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Power-to-Heat in CSP Systems for Capacity Expansion

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Abstract. The objective of this paper is the evaluation of trends when a power-to-heat system with electrical heaters is integrated to a molten salt solar tower to additionally charge the thermal energy storage system and to expand the capacity of the CSP plant. Therefore a techno-economic analysis was carried out considering several economical and technical boundary conditions. The results show a significant impact on the availability of excess electricity and its cost. Depending on system layout and the cost of the used electricity the overall LCOE of such plants can be reduced by up to 25%. Therefore such power-to-heat systems can offer an economic and strategic benefit to solar thermal power plants.

INTRODUCTION

Without electricity storage options an increasing share of renewable and intermittent renewable electricity generation is limited [1]. Currently several options for storing electricity from renewable energy (RE) sources are discussed. Beside of batteries also Power-to-Heat-to-Power is one of the favored options for storing electricity in the utility scale with almost known and reliable technology from the conventional power market.

Interesting sites for CSP power plants are most often also interesting sites for PV power plants that offer low cost, but also a volatile (weather-dependent) power generation. Those sites have also often a high wind power potential. To provide a supply security storage options for electricity from various regenerative sources are required, for which until today no clear, conclusive and economical solution was found.

Concentrating solar power plants (CSP) can offer firm capacity by integration of thermal energy storages and/ or by using a solar fossil hybrid operation strategy. Only few technologies among the renewables offer this ability of secured capacity. A CSP system has already an integrated thermal storage system. With relatively low additional technical and financial efforts an electrical heater can be integrated to the system to charge the storage by (renewable) excess electricity in times when the storage capacity of the CSP plant is not totally used.

Within a techno-economic study the question of the cost reduction potential of using a power-to-heat system in a CSP plant was analyzed. The main focus was to find out how much additional energy can be provided by such a system when charged by (renewable) excess power (and avoiding solar dumping) and to find out if this is economical. However, the analysis is based on some simplified assumptions most of all on the question when and at what cost the (renewable) excess electricity is available. The results should be therefore understood as trend indicators to explore the technical and economic potential of such combined systems.

OVERVIEW OF VARIANTS AND BOUNDARY CONDITIONS

In this study a molten salt solar tower with an integrated electrical heater system (power-to-heat or P2H) is analysed. Figure 1 shows a schematic of the system layout with the integrated electrical heater system that converts the excessive power from e.g. renewable energy sources, including PV and wind, to heat the molten salt. The design power level of the plant is 100MWe and the solar multiple is 3. The optimized systems use different storage

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capacities and different Heater Multiple (HM[1]) and are analysed on an annual basis. The results of the solar hybrid power plants are compared to each other in terms of technical and economic figures.

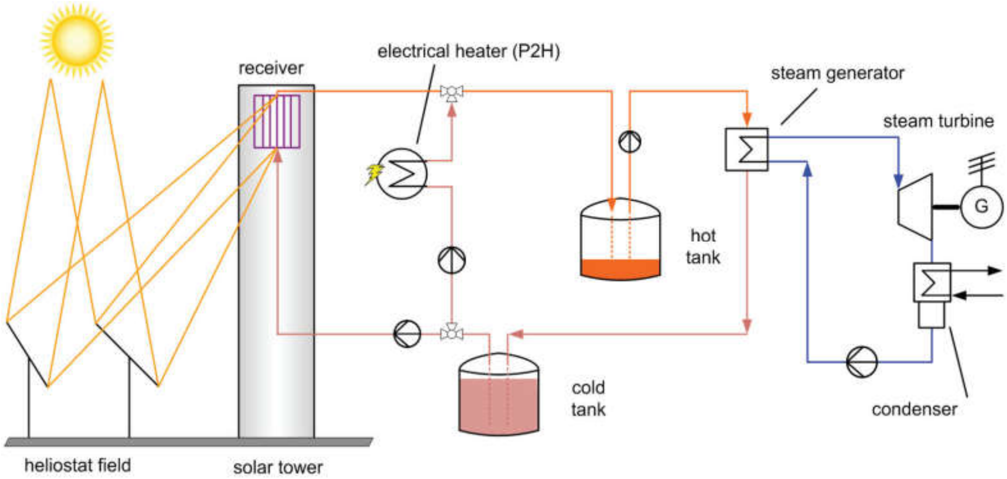

FIGURE 1. Example system layout of a molten salt solar tower with integrated electrical heater (P2H).

