SolarPACES 2024, 30th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Analysis and Simulation of CSP and Hybridized Systems

https://doi.org/10.52825/solarpaces.v3i.2440

Published: 26 Nov. 2025

Techno-Economic Study of a Hybrid CSP-CPV Plant in Tower Configuration

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Abstract. Despite being a mature technology, CSP plants with thermal energy storage (TES) are unable to achieve the levelized cost of electricity (LCOE) values of commerical PV plants. The high costs of the tower, heliostat field, and thermal energy storage (TES), among other factors, hinders the achievement of such values. In this study, we present a multi-tower plant with two solar concentration technologies: each tower features a cavity thermal receiver (coupled to a molten salt TES and a power block) and a concentrated photovoltaic (CPV) receiver. The shared investment costs of the solar field and the tower may allow to obtain more competitive economic indicators. This study goals to analyze the techno-economic feasibility of the hybrid solution by evaluating the LCOE and the Cost of Valued Energy (COVE) of different system configurations (e.g. 4, 8 and 12 h of TES). Optimal system configurations reach a LCOE and a COVE of 56.8 €/MWh and 61.9 €/MWh, respectively. Highly favorable results compared to the values obtained for a conventional tower CSP plant with molten salts TES: 106.05 €/MWh, and 90.27 €/MWh. In conclusion, the present study proves the tecno-economic viability of a multi-tower plant hybridizing two solar concentrating technologies: thermal and concentrated photovoltaics.

Keywords: Techno-Economic Analysis, Multi-Receiver, Solar Concentration Hybrid Plant

1. Introduction

It is well known that concentrated solar power (CSP) plants with thermal energy storage (TES) add flexibility to the grid and allow to supply electricity during non-solar hours. Nevertheless, if the dispatchability is not valued in certain electricity markets, the levelized cost of electricity (LCOE) of a CSP plant can hardly compete with utility scale PV plants. Hybridization of a solar tower CSP plant and a solar PV plant has been already explored to reduce the LCOE of the whole plant (i.e. Cerro Dominador in Chile, or Noor in Morocco). Nevertheless, this type of hybridization does not profit from the dual use of land, shared heliostats and shared solar tower to reduce the investment cost per MW of generated energy.

In this study, a multi-tower solar field which combines two solar concentration technologies in the same tower, a solar thermal receiver and concentrating photovoltaic (CPV) cells, is proposed and techno-economically evaluated using numerical simulations. The heliostat field can supply solar flux to the CPV receiver, to the thermal receiver, or to both depending on the solar resource, storage capacity and energy market prices. Hence, due to the high operation complexity of the solar field throughout the year, a highly advanced heliostat tracking control is developed to maximize the performance of the plant. Furthermore, the hybrid concept allows that the costs of the heliostats, their tracking system and control, as well as the construction of the tower can be shared among both technologies, which could considerably improve the key economic indicators. The LCOE and the cost of valued energy (COVE) of the concentrating solar plant are used to evaluate the multi-receiver concept and prove its techno-economic viability.

This study has four sections. Section 2 includes a description of the system. Then, the methodology applied throughout the study is presented in Section 3. Section 4 includes results and discussion, and finally Section 5 reports the conclusions of the study.

2. System description

The proposed system (see Figure 1) consists of 25 identical solar towers with a multi-receiver approach: each heliostat field has its corresponding solar tower, which contains two receivers: a CPV receiver and a solar thermal receiver. The solar energy absorbed by the 25 thermal receivers, as in a conventional CSP plant, is stored in a single thermal energy storage system (composed by a hot and cold storage tank) and, when required, converted into electricity thanks to a power block. The operational mode at each time-step of the 25 thermal receivers is the same. In the same way, the operational mode of the 25 CPV receivers is also the same.

The dimensions of each CPV receiver are 2x2 m^2, which corresponds to a nominal power of 1 MW_{el} (for a DNI of 1000 W/m^2, and a solar concentration of 1000). In a CPV receiver, the illumination profile plays a relevant role in the system performance, since it causes a current or voltage mismatch between cells connected in series or parallel, respectively. In this study, each CPV receiver is composed by four modules of 1 m^2 and contains the optimal electrical configuration of cells in series and parallel that maximizes the power generation. Furthermore, a novel cooling system for the CPV receiver is implemented to avoid the cells to be operated under a highly non-uniform temperature profile caused by the non-uniform illumination profile.

