Annual Performance Assessment of a 50 MW_e Commercial Solar Tower Plant with Improved Open Volumetric Receiver

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Abstract. Central receiver systems with open volumetric air receiver and packed bed thermal storage are an alternative to the currently deployed salt and steam receiver plants. The air receiver technology is being tested as a complete system at the 1 MW_e test and demonstration plant Solar Tower Jülich since 2009 and shows high robustness and availability. Recent developments focused on increasing the thermal receiver efficiency. Changing the receiver geometry to a cavity type and further structural improvements resulted in an efficiency increase to above 85%, as experiments and CFD simulation models show. The high dynamic flexibility could be further enhanced. A commercial reference plant with 50 MW_e power level was defined for a potential location in South Africa. An LCOE analysis based on an annual performance simulation was conducted for several design and operational alternatives. Under good conditions, results show LCOE values below 90 €/MWh for the single 50 MW_e standard unit. Higher power levels can be reached by multiplying such standard units, leading to further cost savings.

INTRODUCTION

The open volumetric receiver is one of the 2nd Generation Receiver Technologies that are being developed since the 1980's ([1], [2]). Similar to the molten salt receiver, the volumetric air receiver system can also be coupled to a simple and scalable thermal storage ([3]).

The highest TRL for air receivers is reached up to now by the so-called HiTRec receiver technology, where ceramic honeycomb modules are deployed as absorber elements and the metallic receiver support structure is cooled by warm return air from the steam generator or storage ([4], [5]). A complete solar power plant with open volumetric receiver of the HiTRec type and thermal storage was realized at the Solar Tower Jülich in Germany in 2009 ([6], [7], [8]). The receiver is operated for testing and demonstration purposes under the local volatile DNI conditions since then without damages or major incidents.

The Jülich receiver's thermal performance shows a moderate level at the demonstrated small scale, but lies within the expectations. Recent experimental and numerical works analyzed the air flow and heat exchange conditions of the Jülich receiver in great detail, giving design point values of 60% for the air return ratio and 71% for the thermal efficiency ([9], [10]). The main sources of heat loss are radiation losses, internal heat transfer between hot and warm air and the loss of return air. Radiation losses are most effectively reduced by improving the absorber structure and trying to exploit the potential of the volumetric effect ([11], [12] and [13]). Most absorber structures are compatible with the HiTRec receiver concept due to its modular layout.

IMPROVED OPEN VOLUMETRIC RECEIVER

The recent development efforts of the HiTRec receiver structure resulted in changing the external receiver geometry from a convex cylinder to a cavity type by arranging convex shaped receiver segments to form a concave structure, which has a positive effect both on radiation losses and air return. These effects shall be further enhanced by equipping the receiver with a roof, front and side shields (see Fig. 1 right). To reduce the internal heat transfer, the air cooled metallic support structure was also revised and partly redesigned. A complex numerical model was developed to simulate the heat transfer in the ceramic absorber elements coupled with the air flow inside the receiver cavity ([10]). The air return ratio can be improved to more than 85% and the thermal efficiency can be increased to between 84% and 90%, depending on the return air temperature.

