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Analysis of an Integrated CSP-PV Hybrid Power Plant

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Abstract. In the past, CSP and PV have been seen as competing technologies. Despite massive reductions in the electricity generation costs of CSP plants, PV power generation is - at least during sunshine hours - significantly cheaper. If electricity is required not only during the daytime, but around the clock, CSP with its inherent thermal energy storage gets an advantage in terms of LEC. There are a few examples of projects in which CSP plants and PV plants have been co-located, meaning that they feed into the same grid connection point and ideally optimize their operation strategy to yield an overall benefit. In the past eight years, TSK Flagsol has developed a plant concept, which merges both solar technologies into one highly Integrated CSP-PV-Hybrid (ICPH) power plant. Here, unlike in simply co-located concepts, as analyzed e.g. in [1] – [4], excess PV power that would have to be dumped is used in electric molten salt heaters to increase the storage temperature, improving storage and conversion efficiency. The authors demonstrate the electricity cost sensitivity to sub-system sizing for various market scenarios, and compare the resulting optimized ICPH plants with co-located hybrid plants. Independent of the three feed-in tariffs that have been assumed, the ICPH plant shows an electricity cost advantage of almost 20% while maintaining a high degree of flexibility in power dispatch as it is characteristic for CSP power plants. As all components of such an innovative concept are well proven, the system is ready for commercial market implementation. A first project is already contracted and in early engineering execution.

INTRODUCTION

Over the past few years PV prices have dropped consistently and are supposed to do so in the future. CSP prices have also fallen, but at a slower pace in comparison to PV. The situation today is that PV has lower electricity costs during daylight than CSP, leading to a higher peak power supply from PV. To limit strain on the electric grid, large PV plants usually have a contractually agreed limited maximum power to inject into the grid. Economic optimization leads to an oversizing of a PV plant to achieve high energy production, i.e. the rated peak power is significantly higher than the feed-in limit. This leads to a power curtailment in most days of the year. The CSP system on the other hand generates electricity at higher cost during daylight, but has a significantly higher dispatchability, being able to operate 24 hours per day.

Addressing the above listed advantages and disadvantages of the two systems, an ICPH power plant has been designed to minimize the shortcomings and make use of the advantages of the two systems, by shifting part of the PV-generated electricity into the thermal part of the plant. Thus, the ICPH system considered in this paper takes advantage of the low electricity cost of PV, better use of the curtailed power and the dispatchability of CSP. Besides that, hybridization of the two systems leads to a better use of PV power and even to a significant improvement of the CSP efficiency. The production profile of a CSP solar field and a one-axis tracking PV plant are similar. So an increase in thermal energy production leads to an increased PV power requirement to MSEH. The power curtailment is thus

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minimized for ICPH plants. Owing to these advantages of an ICPH system, new hybrid power plants are under development, while a first project is ready to start its construction shortly.

An ICPH power plant brings a big advantage for the solar industry – dispatchable electricity at record-low costs. However, as it comprises a PV and a CSP plant in one system the system complexity increases significantly. Thus, applying a systematic optimization methodology plays a paramount role to achieve an optimum configuration of the ICPH plant. In this paper, results of an optimization process of such ICPH power plant are published for the first time.

SELECTION OF SYSTEM CONFIGURATION

The ICPH power plant considered in this project consists of different main subsystems, namely the parabolic trough solar field (SOF), a photovoltaic system (PV), molten salt electric heaters (MSEH), power block (PB) and thermal energy storage (TES). The SOF considered in this study uses a thermal oil as a heat transfer fluid (HTF). A salt/HTF heat exchanger (HX) is used to transfer heat from the HTF in the SOF to the salt flowing from the cold TES tank to the hot TES tank. The efficiency of a CSP plant can be further improved by increasing the steam temperature. One advantage of a CSP-PV hybrid plant is the possibility of using MSEH to further heat the salt before it enters the hot tank. Thus, the MSEH is a core subsystem of an ICPH plant. The MSEH can be connected at different parts of the hybrid system. For this study, an MSEH placed between the HTF/salt HX and hot TES tank is considered. The following figure shows the system configuration chosen for this study.

