Operation Optimization of a Power-to-Heat System in PV-CSP Hybrid Power Plants Together with Molten Salt Thermal Storage

Zahra Mahdi[1,*], Ulf Herrmann[1], Klaus Görner[2]

[1] *Solar-Institut Jülich of FH Aachen University of Applied Sciences (SIJ), Heinrich-Mussmann-Str. 5, 52428 Jülich, Germany*
[2] *Chair of Environmental Process Engineering and Plant Design (LUAT), University of Duisburg-Essen, Leimkugelstr. 10, 45141 Essen, Germany*
[*]*Corresponding author. Email: mahdi@sij.fh-aachen.de*

ABSTRACT

Hybridization of Photovoltaics (PV) and Concentrated Solar Power (CSP) together with Thermal Energy Storage (TES) has been known as a cost-effective solution for on-demand solar power generation with high flexibility and dispatchability. By integrating an Electrical Heater (EH) as a Power-to-Heat (P2H) unit in PV-CSP power plants, a more efficient hybridization can be attained. The operation optimization of such hybrid systems was investigated in this study by deploying a so-called Solar Plant Optimization Tool (SPOT). SPOT simulates the entire system quasi-dynamically and time-dependent, calculates the daily and annual yield of the system, and optimizes the levelized cost of electricity (LCOE) depending on the system configuration considering the operation strategies and Time of Delivery Factors (TOD) for a chosen location and available weather data. Two different operation strategies were applied for the optimization of the coupled configuration with EH, and the results were compared with the optimized co-located hybrid system as the benchmark (BM) model.

Keywords: *PV-CSP hybrid power plant, Electrical resistance heater, Thermal energy storage, Operation optimization*

1. INTRODUCTION

CSP and PV stand out as the primary technologies for converting solar energy into electricity. Despite the achievement of grid parity by Solar PV in numerous countries, the cost-effectiveness of large-scale electrical storage technologies remains a challenge. In contrast, CSP systems harnessing thermal energy offer a suitable option for thermal energy storage; nevertheless, electricity generated from CSP presently incurs higher costs compared to PV electricity. The integration of both technologies within a unified hybrid system holds promise as a financially viable approach for the flexible and reliable production and storage of solar power. While various configurations of PV-CSP hybrids are currently under development across multiple projects, the extent of hybridization has been restricted so far to a collective feed into the power grid from the independent systems.

Integrating a P2H system in PV CSP hybrid power plants with TES has gained attention in recent years. Some of the current research concepts are present in [1–5], which have shown that the integration of a P2H unit can result in more efficient hybridization. The Noor Midelt 1 in Morocco is the only commercial PV-PTC hybrid power plant with integrated EH with a total installed capacity of 800 MW and 5 h of thermal storage, which was announced in 2019 [6]. The current study focuses on the operation optimization of such a hybrid system with EH as a P2H system.

P. Droege and L. Quint (eds.), *Proceedings of the International Renewable Energy Storage and Systems Conference (IRES 2023)*,
Atlantis Highlights in Engineering 32,
https://doi.org/10.2991/978-94-6463-455-6_22

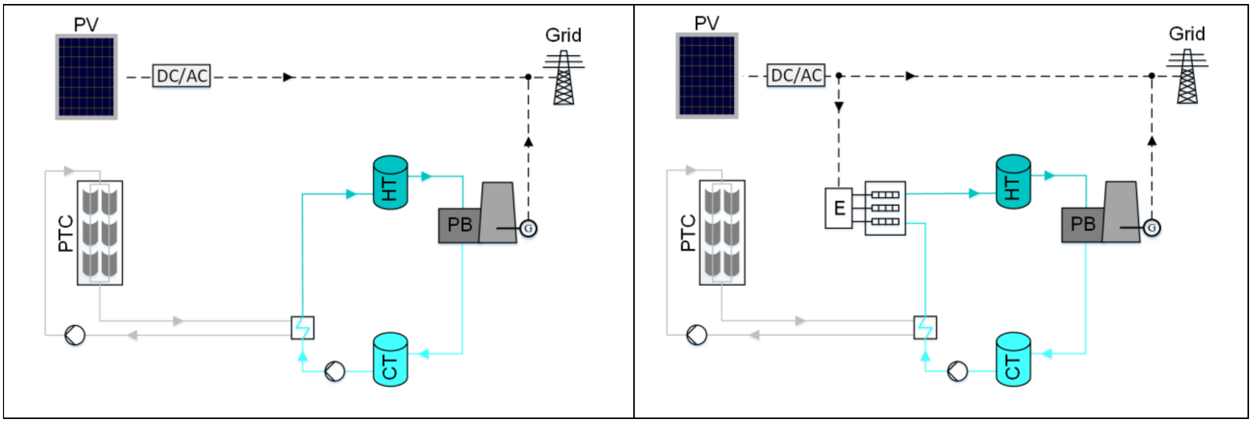

Figure 1. Schematic diagram of the BM system (left) and PV-CSP hybrid power plant with EH and TES (right)

