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Simulation of Hybrid Solar Power Plants

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Abstract. Hybrid solar power plants have the potential to combine advantages of two different technologies at the cost of increased complexity. The present paper shows the potential of the software *greenius* for the techno-economic evaluation of hybrid solar power plants and discusses two exemplary scenarios. Depreciated Concentrated Solar Power (CSP) plants based on trough technology can be retrofitted with solar towers in order to reach higher steam cycle temperatures and hence efficiencies. Compared to a newly built tower plant the hybridization of a depreciated trough plant causes about 30% lower LCOE reaching 104 $/MWh. The second hybrid scenario combines cost-efficient photovoltaics with dispatchable CSP technology. This hybrid plant offers very high capacity factors up to 69% based on 100% load from 8am to 11pm. The LCOE of the hybrid plant are only slightly lower (174 vs. 186 $/MWh) compared to the pure CSP plant because the capital expenditure for thermal storage and power block remains the same while the electricity output is much lower.

INTRODUCTION

Hybridization of solar power plants is usually considered as the combination of solar and fossil parts. In contrast, this paper investigates two different combinations of solar technologies. Both combinations investigated here, CSP trough/tower and CSP/PV, have certain advantages, but in return the resulting plant will be more complex than the individual power plants.

The first hybridization scenario relies exclusively on Concentrating Solar Power (CSP) technology and discusses the retrofit of an existing parabolic trough power plant with a solar tower system. The solar tower allows reaching higher temperatures up to 565°C compared to the trough plant. It provides not only additional high-temperature thermal energy, but also entails a significantly higher conversion efficiency in the power block.

Currently, photovoltaics (PV) technology dominates global solar electricity production due to much lower levelized cost of electricity (LCOE). The major advantage of CSP is the thermal storage which allows cost efficient storage of heat in order to produce electricity according to the demand. The desire for the combination of both advantages, low cost and dispatchability, is one motivation for the conception of solar hybrid power plants. An exemplary PV/CSP hybrid plant is discussed in the second part of this paper.

Both hybrid scenarios are evaluated using the software *greenius* which is developed by the German Aerospace Center (DLR) and available free of charge [1].

HYBRID TROUGH / TOWER CSP PLANTS

Existing parabolic trough plants are limited to maximum live steam temperatures of about 385°C leading to moderate efficiencies of about 39%. The retrofit with a solar tower system allows increasing the steam temperature up to 550°C resulting in about 5-10% higher power block output. Certainly, the existing power block requires massive modification when the steam temperature is increased in those dimensions. Among other components the high- and low-pressure turbines have to be replaced as well as the corresponding piping. Nevertheless, significant parts can be conserved. A detailed analysis of the required power block modifications is in progress and will be published along with a detailed economic analysis in the future. The present paper focuses on the modeling

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approach of such a hybrid plant in *greenius*, the interdependencies of both heat suppliers and an exemplary LCOE calculation.

Plant Design

A simple approach for the integration of heat from a solar tower into an existing power block is the downstream addition of salt-steam heat exchangers in the superheater and reheater sections as shown in Figure 1. An alternative option would be to replace the complete steam generator system with salt-steam heat-exchangers and use the parabolic trough field as preheater for the central tower receiver. Among others, the advantage of such a configuration would be the higher share of tower heat with the downside of higher investment. With the concept presented below the optimum heat input share of the tower is 27%.

