8	2.1	1.9	2.2	2.1	2.4
W auxiliary saved by salt turbine	[GWh]	-	-	6.0	2.7	6.7	3.0	6.5	3.0	6.1	2.8	5.1	2.2	4.6	2.0
W auxiliary total	[GWh]	53.6	59.3	47.1	41.7	46.8	43.8	46.3	42.8	46.2	41.8	43.3	38.6	40.7	37.0
W gross el	[GWh]	661.5	661.4	698.0	695.2	696.3	698.8	667.3	679.8	702.9	694.4	684.6	678.8	674.0	675.1
W net el	[GWh]	607.9	602.1	650.9	653.5	649.5	655.0	621.1	637.0	656.7	652.6	641.3	640.2	633.3	638.1
Annual efficiencies															
Heliostat field	[-]	0.5934	0.6324	0.6015	0.6301	0.5336	0.6318	0.5989	0.6455	0.6027	0.6235	0.6032	0.6251	0.6026	0.6258
Receiver* (eta _{rec} * eta _{int,aim})	[-]	0.8381	0.8426	0.8380	0.8426	0.9014	0.9190	0.8568	0.8597	0.8366	0.8363	0.8310	0.8360	0.8168	0.8277

Solar efficiency (solar to heat)	[-]	0.4617	0.4961	0.4905	0.5181	0.4700	0.5713	0.5031	0.5454	0.4929	0.5110	0.4887	0.5105	0.4776	0.5042
Powerblock net	[-]	0.4028	0.3973	0.4121	0.4118	0.4126	0.4117	0.4116	0.4113	0.4127	0.4113	0.4185	0.4179	0.4250	0.4251
Plant total efficiency (solar to electricity)	[-]	0.1860	0.1971	0.2021	0.2133	0.1939	0.2352	0.2071	0.2243	0.2034	0.2102	0.2045	0.2133	0.2030	0.2143
Investment cost and maintenance															
solar field per reflective area	[€/m ²]	130	130	130	130	130	130	130	130	130	130	130	130	130	130
	[k€]	158800	148400	156500	148800	162700	135300	145700	138000	156800	150900	152400	145800	151600	144600
receiver	[€/kW]	115	115	65	95	93	117	107	154	59	85	66	95	66	96
	[k€]	80100	80100	45300	66100	64700	81500	74500	107200	41100	59200	44700	63800	44000	64000
tower	[k€]	13700	14100	11900	14000	14100	18800	14000	17600	12100	13200	11400	12400	11800	13400
thermal energy storage	[€/kWh]	25	25	25	25	25	25	25	25	25	25	25	25	25	25
power block	[€/kW]	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
	[k€]	125000	125000	125000	125000	125000	125000	125000	125000	125000	125000	125000	125000	125000	125000
cost for land (w/o leveling)	[€/m ²]	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	[k€]	17500	16900	16900	15600	16800	14400	15400	16300	16300	15800	16500	16800	15800	15000
cost htf system	[k€]	12500	59600	18900	65900	18900	65900	18900	65900	18900	65900	19000	69500	19000	69500
total cost piping (without EHTS)	[k€]	10300	50200	13800	56600	13800	56600	13800	56600	13800	56600	13900	60100	13900	60100
total heat tracing (EHTS)	[k€]	2200	7500	2200	7500	2200	7500	2200	7500	2200	7500	2200	7500	2200	7500
annual O&M cost (fixed & variable)	[k€]	10400	10400	10600	10600	10600	10600	10500	10500	10600	10600	10500	10500	10500	10500
LCOE (rel.)	[%]	100.0	107.2	88.3	97.7	92.9	98.3	95.6	105.7	86.9	96.9	88.5	99.1	89.1	98.9

TABLE 4. Definition of system efficiencies

	Abbreviation	Definition
Heliostat field efficiency	eta_field	Receiver intercepted energy without aimpoint strategy / (Reflective area heliostat field * Annual DNI)
Aiming efficiency	eta_aiming	Receiver intercepted energy with aimpoint strategy / Receiver intercepted energy without aimpoint strategy
Receiver efficiency	eta_rec	Receiver thermal energy output / Receiver intercepted energy without aimpoint strategy
Solar efficiency	eta_solar	Receiver thermal energy output / (Reflective area heliostat field * Annual DNI)
Power block net efficiency	eta_pb_net	(Gross electricity generation – Own consumption plant) / Thermal energy input plant
Total efficiency	eta_total	(Gross electricity generation – Own consumption plant) / (Reflective area heliostat field * Annual DNI)

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