2. APPROACH

The application of EH as a P2H unit in PV-CSP hybrid plants with TES is explored in the present work compared to the co-located PV-CSP hybrid plants, considered as BM system. A schematic diagram of the BM system has been shown in Figure 1, left. Thermal oil is regularly deployed in PTC systems as heat transfer fluid (HTF) and operates with a maximum temperature of ca. 390 °C. The solar thermal energy is transferred to the molten salt via an oil-salt heat exchanger (HX) and stored in the hot tank (HT) at a temperature lower than the maximum temperature allowed for HTF. The PV field only produces electricity during the day and feeds it directly into the grid, i.e., the PV and PTC systems operate independently. At night, the thermal energy from the hot molten salt is used to generate electricity in the power block on demand.

In the proposed configuration, the couling of the two systems is achieved by integrating an EH in the storage cycle of the PTC, which is powered by the PV-system as shown in Figure 1, right. In such a system, molten salt can be heated up in EH to 565 °C and stored in HT after it is preheated in the oil-salt HX, therefore boosting the power block efficiency of the system from 39.5% to 46.5%. The PV field supplies the power for the EH so that the PV electricity is stored cost-effectively in the molten salt TES.

Depending on the Power Purchase Agreement (PPA) electricity produced during non-sunshine hours is often valued higher than daytime production. This can ve considered by Time-of-Delivery (TOD) factors. Depending on these facors different strategies can be applied to optimize the operation of hybrid systems. In this study, two strategies have been defined for the proposed hybrid system.

(1) The first strategy, the Network Priority Strategy (NPS), prioritizes the network. i.e., a maximum prespecified share of the PV power is first injected into the grid, and the rest of the PV output, together with the power from the PTC field, is stored in the HT. (2) The other strategy, the Storage Priority Strategy (SPS), gives priority to the TES. In this case, the energy of the PTC and the PV field is used in the first place to fill the HT, and the surplus power from the PV field is then injected into the grid. An overview of the the two strategies is shown in Table 1.

Table 1. The operation strategies

Strategy	Approach
NPS	PV available output injected initially into the grid; the rest of PV output together with PTC field output is stored in TES.
SPS	PV available output together with PTC field output is stored initially in TES; the rest of PV output is fed to the grid

In the framework of an ongoing dissertation project at Solar-Institut Jülich (SIJ), a so-called Solar Plant Optimization Tool (SPOT) has been developed. The tool simulates the entire system quasi-dynamically and time-dependent and calculates the daily and annual yield as well as the LCOE of the system. It also has the option to optimize the LCOE depending on the system configuration for hybrid PV-CSP power plants both as only co-located or coupled with EH, considering the operation strategies and TOD factors for a chosen location and available weather data. As the tool performs the calculations with time steps of 10 minutes and can use even smaller intervals, the start-up and shut-down profiles can also be reflected in the simulation results.

In the calculation mode, no optimization of the system configuration is carried out; instead, it is possible to predict the energy yield and LCOE of the system after all the technical and financial specifications are provided. For each time step, SPOT initially computes the power generated, stored, injected into the grid, or dumped and subsequently performs the daily calculations. In the final

Table 2. Technical data of the simulations

System Component	Technical Data
PTC	Heat transfer fluid (HTF): Therminol VP-1 Nominal field outlet temperature: 393° C Nominal field inlet temperature: 300° C
PV	Single-Axis Tracking Systems DC/AC ratio: 1.3
TES	Storage Medium: Solar Salt (60% NaNO3, 40% KNO3) Nominal hot temperature: 565 C (385° C for BM) Nominal cold temperature: 300° C
P2H technology: EH	HTF: Solar Salt (60% NaNO3, 40% KNO3)
PB	Gross efficiency: 46.5 % (39.5 % for BM)

stage, the annual yield is calculated, and the LCOE is determined. The annual yield (E_n) is the summation of the total electrical output of the system from PV directly to the grid (E_G) and the electricity generated via PB in the nighttime (E_{PB}).