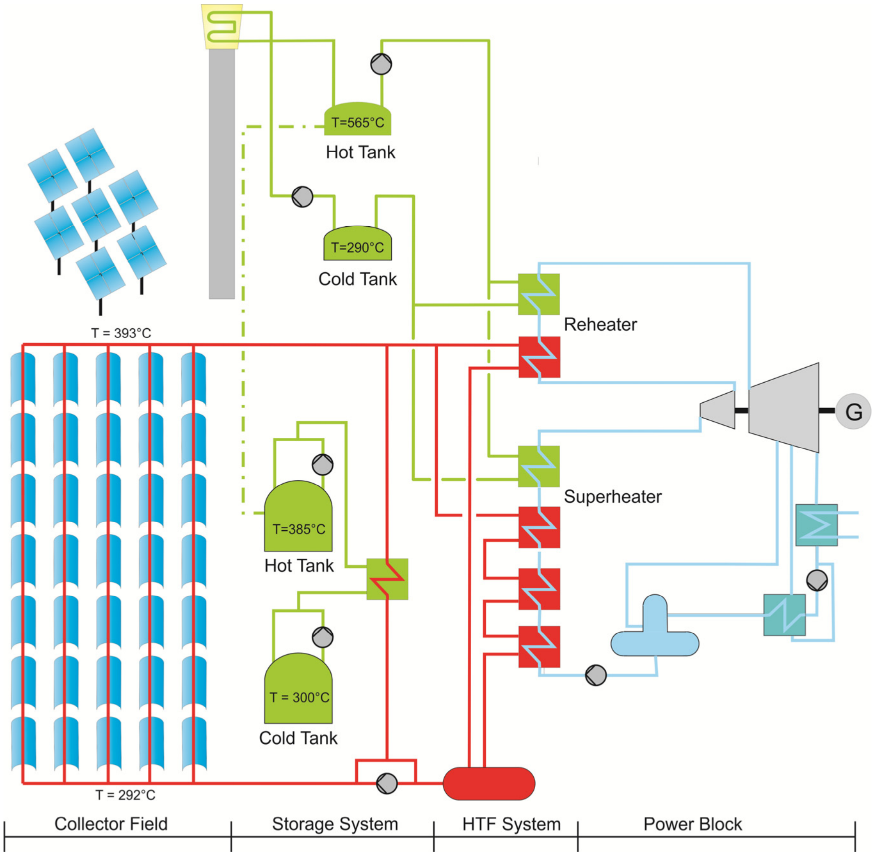


FIGURE 1. Retrofitted trough plant with tower-driven superheater and reheater for temperatures up to 565°C (red: thermal oil, green: molten salt, blue: water/steam)

The performance and economics of the hybrid plant are compared to a reference tower plant with molten salt receiver of similar size. The main properties are summarized in Table 1. The parabolic trough field of the hybrid system is dimensioned according to the 50MW Andasol 3 power plant in the south of Spain. The thermal input from the trough field to the power block is limited to 112.5 MW which is lower than before the retrofit (129 MW) because the live steam mass flow in the cycle is limited to the original 55 kg/s in order to preserve major existing components. The heliostat field size of the tower system is optimized for minimum LCOE.

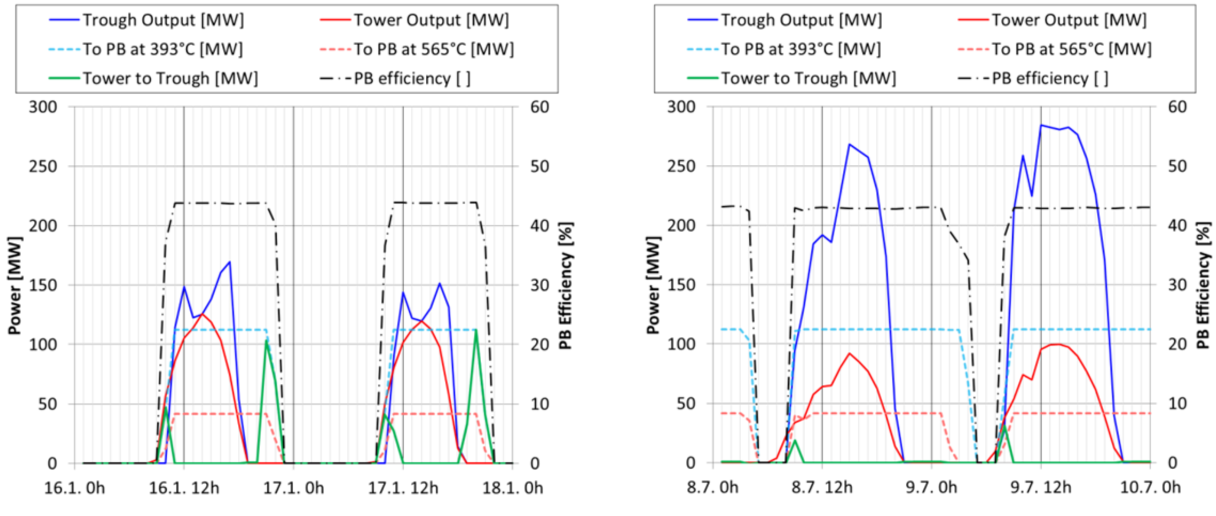
TABLE 1. Technical details of the reference tower plant and the trough-tower hybrid plant