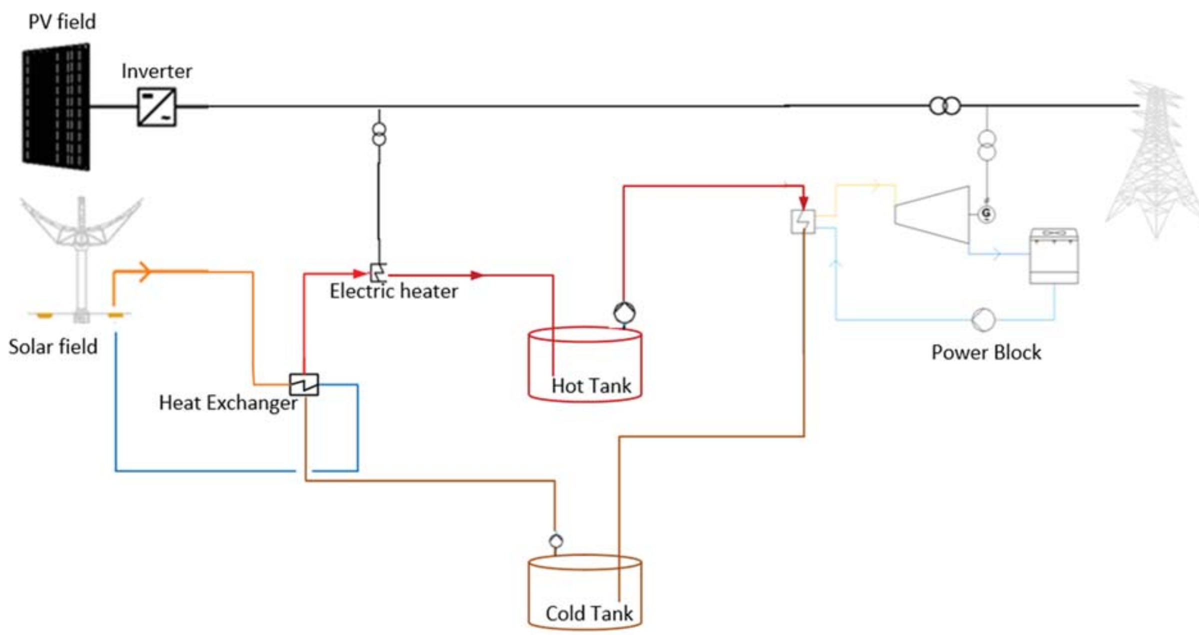

FIGURE 1. Schematic diagram of a CSP-PV hybrid plant configuration

As shown in figure 1, before entering into the MSEH, the salt first flows from the cold TES tank to the HTF/salt HX. The maximum HTF operation temperature is limited to around 393 °C. Therefore, the salt temperature at the exit of HX will be slightly below 393 °C. The salt that exits from the HX further flows through the MSEH. The MSEH uses the electric power from PV to elevate the salt temperature to a maximum salt temperature of 565 °C, which was set for this study. In this system, there is no direct heat transfer from HTF to the PB. The steam generation system, i.e. the super heater, reheater, evaporator and the economizer, uses only molten salt as a heat source.

TSK Flagsol's in-house performance model, PCTrough, is used for an annual simulation of the ICPH system. PCTrough includes different operation strategies that highly dependend on the following factors:

- Solar radiation,
- Actual electric and thermal power produced from PV field and SOF, respectively,

- Grid power demand and
- Tariff of the hour.

One main operation strategy is an operation strategy for high-DNI periods, in which both, PV field and SOF, are in operation and energy is available from both subsystems at almost the same time. During this operation period, PV continues to produce as much power as possible depending on the available solar irradiation. The resulting electrical power from PV is then divided into power to be injected into the grid and power to be supplied to the MSEH. Depending on the selected operation strategy, PCTrough calculates the power required by the MSEH, which is highly dependent on the salt flow and the maximum salt temperature required. Thus, for each specific simulation time PCTrough calculates the salt mass flow and the required PV power to elevate the salt temperature at the exit of MSEH to 565 °C. The hot salt coming from MSEH is stored in the hot TES tank. Another operation strategy is used for during low-irradiation hours. During these periods, PCTrough determines which strategy to follow depending on the tariff of the hour. If power is to be produced during these hours, the energy stored in the hot tank is then used to generate power.