$$E_n = E_{PB} + E_G \tag{1}$$

The night share (NS) of system output is calculated as follows:

$$NS = \frac{E_{PB,tot}}{E_{tot}} \tag{2}$$

Once the annual yield of the system is determined, the financial simulation, i.e., LCOE calculation, can be performed:

$$LCOE = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+dr)^n}}{\sum_{n=1}^{N} \frac{E_n}{(1+dr)^n}} \tag{3}$$

In this equation, N is the analysis period in years, dr is the discount rate, and C_n is the annual cost, including direct and indirect capital costs of PV and PTC systems for the year zero (CAPEX) and their operation and maintenance, and other financial costs and fees for the analysis period. E_n from Equation 1 is the annual energy for year one and decreases from year to year if the degradation rate is greater than zero. As the degration rate in the present study is assumed to be zero, the annual energy is constant over the analysis period.

For the financial modeling, three scenarios were defined for the TOD factors:

(1) TOD 1/1: in this scenario, the produced electricity in the nighttime and daytime are valued the same,

(2) TOD 2/1: in this scenario, the generated electricity in the nighttime is weighted two times more than the daytime produced electricity,

(3) TOD 3/1: in this scenario, the electricity produced in the nighttime weighs three times more than the daytime produced electricity.

Using TOD factors, the calculation of E_n from Equation 1, is adjusted as follows:

$$E_n = \alpha \cdot E_{PB} + E_G \tag{4}$$

Where α is the night tariff weight which is 1, 2, or 3 for the three TOD scenarios, respectively. Considering α for the calculation of the annual yield, a modified LCOE value LCOE* is determined.

In the optimization mode, SPOT can optimize one or more key variables of the system at the same time including PTC and PV field size, EH nominal power and TES storage capacity with the goal of minimization of the expected cost of energy (LCOE). The applied optimizer is the Surrogate optimizer. Surrogate optimization is especially suitable for time-consuming objective functions, its solver requires finite bounds on all variables, and accepts integer constraints on selected variables [7]. Therefore, it has been chosen as the optimizer for SPOT. The optimization variables are all chosen as integers and are defined as follows:

(1) PTC field size: one pair of loops steps, from 1 to 100 corresponding to 2 to 200 loops,

(2) PV field size: 5 MW peak output steps, from 1 to 100 corresponding to 5 to 500 MW,

(3) EH nominal power: 10 MW peak output steps from 1 to 100 corresponding to 10 to 1000 MW, and

(4) TES storage capacity: 0.25 FLH steps from 1 to 100, corresponding to 0.25 to 25 FLH.

The grid injection limit (for both PB and PV systems), desired operation strategy, and TOD scenario should be selected before the optimization starts.

3. INPUT DATA

The simulations were carried out for a chosen location Midelt, Morocco, with good solar resources with the direct normal irradiance (DNI) exceeding 2.3 GWh/m² a year. The meteorological data is for a typical year with 10-minute time steps to include the start-up and shut-down procedures as well as weather

Table 3. Cost assumptions from [4]

System Component	Component	Cost per unit	Unit
PTC	PTC field	202	$\$/m^2$
	TES	23 (38 for BM)	$\$/kWh_{th}$
	PB	930	$\$/kW_e$
	EPC	20 %	of CAPEX
	O&M	1.5 %	of CAPEX
PV	PV field	454	$\$/kW_{dc}$
	Inverter	53	$\$/kW_{ac}$
	EPC	20 %	of CAPEX
	O&M	1 %	of CAPEX
EH	cost per kW	100	$\$/kW$
	EPC	10 %	of CAPEX
	O&M	0.5 %	of CAPEX

changes with a better resolution. The technical data of the simulations and the costs assumptions for the simulation are shown in Table 2 and Table 3, respectively.

The molten salt used in this work has a nominal composition of 60% by weight NaNO3 and 40% by weight KNO3. In [8] the temperature dependency of the properties of such fluid nitrate salt was investigated and specified as a function of temperature. These functions were used for the present simulations.

The costs of each component shown in Table 3 are from [4], which were assumed by DLR and Dornier Suntrace GmbH based on their experience for the year 2021. The TES cost for the hybrid system is from project experience of SIJ. A lower value was choosen here, since the specific storage capacity increases in the coupled system because of the higher upper temperature in the storage of 565 °C instead of only 385 °C. An analysis period of 25 years, an inflation rate of 1% and a discount rate of 6% were assumed for the simulations.