For this study the operation strategy of the hybrid system needs to ensure that no dumping of solar energy in the CSP system takes place. This is mainly to make use of the excessive energy produced by the other RE sources and not reducing the performance of the CSP plant itself. For this, it has to be asserted that the thermal energy storage (TES) tanks are fully discharged before the start of production on the next day. As a result, the P2H system charges the storage just enough while avoiding dumping i.e. defocusing of the heliostat field. The goal is to constantly operate the power block (PB) at the design capacity. To achieve this, DNI forecasts are used at the beginning of each day to anticipate the production of the CSP plant and complement it by the P2H system. For this study it is assumed that the forecasts are perfect and the energy from the P2H system is unrestricted and can be readily available as soon as the conditions of the TES are met.

It is important to understand that this hypothetical assumption gives the maximum potential for the energy output from the P2H system in this CSP system. In reality the availability of excess (and cheap) electricity from RE is not guaranteed exactly in time when the storage is not fully charged. However, with this assumption the technical and economic potential of such combined systems can be explored.

Figure 2 shows an illustrative schematic of 2 days with uninterrupted irradiation that is, however, insufficient to fully charge the TES tanks for 24-hours production in a standard CSP plant as shown in Figure 2(a). The P2H system is then used to increase the stored thermal energy and provide continuous electricity production as in Figure 2(b). Energy is used from the P2H system only at specific times that meet the TES conditions and to avoid dumping.

To investigate the findings of the research project, a hypothetical 100 MW_{el} molten salt solar tower power (MSSTP) plant located in Ouarzazate, Morocco with a solar multiple of 3 is defined as a base for the comparison. This results in a power plant with approximately 700 MW_{th} of thermal power at design conditions. A 121m² heliostat based on Abengoa's Sanlucar 120 is chosen for all 11146 heliostats in the field. The power block operates with solar salt at 565 °C salt inlet temperature. It includes dry-cooling and achieves a gross efficiency of 43.1% with steam parameters of 125 bar / 550°C[2].

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. The storage capacity was varied from 8 to 18 hours. Additionally, a P2H system is added to the system with a heater multiple (HM) varying from 0 to 2 corresponding to 0 to 469 MW of heating power. The systems with HM=0 represent systems with no P2H.