In this study, a 100 MW ICPH power plant with the capability of producing electricity up to 24 hours per day is optimized. To account for different nighttime demands in different energy markets, different tariffs were selected for the hours after sunset and before sunrise ("peak hours"). The higher the hypothetic demand at nighttime, the higher the peak tariff. This classification of peak and offpeak hours is common for defining the PPA price of a plant and has been used in South Africa and Morocco CSP projects. The differences in demand and tariff will become more pronounced as more cheap but non-dispatchable PV power is injected into the grids. For the ICPH power plant configuration analyzed in this study, the following boundary conditions are considered:

TABLE 1. Main boundary conditions of an ICHP power plant

Parameter description	Value
ICPH power plant location	Morocco
TMY Resolution	Hourly
Maximum power to the grid	100 MW_e
Turbine capacity	100 MW_e
SOF collector type	Parabolic trough
Name of SOF collector	HelioTrough®
Tracking of PV	Single axis (North-South axis)
Peak-to-off-peak tariff ratio	1, 2 or 3
Peak hours	from sunset until sunrise
Off-peak hours	from sunrise until sunset
Minimum STO capacity	6 FLHs

SYSTEM OPTIMIZATION

The CSP and PV systems are highly integrated by the use of MSEH. Thus, the optimization methodology applied in this study is to make an annual simulation of the complete hybrid system by varying some main parameters. To obtain an optimum hybrid power plant configuration, parameters that represent each of the main subsystems are chosen as an optimization parameter. As discussed in the previous sections of this paper, the CSP-PV hybrid system comprises different main subsystems, namely PV, SOF, TES and MSEH.

To reduce the complexity of analysis and to minimize the number of permutations a preselection of plausible parameter value ranges and simulation steps has been made as shown in the following table:

TABLE 2. Description of main optimization parameters

Subsystem	Description	Range	Simulation Step
PV plant	Peak power	250 -600 MW_p	50 MW_p
TES	Full load hours (FLH)	6 -14 h	1 h
SOF	Parabolic trough loops	24 – 68 loops	4 loops
MSEH	Maximum power	100 -350 MW	50 MW

Note: The number of loops may seem low in comparison with pure CSP plants. This is due to the fact that in the arrangement as proposed in Figure 1 only part of the temperature gain of the storage medium can be delivered by the oil-based HTF (roughly from 300 to 390°C), while the electric heaters deliver the remaining temperature lift (from 390 to 565°C). Correspondingly, the heat from the SOF is limited.

METHODS OF ANALYSIS

Based on the steps and ranges of parameters defined, 4752 possible configurations are simulated. An annual simulation is performed for each configuration defined by the specific subsystem sizes. The selection of an optimum configuration can be made using different criteria. The results of all annual simulations are then compared, using for comparing the different configurations a figure of merit, that incorporates the height of cost associated with the optimized parameters, offset by the energy production. As explained in Section 2, the energy produced at peak time is assumed to have higher value, the corresponding energy sales amount is increased. The resulting figure is not really electricity cost, but called LEC for the sake of simplicity in this paper.

The levelized electricity cost is calculated as:

$$LEC = \frac{INV*FCR+O\&M}{WAEP} \quad , \tag{1}$$

Where INV is the total investment cost, FCR is the fixed charge rate, O&M is the annual O&M cost, and WAEP stands for the weighted annual electricity production.

Using TSK Flagsol's cost data bases (based on projects executed in the past), the total investment (I) and operation and maintenance costs (O&M) of each configuration are calculated.

Since three different tariff structures are considered in this study, the effect of a particular tariff needs to be included in the LEC calculation. Depending on the power production period, peak/off-peak, the resulting electricity production is weighted with a factor of 1 for daytime and factors of 1, 2 and 3 for nighttime. The weighted annual electricity production (WAEP) is calculated as:

$$\mathrm{WA}EP = (PEP \ * (1,\ 2\ or\ 3) + (OPEP \ * 1) \tag{2}$$

Where OPEP is the off-peak electricity production and PEP is the peak electricity production.

The LEC value of a configuration is calculated using the costs and annual electricity production and compared with LEC values of other configurations. A plant configuration with a minimum LEC value is considered as an optimum CSP-PV hybrid plant configuration.

ICPH OPTIMIZATION RESULTS AND DISCUSSION

The simulation results can be analyzed in various ways and allow conclusions regarding the impact of a specific subsystem size on the overall LEC of a configuration. The optimum configuration is selected by only comparing LEC values. The optimum ICPH configuration is the one that results in the lowest LEC value. Besides selection of the optimum plant configuration, it is worth analyzing the interdependence of the optimization parameters and effects of each optimization parameter on the overall result. Some optimization results are shown below, and for clarity, all resulting LEC values shown are normalized to the lowest overall LEC as:

$$Normalized\ LEC = \frac{LEC\ value\ of\ a\ given\ plant\ configuration}{Minimum\ LEC\ value\ of\ all\ ICPH\ configurations} \tag{3}$$