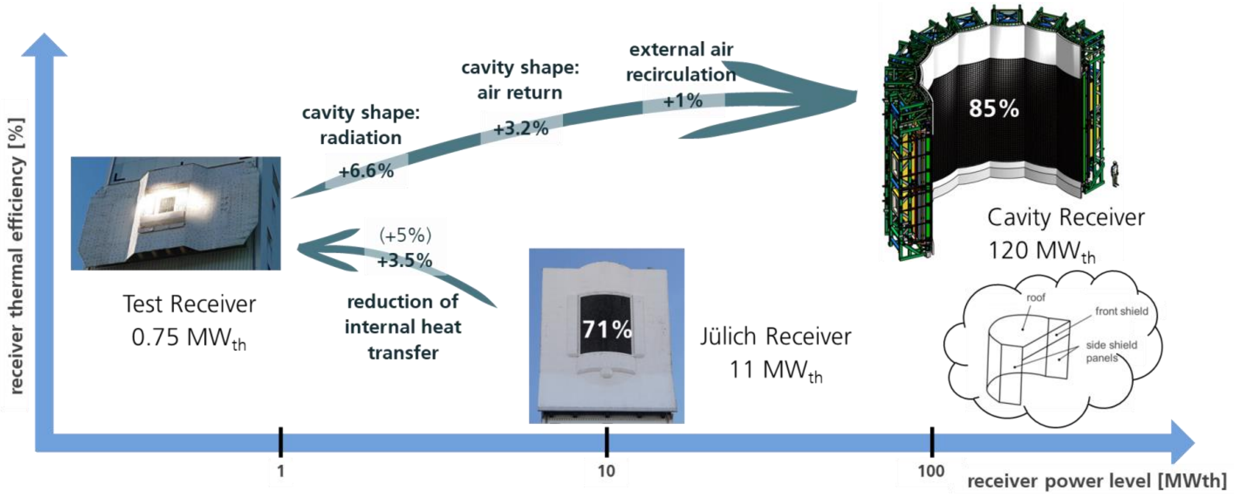


FIGURE 1. Development steps from the 11 MW$_{th}$ Jülich receiver to the new 120 MW$_{th}$ cavity type receiver (*all receiver power levels are given for incident power).

The improvement steps from the Jülich receiver to the new cavity design are shown in Fig. 1. The internal heat transfer between hot and warm air could be reduced by a series of measures, namely decreasing the flow velocity of the warm air, improving the insulation of the hot air pipes, reducing the heat transfer area between hot and warm air and using external ambient air instead of warm air for cooling of the support frame. These measures were realized in a 750 kW$_{th}$ test receiver and showed an efficiency gain of 5%-points compared to the version before (tested in 2016 in the same test bed), see Fig. 2.

Simulations with the raytracing tool STRAL ([15]) revealed a reduction of heat loss due to a reduced view factor to the environment, which leads to a gain in efficiency of about 3.6%-points. An additional gain of 3% is caused through reflected radiation from the roof, front and side shields.

A reduction of return air loss is achieved by the partial suppression of the buoyancy flow through cavity and roof ([14]) leading to a gain in efficiency of 3.2%-points. Finally, the use of partially external air return leads to further increase of the air return ratio and an efficiency gain of another %-point ([14]). But an increased air return rate mitigates the effect of heat transfer between hot and warm air. As a result, the efficiency gain of the first improvement step is reduced to about 3.5%-points. All measures combined lead to an increase in efficiency to more than 85%. The thermal efficiency of the new receiver design as a result of extensive CFD simulations ([10], [14]) is shown in Fig. 3 (a) depending on hot air temperatures for an air return temperature of 180°C.