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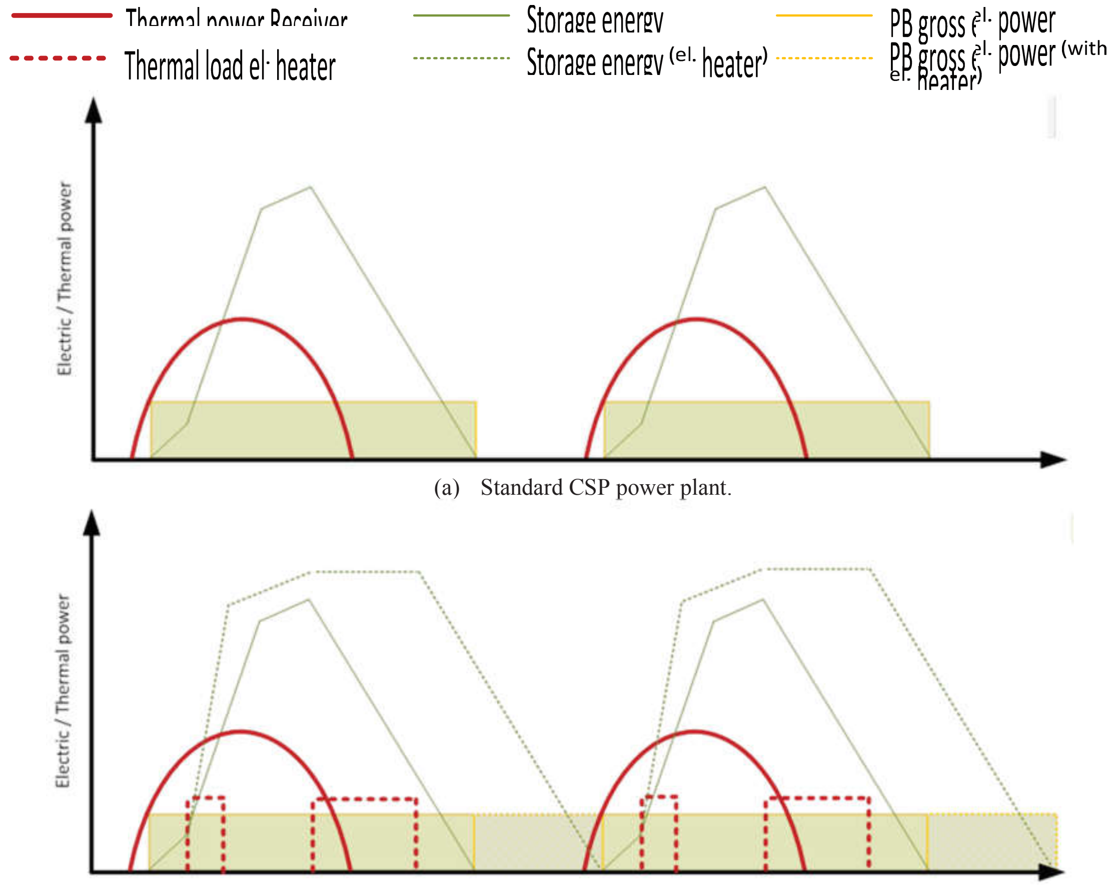
[1] HM = 1 means that the electrical heater has a nominal power that is equivalent to the nominal power of the steam generator. Thus the power cycle could be run on full load.

[2] Further specifications can be found in the Appendix.



(a) Standard CSP power plant.

(b) CSP plant with unrestricted P2H.

FIGURE 2. Schematic illustration of thermal and electric power generation.

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 Figure 3 [2].

The software HFLCAL [3] 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 Ebsilon Professional [4] model of the MSSTP with integrated electrical heater 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.