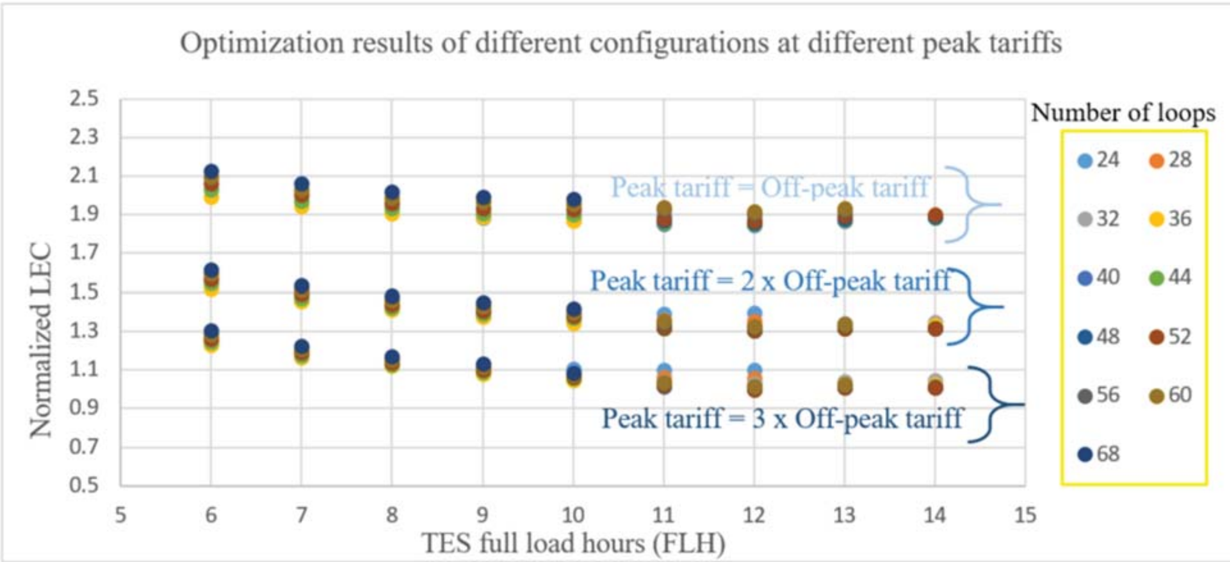

FIGURE 2. Normalized LEC value for different configurations and tariff structure

A graphical representation of TES size against normalized LEC values is shown in figure 2. The color of the dots represents the number of loops in the solar field. The results obviously show that as the peak tariff increases, the absolute LEC value decreases. This is a direct implication of the advantage of a higher tariff payment for the energy produced during peak hours. The other important result shown in figure 2 is that the optimal storage capacity, 12 FLH, remains the same in all the three different tariffs. This implies that the optimal TES size is independent of peak tariff.

Besides that, looking at specific TES sizes in the above figure, one can conclude that the optimum number of loops depends on the TES size. As the TES size increases from 6 FLH to 14 FLH, the optimum number of loops also increases from 36 to 52, respectively. For further description of the results, in the following graphs results with a tariff factor of 2 are used.