4. RESULTS AND DISCUSSIONS

The optimizations were performed initially for a fixed PB size and grid injection limit of 100 MW with TOD of 1/1 for three different configurations: (1) the BM system, (2) the coupled configuration with NPS, and (3) the coupled configuration with SPS. The configuration optimization results have shown that with the present criteria, independent of the chosen configuration or strategy, the optimized system tends to use only the PV field to generate electricity and inject it into the grid as a

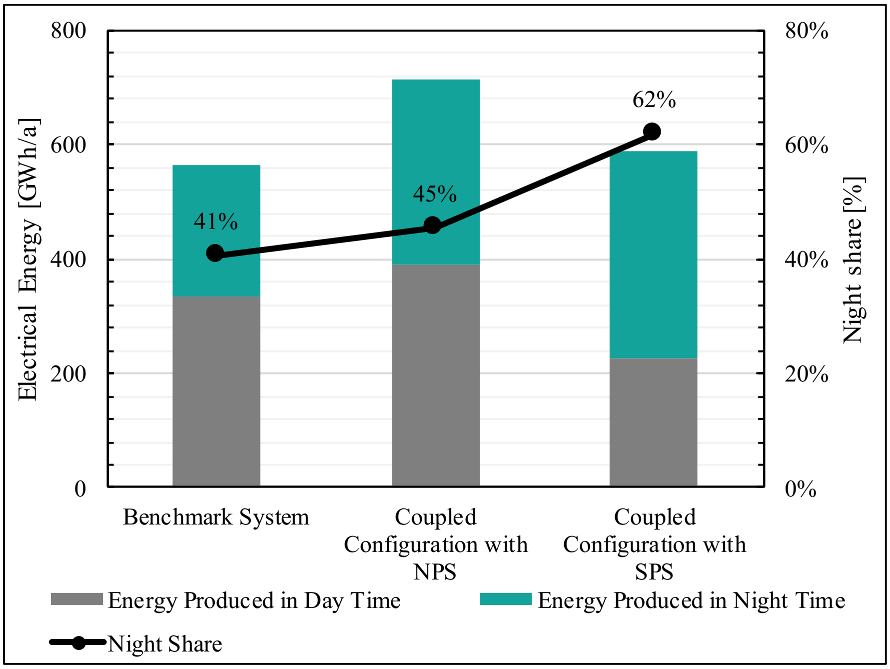

Figure 2. Annual yield and the night share of the optimized configurations

standalone system, and in all cases, it reduces the PTC, EH, and TES sizes to the minimum allowed. It means electricity production only occurs in the daytime, and there is no storage, night share production, or dispatchability provided in this case. The PV electricity can be injected directly into the grid, and the PTC thermal energy is transformed into electricity with the PB efficiency.

In order to value a higher degree of dispatchability and night time production a new set of optimizations was performed. In the new optimization set, all criteria are the same as before, except that TOD 3/1 is used instead of TOD 1/1, which means that the nighttime electricity is weighted three times more than daytime electricity.

Table 4. Optimization results for TOD 3/1

System configuration	PTC [number of Loops]	PV [MW_{DC}]	EH [MW]	TES [FLH]
BM system	94	170	-	8
Coupled Configuration with NPS	32	430	190	11.75
Coupled Configuration with SPS	36	370	170	11. 5

The optimization results for all three configurations are shown in Table 4. As it can be seen, for the BM system no EH is provided. The PTC field for BM is over 2.5 times bigger than the coupled configurations, as it is alone responsible for the nighttime electricity. The TES size for the BM with 8 FLH is smaller than the other configurations in terms of full load hours capacity. The PV field for the coupled configurations is more than two times larger than that for the BM system; for the hybrid system with NPS, it is even larger than the hybrid system with SPS. It can also be seen that the coupled configuration with NPS with a larger size of EH also has a larger PV field size in comparison with the coupled configuration with SPS.

The annual yield of the three optimized systems can be seen in Figure 2, scaled on the left y-axis. The electricity from the PV field injected into the grid during the daytime is shown in gray, and the electricity produced in PB during nighttime is shown in mint. The night share of each system is scaled on the y-axis on the right side. As can be seen, the coupled configuration for both strategies results in a higher yield in comparison with the BM system. The coupled configuration with NPS has the highest annual yield and the highest energy produced during daytime with a night share of 45 %, whereas the coupled configuration with SPS has the highest energy produced in nighttime with the highest night share of 62%.