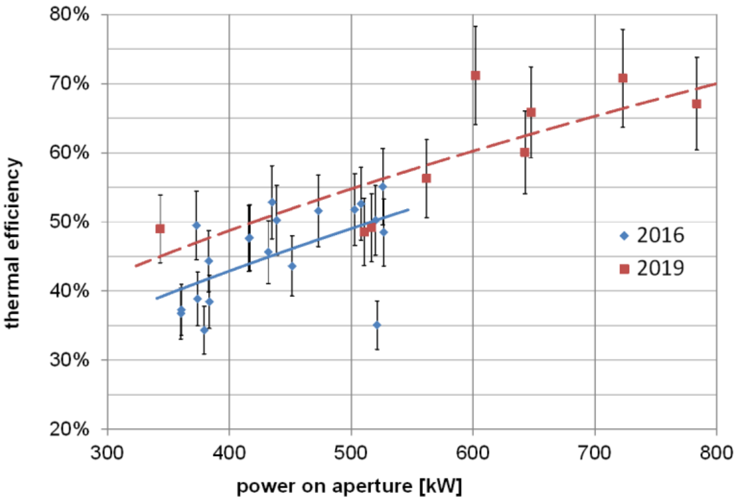
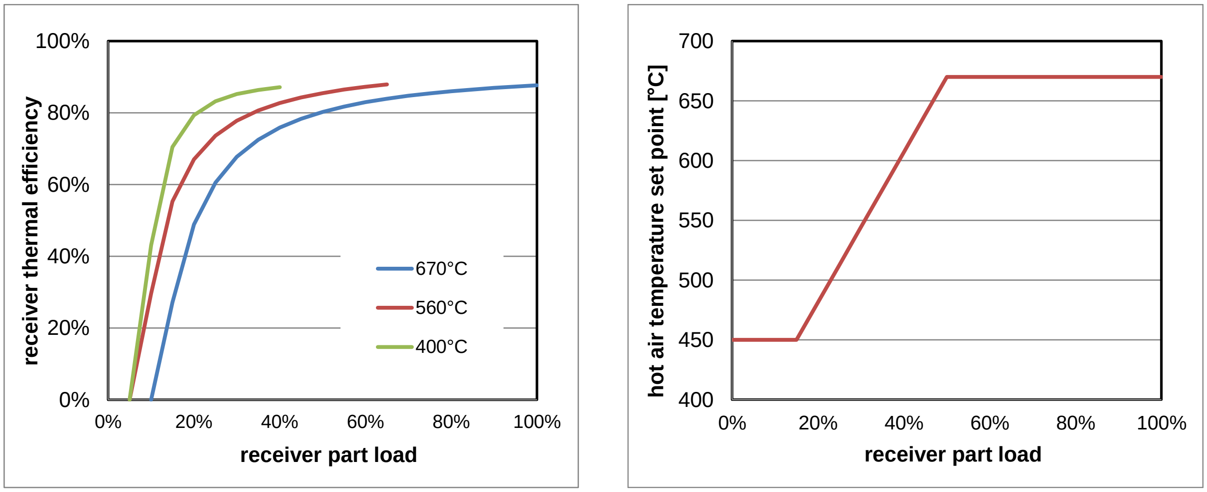


FIGURE 2. Comparison of the 750 kW$_{th}$ test receiver thermal efficiency before (2016) and after (2019) changes of the internal receiver structure.



(a) (b)

FIGURE 3. (a) Thermal efficiency of the new cavity receiver for 180°C return air and varying outlet air temperature. (b) Optional regulation of receiver hot air set point under part load conditions.

An additional achievement of redesigning the internal support structure was a further improvement of the dynamic behavior, which could also be shown experimentally in 2019. The test receiver was able to run-up from 10% to 90% load in less than 5 minutes after a cloud passage (see Fig. 4). Beyond peak receiver efficiency, this ability of the redesigned receiver for DNI-following operation is important to achieve a high annual average solar efficiency. After the redesign of the receiver structure by Kraftanlagen München the decisive limitation of the temporal gradients is now solely determined by the ceramic components and no longer by the metallic structure.

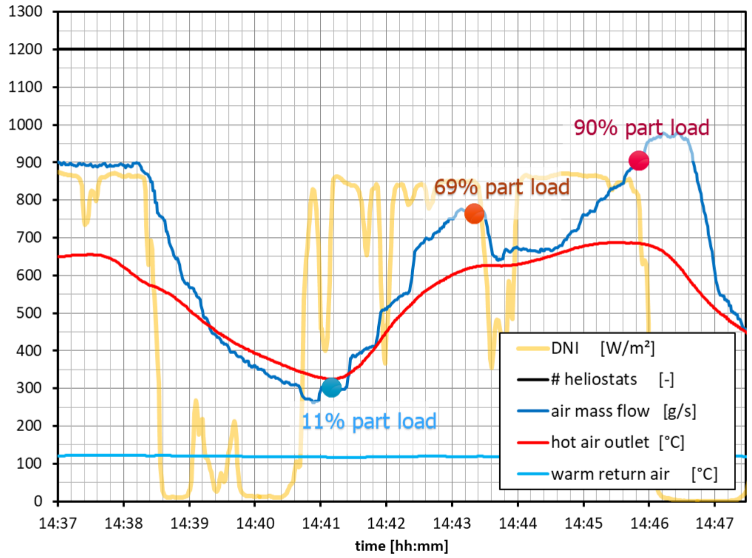


FIGURE 4. Dynamic behavior of the 750 kW test receiver: during cloud coverage of the field the receiver drops from 90% to 11% part load in less than 3 minutes and returns to 90% part load in less than 5 minutes after the cloud disappears.