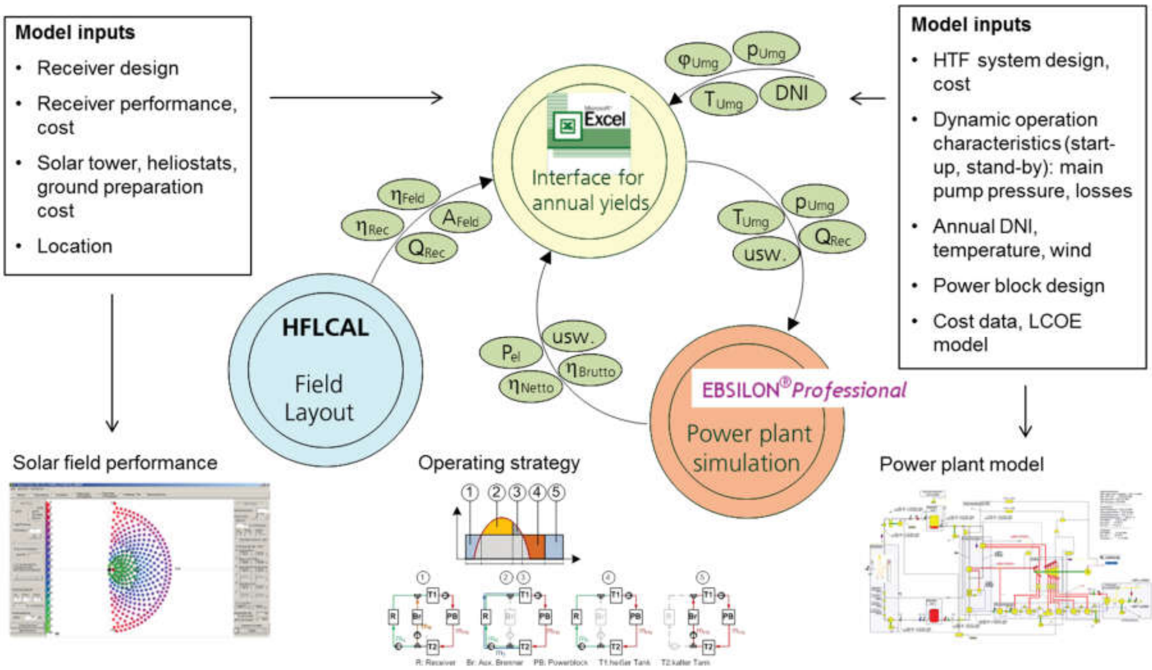


FIGURE 3. Overview of the annual yield model [2].

ANNUAL YIELD AND ECONOMIC RESULTS

The results show a significant impact on the availability of excess electricity and its cost. Also the combination of solar field size, storage capacity and heater multiple has a high relevance in system layout and on the LCOE. Figure 4 shows the total calculated annual electric energy produced for all investigated system variants. For the cases without P2H, larger TES capacity results in better used of the incident solar irradiance through less dumping. The addition of a P2H system with HM 0.25 increases the electricity yield by approximately 15% with higher benefit as the HM increases reaching saturation at approximately 36% benefit with HM 1.5.

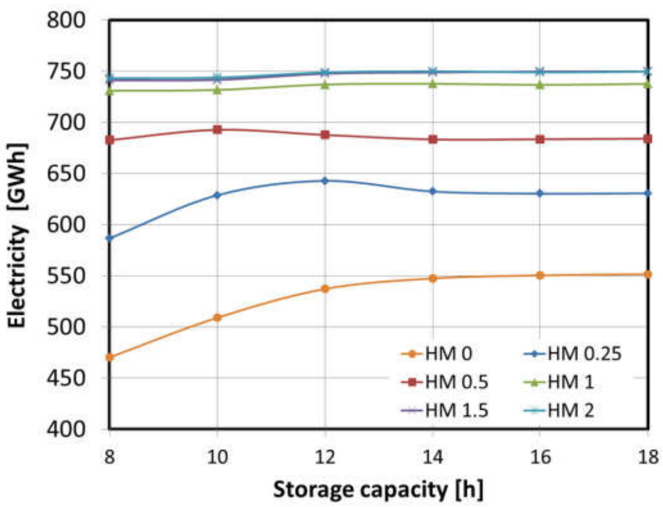
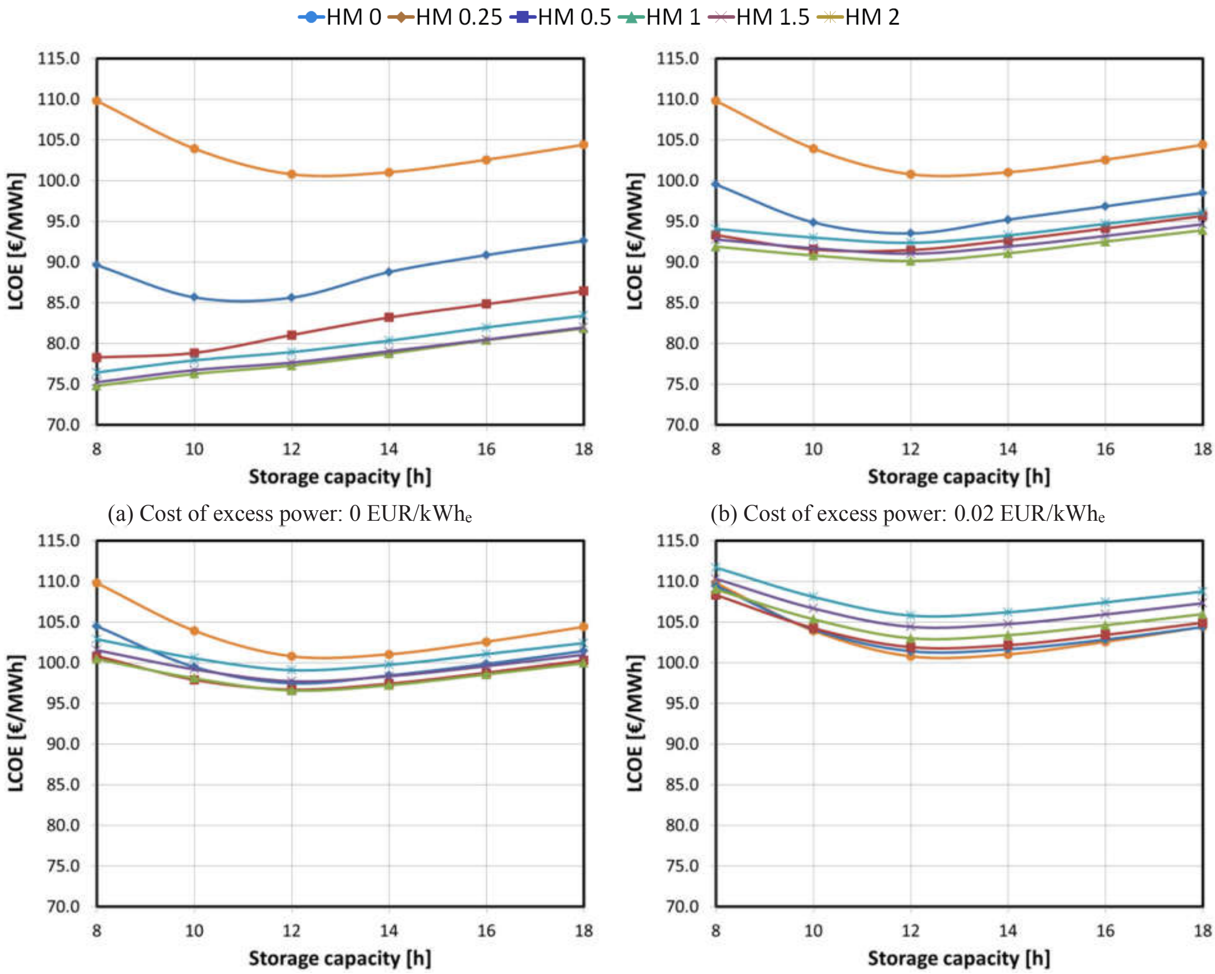