Parameter	Tower Reference	Trough-Tower Hybrid	Unit
Tower aperture area	759,648	199,184	m²
Tower nominal thermal output	396	116	MW
Trough aperture area	-	510,120	m²
Trough nominal thermal output	-	274	MW
Net Storage capacity at 383°C / 565°C	0 / 1280	940 / 340	MWh
Nom. PB thermal input at 393°C / 565°C	0 / 151.8	112.5 / 41.4	MW
Nominal gross output	65.9	65.2	MW
Nominal power block efficiency	43.4	42.4	%

Annual Yield Calculation

The software *greenius* developed by the German Aerospace Center (DLR) was used for the annual yield analysis and upgraded in order to allow the hybrid operation of trough and tower plants [1]. This tool allows energy based calculations with hourly resolution and relies on lookup tables for the definition of the power block, heliostat field and central receiver efficiencies. The thermodynamic simulations of the steam cycle were performed with *Ebsilon Professional* [2], the tower system was dimensioned using *HFLCAL* [3].

The daily heat output profiles as well as the influence of the season differ significantly between trough and tower system as shown in Figure 2. On a typical summer day the trough field delivers about three times more energy than the tower. In contrast both systems have the same output at solar noon on a winter's day. The most cost-efficient tower field reaches the optimum heat input share of the power block during summer and produces a significant amount of excess heat in winter. Since the salt-steam heat exchangers are not sufficient to run the steam cycle, it is indispensable for efficient operation to foresee a possibility to shift energy from the tower storage to the trough storage or directly to the thermal oil. The easiest approach is to charge the hot trough storage tank with a mixture of salt from the hot tower storage tank and the cold trough storage tank. In contrast the operation with heat input exclusively from the trough system is possible at the cost of lower power block efficiency as shown by the data for the night of July 8-9.



(a) Winter day

(b) Summer day

FIGURE 2. Typical profiles of thermal output and heat supply to power block for trough field and tower system.

LCOE Calculation

As mentioned above, the detailed assessment of different retrofit options for parabolic trough power plants is not the subject of this paper since it requires intensive research and assumptions on the expectable state of the trough plant at the moment of the retrofit as well as an in-depth assessment of the required power block modifications. The cost assumptions for the LCOE calculation are based on data from [4] for the year 2015 and summarized in Table 2. The investment cost for the power block, solar field and thermal storage of the trough plant are so low because those components receive a major overhaul and must not be rebuilt. It is assumed that this overhaul requires 20% of the turn-key cost of a new solar field and thermal storage and 60% of a new power-block.

It should be noted that the cost figures in this table are final figures including all surcharges for profit margin, contingencies and owners cost. These specific cost assumptions have been used for the reference plants as well as for the corresponding parts of the hybrid plant.