COMMERCIAL PLANT LAYOUT

To assess the thermo-economic performance of the improved receiver a commercial plant was defined. As power level a value of 50 MW_e was chosen (Remark: the choice of this power level was based on a corresponding tender; additionally, the authors expect that the optimum size for this technology is certainly below 100 MW_e per plant unit but depends on individual project parameters). The layout of the heliostat field was combined with a study on number and size of the required receiver cavities. The result is shown in Fig. 5: a three-face cavity receiver on top of a 200 m tower surrounded by a shamrock shaped heliostat field. The main receiver with an intercepted power of 125 MW_{th} faces south and the side receivers with 80 MW_{th} each face north-east and north-west at 60° and 300°, respectively. The heliostat field consists of 41,338 units of KAM’s 14.1 m² heliostat ([16]). The heliostats were assigned fixed to one receiver face for this study.

For the conventional part, i.e. the Rankine power cycle, two alternatives were considered: a high-efficiency single pressure power block with several feedwater heating steps and hence elevated air outlet temperature of 270°C and a triple pressure base case version with 180°C air outlet temperature and lower efficiency (see table 1). These alternative power blocks were chosen to evaluate if an elevated process temperature at the “cold” end – similar as in molten salt systems – has advantages for the air system, especially after improving the air return ratio. As thermal heat storage a fixed bed thermocline storage with ceramic storage material was considered. The storage is designed in a modular concept and can be varied in units of 100 MWh.

TABLE 1. Variants of Rankine steam power block

Type	Live steam cond.	Air temperatures [°C]	Design point efficiency
Base	140 bar / 500°C	180°C / 650°C	38.8 %
High-efficiency	140 bar / 560°C	270°C / 650°C	41.9 %