FIGURE. 4. Total electricity produced.

Figure 5 shows the results on LCOE for the analysed systems with also the variation of the storage capacity and the HM. In Figure 5(a) the annual mean cost for the excess electricity used for storage charging is assumed to be 0 EUR/kWh$_e$ (as mean throughout the year). The solar tower with P2H can reduce in this case the LCOE by about 25% compared to the solar tower without P2H (no P2H). This scenario can be realized during cases when the tariff policy is made to encourage production at peak times only. When the mean cost for excess electricity are increased to 0.02 and 0.03 EUR/kWh$_e$ as shown in Figures 2(b and c) the reduction in LCOE becomes less significant. While if the energy feed-in price in the P2H system rises to 0.04 EUR/kWh$_e$, the integration of the system becomes uneconomical.

Figure 6 shows the simulation results for 2 sets of days illustrating the power balance. The system without P2H is illustrated by the solid lines, while the dotted lines show the integrated P2H system which is labelled as the virtual system. Figure 6(a) shows the results for 4 winter days without disturbances in solar irradiation. The excessive energy from RE sources is used to store more energy in the TES as indicated by the cyan dotted line as compared to the solid blue line. This allows the power plant with P2H to continuously provide the designed power output shown by the orange dotted line. Also to be noted here is the full discharge of the TES before the start of the new day. In Figure 6(b), some disturbances during day 2 (from 4449 hours) hinder the CSP plant from sufficiently charging the TES, which is then made-up for using the unrestricted virtual P2H source to still achieve the design power output.