The normalized LCOE* values for different TOD tariffs and three optimized configurations are shown in Figure 3. It should be considered that the normalized LCOE* values for TOD 2/1 and 1/1 are only calculated for the same optimized configurations of the three systems, shown in Table 4. The coupled configurations show approx. 25 % reduction in LCOE* for TOD 3/1 in comparison with the BM system. For the BM system, the PB has lower efficiency due to lower storage

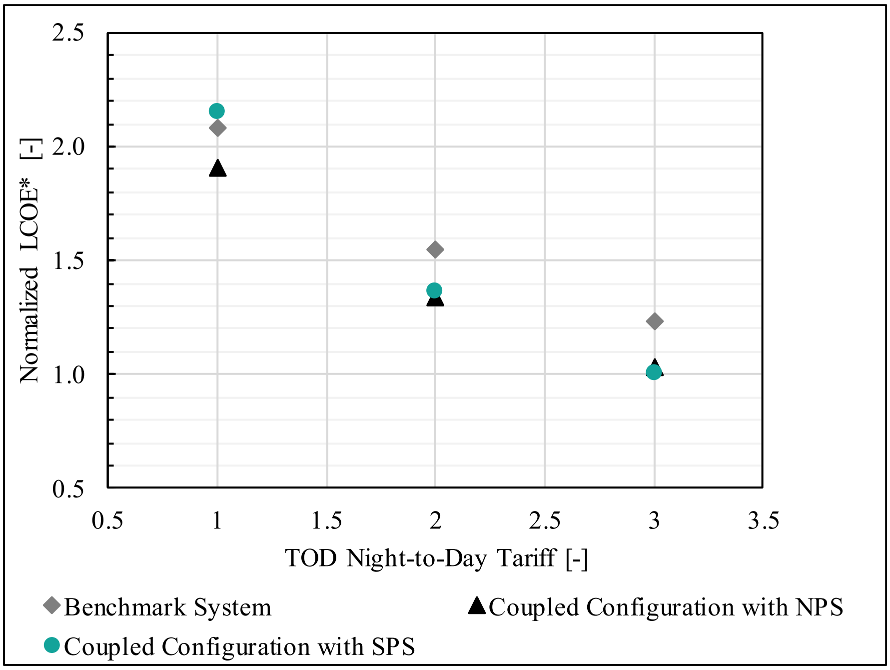

Figure 3. The normalized LCOE* values for different night-to-day tariffs and system configurations

temperatures in HT. In addition, the amount of necessary salt for the same storage capacity is higher, leading to higher storage costs per kWh compared to the coupled configurations.

The coupled configuration with SPS shows a 3 % lower LCOE compared to NPS for TOD 3/1. For smaller night-to-day tariffs, the NPS results in smaller LCOE than the SPS.

4. CONCLUSION

The operation optimization of PV-CSP hybrid power plants with TES was investigated in this study by deploying a so-called Solar Plant Optimization Tool (SPOT). SPOT simulates the entire system quasi-dynamically and time-dependent, calculates the daily and annual yield of the system, and optimizes the LCOE considering the operation strategies and TOD factors for both co-located as well as fully coupled hybrid systems with an EH. It was shown that by integrating an EH as a P2H unit in PV-CSP power plants, a more efficient hybridization can be attained resulting in higher grade of flexibility and dispatchability.

Two different operation strategies were applied for the optimization of the coupled configuration with EH and the results were compared with the optimized co-located hybrid system as the BM model for the location Midelt in Morocco. The optimized configurations with TOD 1/1 have shown that giving no additional value to the nighttime power generation results in standalone PV systems with zero night share. Only by applying a higher value for the electricity produced at nighttime using TOD 3/1 PV-CSP hybrid power plants gain an economic advantage . The integration of EH in such systems results in approx. 25 % lower LCOE* values in comparison with the BM system. The coupled configuration with SPS shows approx. 3 % lower LCOE* for TOD 3/1 compared to NPS. For smaller night-to-day tariffs, the NPS results in smaller LCOEs.

AUTHORS' CONTRIBUTIONS

Z. Mahdi: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing;

U. Herrmann: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing;

K. Görner: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing;

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of Solar-Institut Jüllich of FH Aachen University of Applied Sciences and the University of Duisburg-Essen.

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