TABLE 2. Assumed specific investment cost per component and economic boundary conditions

Component / Parameter	Tower Reference	Trough-Tower Hybrid	Unit
Heliostat field	197	197	\$/m²
Central receiver	173	173	\$/kW
Tower	124,200	124,200	\$/m
Thermal storage at 565°C	36	36	\$/kWh
Power block	1753	1010	\$/kW
Parabolic trough solar field	-	64	\$/m²
Thermal storage at 383°C	-	12	\$/kWh
Land cost	1	1	\$/m²
Interest rate	5.4	5.4	%

The software *greenius* does not only yield calculations but offers also economic figures for renewable energy plants. The key results of the retrofit example are given in Tab. 3. The total investment for tower reference plant is about twice as much as for the retrofit. The levelized cost of electricity are 143 \$/MWh compared to 104 \$/MWh for the retrofit plant.

TABLE 3. Techno-economic key results of the trough / tower hybrid plant

Parameter	Tower Reference	Trough-Tower Hybrid	Unit
Total investment cost	412	207	Mio. \$
Net electricity output	290,914	239,835	MWh
LCOE	143	104	\$/MWh

From an economic point of view the correct reference case for the retrofit option is the continued operation of the trough plant after a major overhaul without retrofit. The surplus of energy produced thanks to the retrofit must be taken into account. The detailed analysis of different retrofitting strategies is the next step in this project.

HYBRID CSP / PV POWER PLANTS

The second hybrid system considered is a combination of a 53 MW_e photovoltaic (PV) plant and a 50 MW_e gross CSP plant to fulfill a predefined load curve with a maximum load of 40 MW_e. The idea of such a plant is to combine cheap solar electricity from PV with dispatchable but more expensive solar electricity from CSP with thermal storage. Such a system is currently constructed in the Copiapó project in Chile [5]. Due to the fact that installation prices for PV have been fallen rapidly during the last decade, it is currently the cheapest technology for production of solar electricity. On the other hand, large battery storage is quite expensive (480 \$/kWh_e in 2016[1]) and other storage options like pump storage are limited in their availability. CSP power plants are more expensive but they can easily use large inexpensive thermal storage tanks to produce solar electricity on demand (145 \$/kWh_e in 2016[2]).

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[1] Based on [6] for an energy-to-power ratio of 6 and with an exchange rate of 1.1 \$/€.

[2] Based on 58 \$/kWh_{th} from Tab. 5 and a mean power block efficiency of 40%.

From these considerations the combination of both technologies seems to be a good idea in order to extend the fraction of solar electricity in a certain area and keep the costs at a reasonable level.

Unfortunately the output of each of the plants and therefore also electricity production cost will be affected by the other plant in such a hybrid arrangement. Therefore the restrictions have an effect on overall production and cost. One cannot just sum up the electricity production of two standalone solar power plants and calculate the LCOE from a weighted average of the standalone plants but the yield calculation is more complicated. The design of individual plants in combination will be different compared to standalone plants for the same load demand.

For this study a hypothetic load curve as shown in Fig. 3 has been assumed. That is a constant load of 40 MWe (net) from 8:00 to 23:00 for each day of the year. The hybrid plant is not allowed to deliver more than the required 40 MWe and electricity production between 23:00 and 8:00 is prohibited. This is of course a kind of artificial load curve but it seems not unrealistic for a certain market. South Africa e.g. has a kind of feed in tariff for CSP plants where the operators will get no remuneration for electricity produced between 22:00 and 5:00 [7]. Typical load demand curves from the Spanish grid show that the demand decreases considerably between 23:00 and 8:00 compared to the remaining hours of the day [8]. The limitation of net power delivered to the grid could also be reasonable for sites with restricted grid capacity. Anyway in this case the load curve is just an example to demonstrate the methodology.