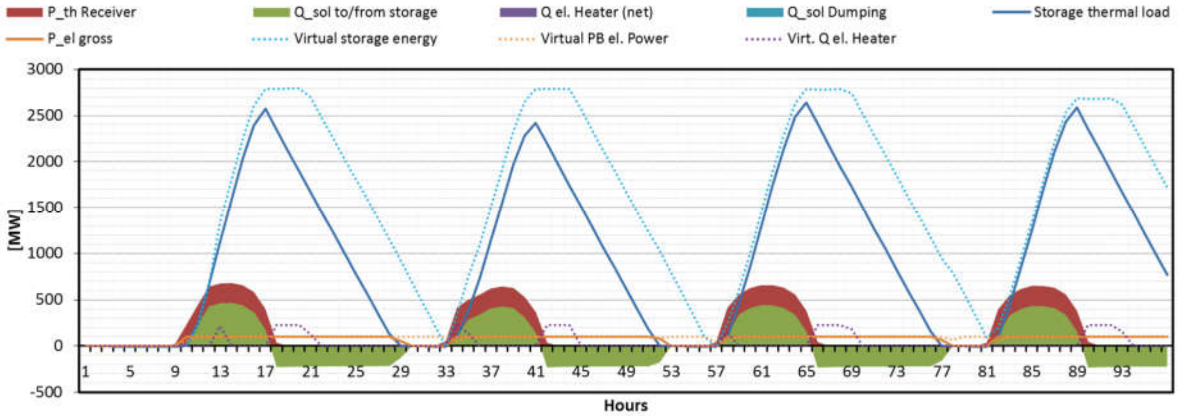
(a) Cost of excess power: 0 EUR/kWh$_e$

(b) Cost of excess power: 0.02 EUR/kWh$_e$

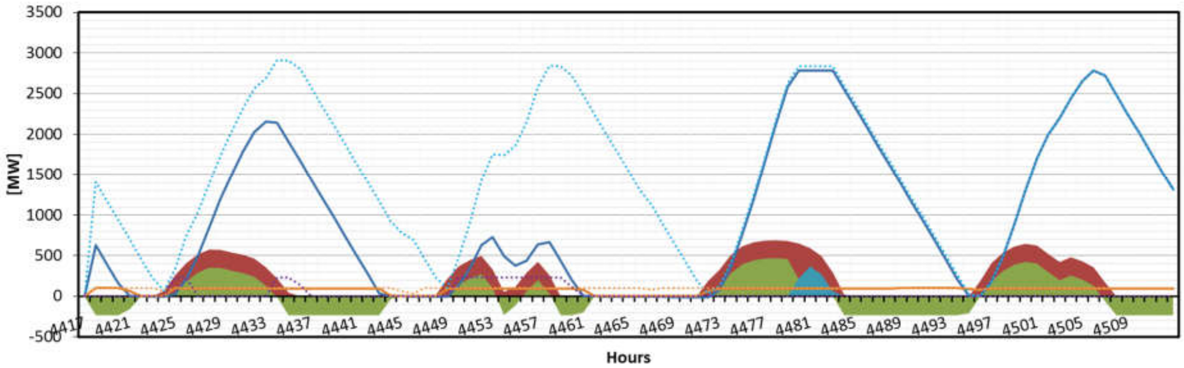
(c) Cost of excess power: 0.03 EUR/kWh$_e$

(d) Cost of excess power: 0.04 EUR/kWh$_e$

FIGURE. 5. LCOE comparison for CSP Tower with thermal storage and P2H.



(a) 12h thermal storage capacity, HM1, 4 winter days without disturbance (days 1-4)



(b) 12h thermal storage capacity, HM1, 4 days in summer with disturbance (days 187-191)

FIGURE 6. Thermal and electric power balance for exemplary days with a virtual P2H system.