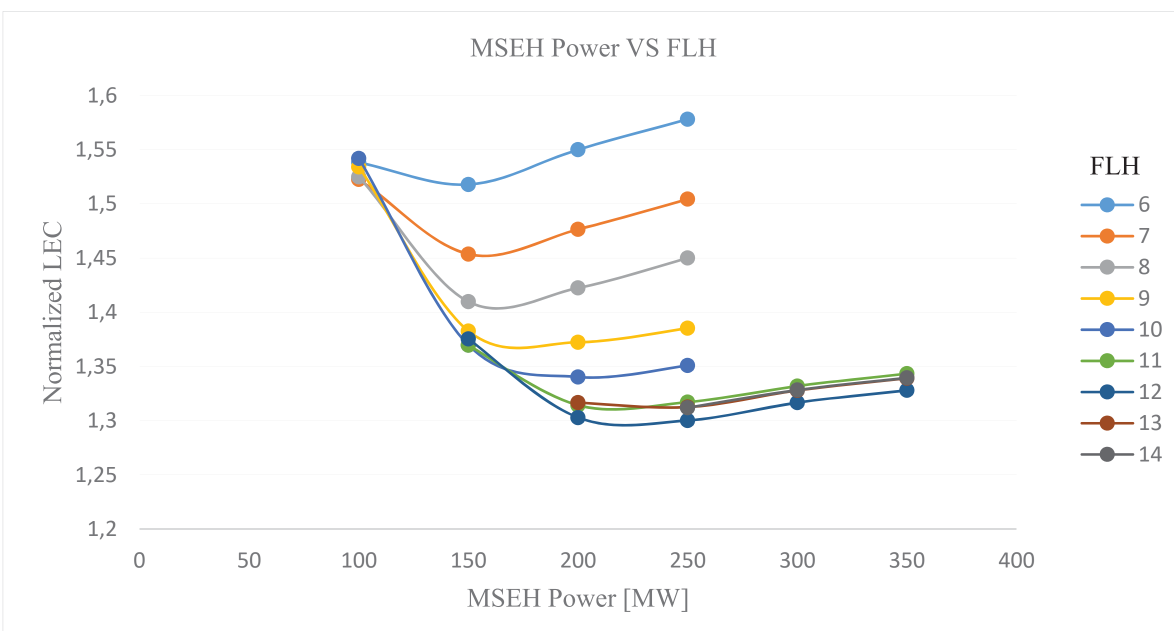

FIGURE 3. Normalized LEC value for different MSEH with respect to different FLH (tariff factor 2)

Figure 3 shows the dependence of the LEC on MSEH power for various TES sizes. The optimum TES size for MSEH capacities above 200 MW is around 12 full-load hours. For MSEH capacities below 200 MW, the optimum TES size decreases. For MSEH sizes of 100 MW and 150 MW, the optimum TES sizes are 7 FLH and 11 FLH, respectively. The results clearly show that for a given MSEH size there exists an optimum TES size.

Figure 4 shows the effect of changing PV, MSEH power and SOF sizes for a TES with 12 FLH. It also shows that the optimum size of MSEH is strongly related to the PV size. For each size of MSEH, there is an optimal PV size. In general, as the size of the electric heater increases, the resulting optimum PV size also increases. Referring to the system configuration as a whole, an increase in loop numbers increases the mass flow through the SOF. This will demand an increasing MSEH size.

It is noteworthy that for a plant that may only deliver 100 MW into the grid, a PV system with a nominal capacity of 450 to 500 MW leads to optimum results, in the case of a tariff factor of 2 at nighttime. The MSEH then have a capacity of 200 to 250 MW.

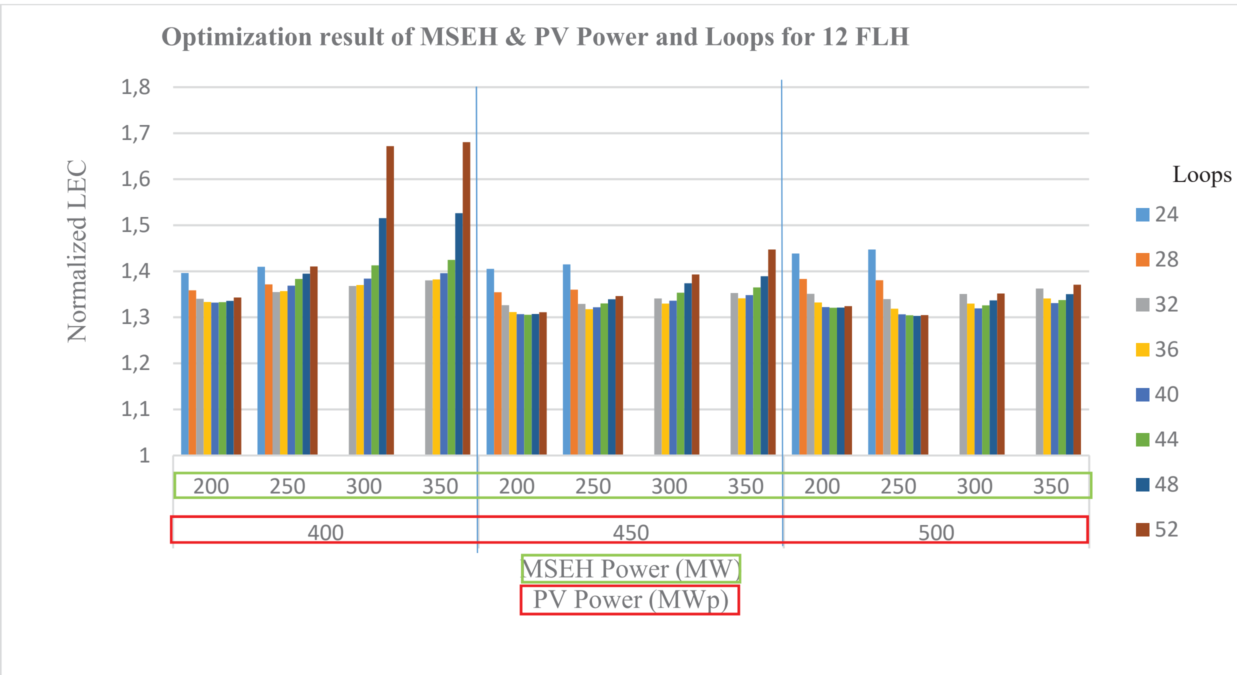

FIGURE 4. Optimization result of different parameters at FLH of 12 (tariff factor 2).