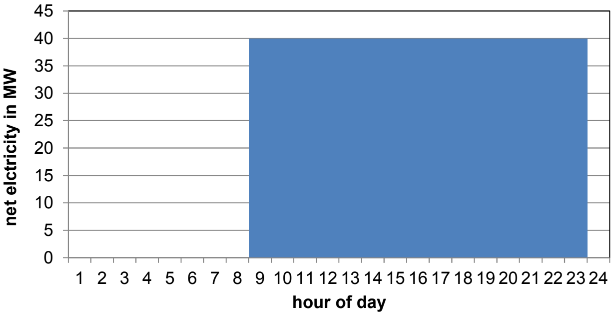

FIGURE 3. Load curve for the CSP/PV hybrid power plant

Of course a solar only power plant cannot fulfil this load curve completely because there will be longer time periods without sufficient solar radiation. Instead it is considered as upper limit and the hybrid solar plant shall try to cover as much as possible of this demand. The software tool *greenius* has been used for this study. Both solar technologies are implemented in *greenius* and it is capable to follow a user-defined load curve as in this example. Not yet implemented is the combination of the two technologies in a single simulation run. Therefore two runs were made: one for the PV plant which has production priority during sunshine hours and a second run for the CSP plant with a modified load curve. This modified load curve was made by using the one shown above and subtracting the electricity production of the PV plant. Thus the load demand of the CSP plant is varying hour by hour depending on the PV plant output.

Plant Design

In a first step the two plants must be designed for the specific site and the load demand. Table 4 gives an overview of the configuration of both plants. The site assumed for this study was Plataforma Solar de Almeria in southern Spain with a measured meteorological dataset with hourly resolution showing an annual DNI sum of 2418 kWh/m². Since net electricity demand is at 40 MW, the nominal power of both plants must be higher. In order to produce as much electricity as possible by the PV plant, its nominal power was chosen at 53 MW. Since this power is defined for standard test conditions (Irradiance: 1000 W/m², t_{cell}: 25°C, AM: 1.5), the actual maximal output under real operating conditions prevailing at this site is 50 MW. For the whole year the PV plant shows 622 hours where it could produce more than 40 MW in this example. It is made of mono-crystalline PV panels with a nominal efficiency of 17.1% (STC) and an area of 1.634 m² each.

The CSP plant considered here is a parabolic trough power plant with 50 MW gross output and 2-tank molten salt thermal storage. The heat transfer medium is thermal oil limiting the outlet temperature of the HTF to 400°C. For this plant the net output depends on the operation mode. The highest net output can be reached when the heat from the solar field is used directly in the power block and when the storage is fully charged. Storage charging requires additional pumping power for the solar field, thus reducing the net electricity output. When the power block is operated solely from the thermal storage the pumping parasitics are lower but the inlet temperature of the thermal oil and thus the live steam temperature are lower compared to direct utilization of heat from the solar field. This again reduces the gross output of the CSP plant. The storage size is 640 MWh which is sufficient to run the power block for 5 hours at maximum load. The CSP plant uses Eurothrough 150 type collectors arranged in loops of 4 collectors in series. This is a typical design like it has been used in many Spanish parabolic trough plants. The total number of loops is smaller than in these Spanish plants. This plant has only 65 loops compared to more than 150 loops for the typical plant in Spain. The reason for this reduction is mainly the reduced demand due to the additional PV system and the smaller thermal storage. The storage size as well as the number of loops was found by LCOE-minimization of the parabolic trough plant using the modified load curve which considers the residual load for the CSP plant.

TABLE 4. Technical details of the CSP/PV hybrid power plant

Parameter	PV plant	CSP plant	Unit
Total aperture area	313632	212550	m²
Total land area	550000	750000	m²
No. of modules/collectors	192000	260	-
Nominal gross output	53	50	MW
Maximal net output at site	50	44.5	MW
Storage capacity	0	640	MWh

Annual Yield Calculation

Figure 4 shows the output of both plants for 2 typical days in summer and winter respectively. During good days in June the PV plant is capable to produce more than 40 MW around noon (red line in Fig. 4). For a standalone PV plant with identical load curve restrictions this would mean that the overproduction could not be used. In this case at least some fraction of the surplus electricity above 40 MW can be used because the CSP plant needs electricity during this time. The CSP plant produces electricity during early morning, in afternoon and evening hours (green line in Fig. 4). The load demand is almost fulfilled during those days in June except for 2 hours (yellow line in Fig. 4). At 11:00 and at 2:00 the plant output is about 2 to 4 MW below the required 40 MW. The reason for this gap is that the PV plant delivers less than the required 40 MW and the power block of the CSP plant is not able operate at this low load. The minimum load for this power block is about 7 MW gross. In December the hybrid plant is only capable to extend the solar electricity production for about 2 hours after sunset even on good days as the 29th shown in Fig. 4. This is caused by the shorter day length and unfavorable incidence angles.