CONCLUSIONS

This paper discusses the results of a techno-economic analysis of a molten salt solar tower with integrated electrical heater system (power-to-heat or P2H) to expand the capacity of the CSP plant. Excessive electric energy from various e.g. renewable sources like PV and wind power plants is used for the power-to-heat system. Advanced software tools were used for design optimization and annual performance prediction for the electricity of the analysed solar hybrid power plants. The heater multiple and storage size are varied and the results show an increase in energy yield of up to 36% for a storage capacity of 18 hours and HM of 1.5. The simulated systems are able to make use of the additional electric energy in the P2H system to adequately load the TES and provide the design output power continuously during days with adequate solar irradiation. This also resulted in a reduction in LCOE by up to 25% which depends on the price of the electric power input to the P2H system. The systems are found to be beneficial for excessive electricity prices of up to about 0.03 EUR/kWh$_e$ in the analysed site with given boundary conditions.

It should be stated that the analysis is based on some simplified assumptions most of all on the question when and at what cost the (renewable) excess electricity is available. The results should be therefore understood as trend indicators to explore the technical and economic potential of such combined systems. To be able to more realistically model the hybrid system, the time depending energy availability and individual hourly cost of the excess renewable energy sources should be investigated more in detail in future work. It is expected that the flexibility of the P2H system will be limited and the economic benefit reduced. However, the integration of the electrical heater to the CSP plant with molten salt can be done with relatively low additional technical and financial efforts to charge the storage by (renewable) excess electricity in times when the storage capacity of the CSP plant is not totally used. This opens also the door for various possibilities for load managing for the utilities.

APPENDIX

TABLE 1. Example of specifications and results for the system with 12h storage capacity and HM=1

	Unit	Ref-12h-HM-1
System layout (@design point)		
Number of heliostats (total)	[-]	11146
Heliostat reflective area	[m^2]	121
Tower heigth	[m]	265.5
Receiver thermal power	[MW]	696.6
Receiver aperture area	[m^2]	1192.7
Powerblock gross power	[MW]	100
Powerblock gross efficiency	[%]	43.1
Plant net efficiency	[%]	39.49
P2H heater electric power	[MW]	232.2
Annual Heat		
Q solar (DNI to field)	[GWh]	3199.8
Q field (optical)	[GWh]	1729.2
Q rec* (Q rec * $eta_{int, aim}$)	[GWh]	1439.3
Q_th input P2H heater	[GWh]	469.1
Q loss operational limit (pumps)	[GWh]	12.6
Q dumping (field)	[GWh]	58.0
Q loss storage	[GWh]	11.0
Q PB solar (used for electricty production)	[GWh]	1360.1
Q PB total (used for electricty production)	[GWh]	1829.1
Annual Electricity		
W P2H input	[GWh]	473.8
W auxiliary consumption rec. & storage pumps	[GWh]	16.6
W auxiliary EHTS	[GWh]	3.1
W auxiliary PB (water pumps)	[GWh]	20.4
W auxiliary startup & standby (pumps & EHTS)	[GWh]	2.0
W auxiliary total	[GWh]	40.2
W gross el	[GWh]	577.3
W net el	[GWh]	537.1
W gross el (solar P2H)	[GWh]	777.1
W net el (solar P2H)	[GWh]	737.0
Annual efficiencies		
Heliostat field	[-]	0.5404
Receiver* (eta_{rec} * $eta_{int,aim}$)	[-]	0.8324
Solar efficiency (solar to heat)	[-]	0.4251
Powerblock net	[-]	0.4028
Plant total efficiency (solar to electricity)	[-]	0.2006
Investment cost and maintenance		
solar field per reflective area	[€/m^2] / [k€]	115 / 155097
receiver	[€/kW] / [k€]	65 / 452790
tower	[k€]	7603
thermal energy storage	[€/kWth] / [k€]	22 / 60589
P2H electrical heater	[€/kW] / [k€]	80 / 18760
power block	[€/KW] / [k€]	1000 / 100000
cost for land (w/o leveling)	[€/m^2] / [k€]	3 / 17500
cost htf system	[k€]	18883
annual O&M cost (fixed & variable)	[k€]	9233
LCOE (@0.03 €/kWhe for P2H)	**[€/MWh_e]**	**96.6**

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