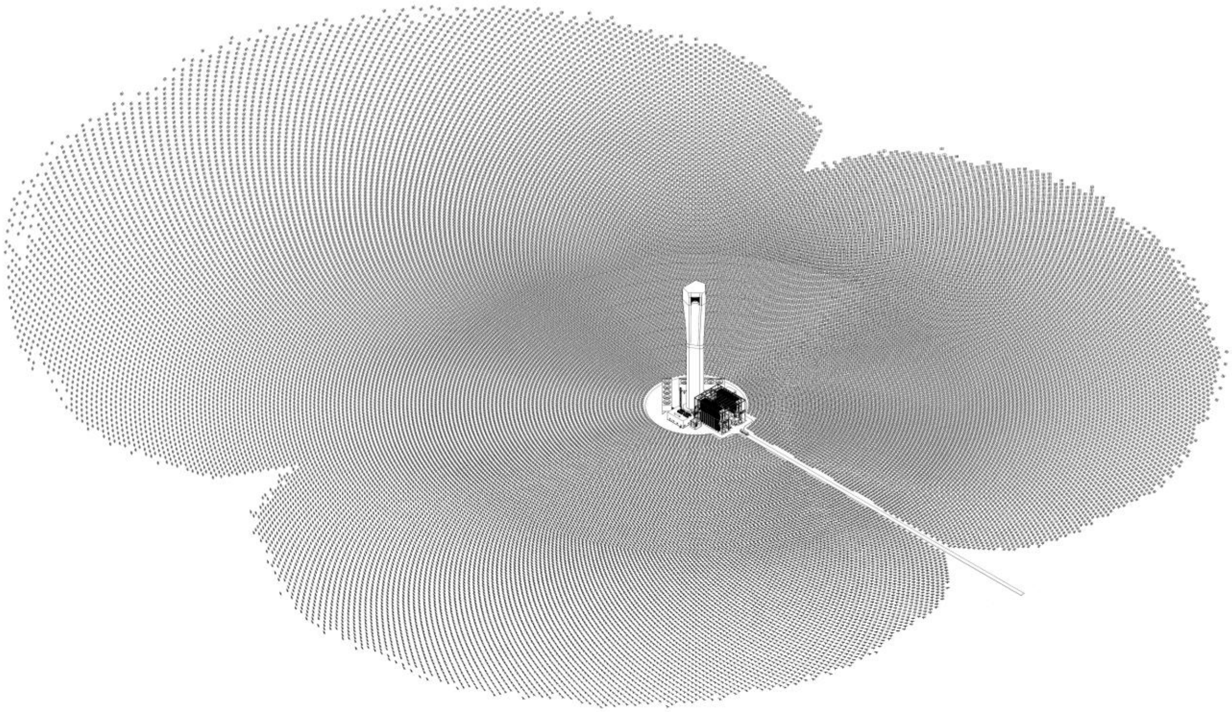


FIGURE 5. Artists view of the 50 MW_e commercial plant layout with a three-face open volumetric cavity receiver. The extension of the heliostat field is 1.68 km x 1.5 km. The optical height of the concrete tower is 200 m.

ANNUAL PERFORMANCE SIMULATION

Annual performance simulation was done on hourly basis including weather and radiation data from Vanrhynsdorp, South Africa, 2015 ([17]), power block performance from the simulation tool EBSILON® Professional ([18]) and heliostat field performance from the raytracing software STRAL ([15]), see table 2.

TABLE 2. Main simulation parameters

Parameter	Value
Location	Vanrhynsdorp, South Africa
Annual DNI	2576 kWh/m²
Design receiver intercept power	285 MW_{th}
Design gross electric power	50 MW_e
Simulation time step	1 hr
Storage capacity	variable

Plant operation was assumed in power priority mode, i.e. electric power is produced as long as there is heat available from either the receiver or the storage. So, time-dependent feed in tariffs or other scheduled power delivery plans were not considered. For the receiver, the option of outlet temperature regulation during part load was considered. As the receiver efficiency drops quite rapidly below 50% part load (see Fig. 3 (a)) the air outlet temperature can be reduced from the design point value of 670°C to 450°C at 15% load (see Fig. 3 (b)). Basic dynamic effects of the receiver and air cycle, like heating-up in the morning or after longer cloud periods were considered with lump sum discounts, which had been validated with dynamic simulations of selected situations.

Figure 6 shows a summary of the simulation results. The annual system efficiency rises with increasing storage size reaching saturation at about 15 storage units (≈12 full load hours). Regarding gross efficiency the high efficient power block has a clear advantage compared to the base case. But this advantage vanishes completely when looking at net power. While the base case plant has an internal consumption of about 10%, the high-efficiency system shows an internal consumption of more than 16%, mostly because of the increased parasitic power for the air fans. Receiver air temperature regulation shows a small but clear advantage in all cases.

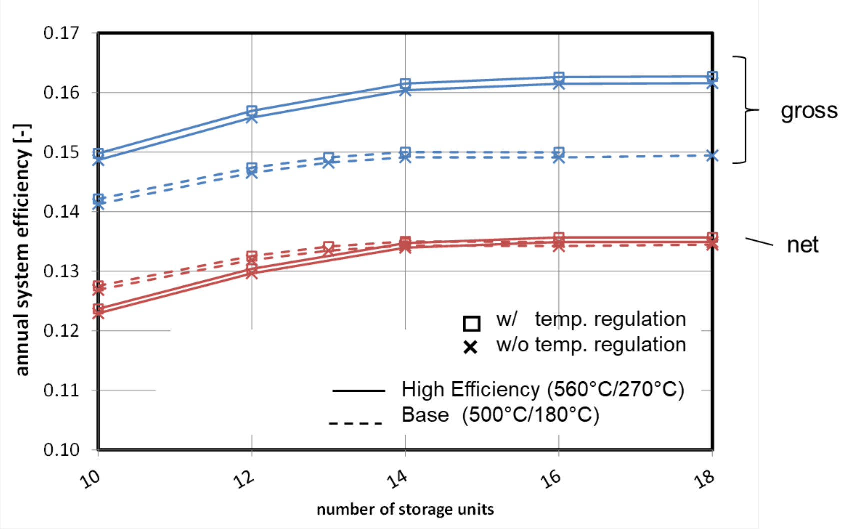


FIGURE 6. Results of the annual performance simulation.