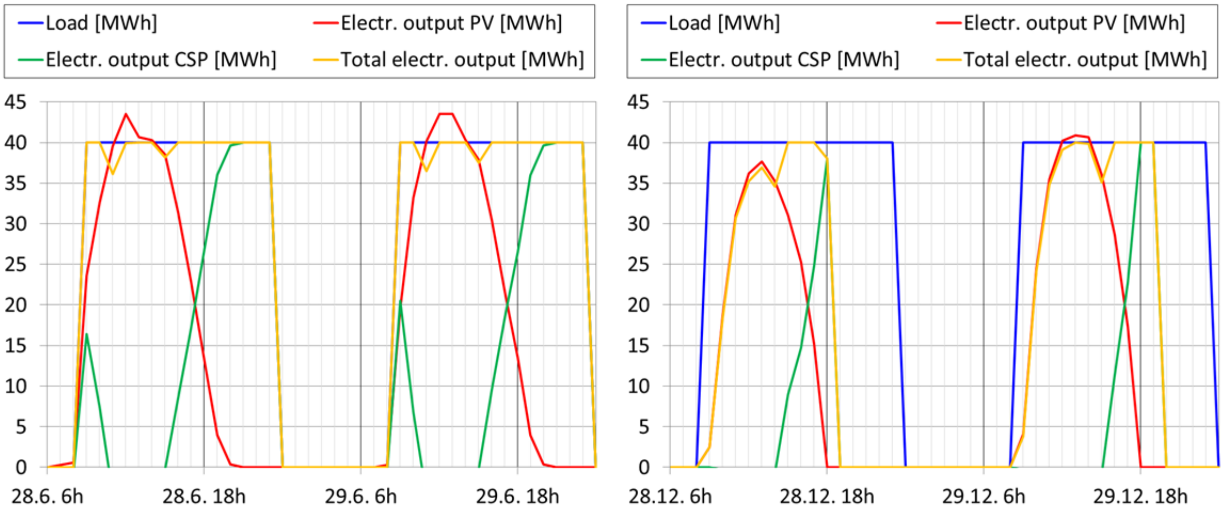

FIGURE 4. Solar electricity produced by a PV and a parabolic trough plant during 2 days in June and 2 days in December

In order to evaluate the hybrid plant in terms of capacity factor and LCOE, reference plants must be defined. For PV it is simply the same plant as foreseen for the hybrid configuration but for CSP the reference plant would be larger because it has to deliver more electricity during daylight hours. Again the least cost configuration was chosen which has 110 loops and 520 MWh of thermal storage in this case.

LCOE Calculation

The most interesting question in this study was: to which extend can the electricity costs of the CSP plant reduced compared to a standalone plant? The answer depends heavily on the cost assumptions for both plants. In this study component costs for 2015 reported in [4] have been used. Details are given in Table 5.

TABLE 5. Cost assumptions for CSP/PV hybrid power plant

Parameter	PV plant	CSP plant
Specific investment SF	1804 $/kW	319 $/m²
Specific investment cost PB	-	1684 $/kW
Specific investment cost storage	-	58 $/kWh
Land cost	1 $/m²	1 $/m²
Interest rate	5.4 %	5.4 %

The technical and economic key results for the hybrid plant as well as for the reference plants are shown in Tab. 6 and Fig. 5. Comparing the annual output of the standalone plants on the basis of capacity factor (for the load curve assumed here) gives 41% for the standalone PV plant, 55% for the standalone CSP plant and 69% for the hybrid plant. That means that the hybrid plant will be able to fulfill the load curve for much more hours than the standalone plants can.