COMPARISON WITH CO-LOCATED HYBRID PLANTS

The interesting question is now, if there is any advantage of the ICPH plant over the less complex state-of-the-art hybrid plant, i.e. a "co-located" CSP-PV hybrid plant, which has no MSEH and in which PV feeds into the grid at daytime and CSP operates as a load-shifter and produces electricity at nighttime.

Such a co-located system follows the same boundary conditions as stated in Table 1. Due to the lacking electric heater, the molten salt is only heated to slightly below 393 °C. For the comparison purpose, the total amount of annual power generation (WAEP) is considered to be same for both ICPH and co-located plants. The consequences are a much higher salt mass (about 150% more!) required for the same number of FLH, and a lower thermal-to-electric conversion efficiency, due to the lower steam temperature that can be achieved.

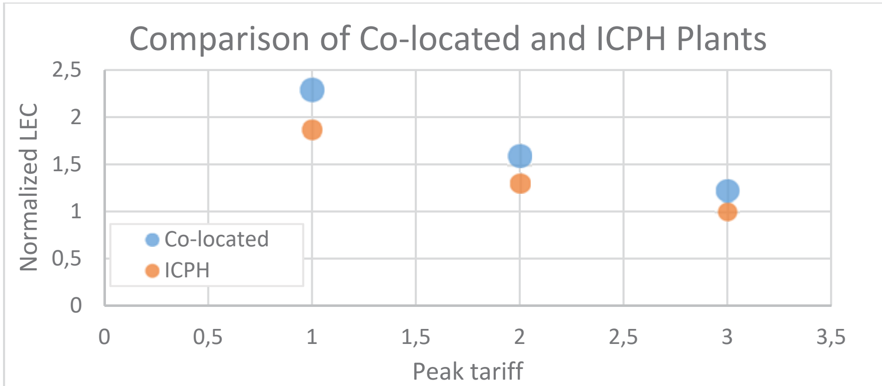

FIGURE 5. Comparison of optimized co-located and integrated CSP/PV hybrid plants, regarding LEC (y-axis) and investment (bubble diameter)

Figure 5 compares the optimum ICPH plant for each of the three tariffs with its equally optimized, co-located counterpart. It can be gathered that for all tariffs the investment is substantially larger in case of merely co-located plants than for the integrated plants. This is due to the higher salt mass and the larger amount of heat required in order to yield an equivalent amount of electric energy produced at nighttime. Also, the PV system becomes ca. 20% smaller, reducing the investment.

Interestingly, the LEC is ca. 23% higher for the co-located plants, independent of the tariff factor. This is probably the most important result of the present study. Just by adding another well-proven apparatus to the co-located plant, a dramatic reduction in electricity cost can be achieved.

CONCLUSIONS

In this paper, a systematic optimization methodology of an integrated CSP-PV system is discussed. Such a system uses electric heaters to transfer part of the PV-produced electricity into a storage system for later re-electrification. The selected optimization parameters – PV capacity, parabolic trough field size, power of heaters and storage capacity – are all necessary parameters for obtaining an optimal plant configuration. The results of this study clearly show that different tariffs for nightly peak hours always lead to the same optimal TES size.

The optimization results show that all mentioned parameters are interrelated. Thus, an optimization of an integrated CSP-PV hybrid plant should at least incorporate the use of these parameters as optimization parameters.

Compared with a merely co-located CSP/PV hybrid plant, the ICPH plant, i.e. one using electric heaters to store excess PV power into the molten salt of the CSP part of the plant, reduces the LEC by about 20%, while at the same time requiring 20% to 25% less investment.

OUTLOOK

In future depending on the market design and on the readiness of the TSO's to accept CSP technology to act as system services provider CSP power plants equipped with sufficiently designed TES including MSEH could be used to stabilize the grid and enable the enhancement of volatile wind and PV capacities.

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