The second receiver, the concentrated solar thermal (CST) receiver, consists of a cavity receiver [1]. To determine the size of the thermal receiver, we conduct a parametric study aimed at maximizing its optical efficiency within the constraints set by the CPV receiver (max incident solar flux of 1000 kW/m^2) and the heliostat field. Based on the CPV receiver requirements, the minimum size of the heliostat field is designed to fulfill the necessary solar flux concentration for efficient CPV operation. With the heliostat field defined, an optical efficiency parametric study on the thermal receiver is performed, varying its size, tilt angle, and mounting height on the tower. Finally, the optimal configuration is identified: a 9 m^2 (3x3 m^2) thermal receiver, and a tower height of 53 m. The heat transfer fluid utilized is molten salts.

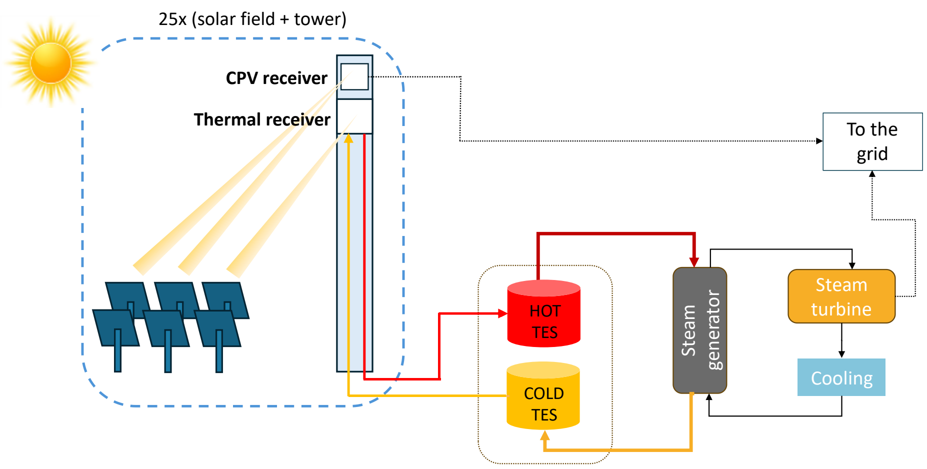

Figure 1. *Multi-receiver solar plant*

The proposed system consists of 25 solar towers and therefore 25 solar fields. The optimal size of the solar field is analysed through a parametric analysis (explained in the following section). The optimal size of the solar field will be the one that strikes a balance between obtaining maximum power generation from both solar receivers and maintaining a reasonable investment cost.

In terms of operation, the system presents a large amount of operational modes: the solar flux can be directed entirely or partially to one or the other receiver depending on the weather conditions, storage state, or energy prices. That is to say, the number of operation modes, which results from the combination of the operational modes of each system component (solar field, receivers, thermal energy storage, and power block) is very large and requires the need of an control optimization algorithm as will be explained in Section 3.

3. Methodology

To carry out the techno-economic analysis of the hybrid solar plant, a set of simulations for different system configurations is performed in the commercial software energyPRO [2]. The optimization of the system control, also performed in energyPRO, aimed at maximizing revenues considering the profits for the electricity sell and the operational costs. Finally, for each system configuration, the economic performance indicators, LCOE and Cost of Valued Energy (COVE) are calculated. Based on these two indicators, the optimal configuration of the hybrid solar plant is selected.

3.1 Numerical models

The optical model [3] used in the simulations discretizes the thermal receiver surface in several bins. For every bin of receiver surface, a specific flux F_k, which represents an effective area (in square meters), is calculated as:

$$F_k = \frac{I_k}{\rho_{ray}} \quad (1)$$

Where I_k is the cumulative intensity from all rays, partially or fully absorbed in bin *k*, measured in arbitrary units proportional to the number of rays, and ρ_{ray} is the ray density, being the global number of simulated rays per unit area perpendicular to the solar vector (in inverse square meters). The heat flux, $\dot{Q}_{abs,k}$ in bin *k* is obtained by multiplying the specific flux F_k by the direct normal irradiance (E_g) and by dividing it by the bin area A_k. Moreover, from F_k, the optical efficiency of the solar field can be derived:

$$\eta_{opt} = \frac{\sum_{k=1}^{K} F_k}{A_{HSF}} \quad (2)$$

Where A_{HSF} is the heliostat field gross mirror area.