TABLE 6. Key results of the CSP/PV hybrid power plant

Parameter	PV reference plant	CSP reference plant	Hybrid Plant	Unit
Total investment cost	97	231	289	Mio. $
Net electricity output	90712	120841	151309	MWh
Capacity factor	41.4	55.2	69.1	%
LCOE	86	186	174	$/MWh

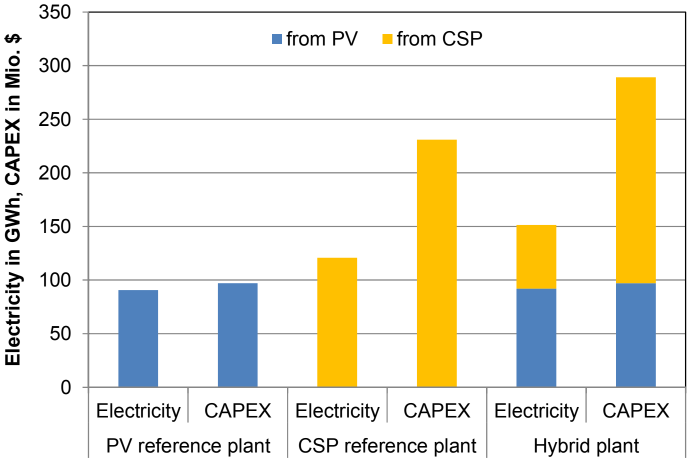

FIGURE 5. Electricity and CAPEX fractions of the standalone and the hybrid plant

The hybrid power plant shows reduced LCOE compared to the CSP reference plant. The important fact to mention here is that the LCOE of the PV reference plant is about 46% of the LCOE of the CSP reference plant and in the scenario considered here the PV plant will deliver almost 60% of the electricity output of the hybrid plant. So why is the LCOE of the hybrid plant close to the LCOE of the CSP reference plant and not below the mean LCOE of both reference plants? The answer is that the LCOE of the CSP part in the hybrid plant increases considerably compared to the standalone variant. The PV plant has priority in terms of electricity production but the CSP plant must fulfill the remaining load curve. Therefore the CSP plant in the hybrid setup will have the same power block as in the standalone plant. The storage of the CSP plant in the hybrid setup will even be larger than for the standalone plant and only the solar field size will be reduced. That means total investment costs for the CSP plant in the hybrid setup will only be reduced by about 17% but its annual electricity output will be reduced by 51%. Consequently, the LCOE for the CSP part in the hybrid plant would be about 306 $/MWh since the electricity production is limited to those hours when PV cannot fulfill the load curve.

CONCLUSION

For CSP technology, the addition of a solar tower can be an attractive retrofit option for depreciated trough plants. The software *greenius* can be used for the techno-economic evaluation of such hybrid plants. An important factor for the efficient operation is the possibility to shift energy from the tower to the trough side in order to compensate the different seasonal variations of the heat output of both technologies.

The LCOE for a retrofitted depreciated trough plant are very attractive compared to a newly built CSP plant. However, the low figures are a result of the fact that the trough part of the plant already exists and causes only minor further investment cost. The economic evaluation of the retrofit concept itself requires a detailed analysis of the required modifications of the power block and comparison with the scenario of continued operation after overhaul without retrofit.

A hybrid solar power plant consisting of a PV plant and a CSP plant might be an attractive solution if high capacity factors are important. Depending on the boundary conditions this combination might also show lower LCOE as a pure CSP plant. For plant design and calculation of LCOE figures the hybrid plant must be analyzed carefully and it must be taken into consideration that the CSP part of such a hybrid plant will typically have higher LCOE than a standalone CSP plant under identical conditions. This is mainly caused by giving the production priority to the PV plant during daylight hours.

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