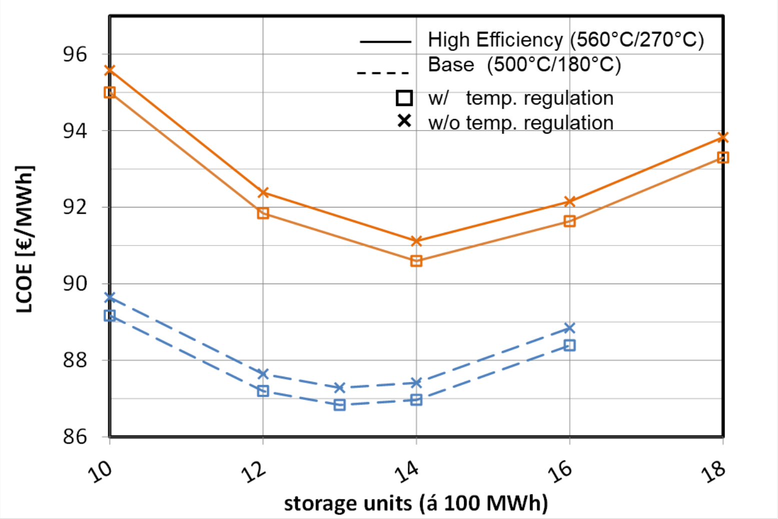


FIGURE 7. Results of the LCOE analysis.

LEVELIZED COST ANALYSIS

Levelized cost analysis was done using the simplified IEA method ([19]) to compare design alternatives on a common basis. Financial parameters (interest rate 5% and depreciation period 30 years) result in a fixed charge rate of 6.5%. The investment cost for the plant with the high efficiency power block is about 5% higher than with the base case power block, mostly due to increased expenses for the air system and the storage because of the lower temperature difference. The O&M cost for the plant with the high efficiency power block is about 2% higher than with the base case power block due to its higher live steam conditions.

Figure 7 shows the main results. The plant with the high efficient power block has its optimum at about 14 storage units (11.7 full load hours) with an LCOE of 90.6 €/MWh. The plant with the base case power block has an optimum at about 13 storage units (10.1 full load hours) with 86.8 €/MWh. So, the chosen high efficiency Rankine cycle with elevated return air temperature shows no advantage in an air receiver plant under the chosen boundary conditions. The option of receiver air temperature regulation shows a cost advantage of about 0.5 €/MWh throughout all cases.

CONCLUSIONS

The so-called HiTRec technology of the open volumetric air receiver with ceramic honeycomb absorber modules and active cooling of the metallic support structure by warm return air has reached the highest TRL for air receivers.

The test experiences at the Solar Tower Jülich since 2009 show high robustness, availability and dynamic flexibility and give a great confidence in the technology. Recent developments to increase the thermal receiver efficiency by changing the receiver geometry to a cavity resulted in efficiency values of above 85%, a comparable level to the molten salt or steam receiver technologies. Additionally, the outstanding dynamic flexibility of the air receiver concept, which is a great advantage compared to the mentioned alternatives, was even further enhanced through the redesign of the receiver structure. This assures high annual average solar efficiencies and electric yields.

A thermo-economic study for a 50 MW_e commercial reference plant at a relevant location gives LCOE values down to below 90 €/MWh, which is already in a comparable range to cost data of the prevailing molten salt technology. With a combination of two or more of these standard plants in a common solar power park to reach power levels of >100 MW_e it is expected that cost parity to molten salt can be reached. Especially at sites with non-optimal DNI conditions the ability of DNI-following operation is likely to further enhance cost competitiveness.

The authors conclude that this technology is on track to get technically and economically viable and due to its simple operability, it will become a serious alternative to the currently deployed receiver systems.

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