The CPV model used considered two models: an electrical and a thermal model, which are related by the cell's temperature. The electrical model, which was exemplified by Regany et al. [4], calculates the electrical output power of the cells through an 8-parameter double-diode model for a multijunction solar cell, two exponential diodes and a parallel resistor. In turn, the thermal performance (cell temperatures) of the CPV receiver was analysed through a correlation obtained by CFD simulations [5]. The efficiencies of CPV cells considered in this study are projected efficiencies based on [6]. Cell efficiencies of 40.7 % at 1,000 kW/m^2 are reached.

The authors of this study did not develop a numerical model of the thermal receiver. Hence, the thermal efficiency of a tubular cavity receiver reported by Montes et al. [1] was considered for its simulation. Nevertheless, those authors only reported the efficiency of the receiver for a specific incident solar flux. Hence, to calculate the receiver efficiencies for a wide range of incident solar flux (100 to 370 kW/m^2) a linear extrapolation based on the efficiency reported by Montes et al. and real efficiencies of a volumetric thermal receiver (provided by Acciona) was used. The TES system was modelled based on a simple energy balance (charged and discharged energy) as two separate storage tanks for hot and cold molten salt. The physical properties for molten salts (solar salt) at 565°C and 290°C were considered in the energy balance. Those temperatures were selected according to the nominal conditions considered by Montes et al. [1] in the steam generator: the molten salts went into the steam generator at 565 ºC and left the preheater at 290 ºC. An overall efficiency of 29 % for the power work was considered, where the input thermal energy is obtained from cooling the molten salt.

3.2 Simulations

The weather data from the database SARAH [7] of the location of Seville and the year 2023 was used in the simulations. The optimal size of the solar field, thermal energy storage and power block, was analyzed through a parametric study. The components sizes considered in the parametric study are shown in Table 1. The total amount of system configurations studied is 36, which corresponds to all the possible combinations presented in Table 1. For each simulation, the system operational mode for each component at each time-step is defined by an optimization algorithm available in the software energyPRO. The optimization in energyPRO is done using a Mixed Integer Linear Programming (MILP) Solver. The components are modelled with piecewise linear constraints. The objective function of the optimization consists of maximizing the system revenues, taking into account the system operational costs and the revenues from electricity sale. Once finalized the simulations, the key performance indicators LCOE and COVE, defined in the next section, are calculated for each of the scenarios presented in Table 1.

Table 1. *Studied size for each component.*

Size of CPV receiver [m^2]	Size of thermal receiver [m^2]	Heliostat field [m^2]	TES [storage hours]	Size of power block [MW$_{el}$]
2x2	3x3	4,000; 6,000; 8,000; 10,000	4, 8, 12	12.5, 18.75, 25

3.3 Techno-economic study

The design of solar plants for utility scale, usually employs the LCOE as performance indicator, however, this parameter fails to take into consideration the time-varying cost of energy. To remedy this, Simpson et al. [8] proposed the cost of valued energy, which can be defined as follows:

$$COVE = \frac{I_0 + \sum_{t=1}^{T} \frac{C_t}{(1+i)^t}}{\sum_{t=1}^{T} \frac{\sum_h^H (p_{h,t} \cdot E_{h,t})}{(1+i)^t}} \tag{3}$$

Where I_0 are the total initial investment costs, t corresponds to each year, T is the lifespan of the system, C_t are the operational and maintenance costs at each year, i is the discount rate, $p_{h,t}$ is the hourly spot price divided by the time-averaged annual spot price, and $E_{h,t}$ is the generated energy at each hour (h) of the year t.

In this study, both key performance indicators, LCOE and COVE were used to analyse the tecno-economic performance of the solar hybrid system. The reference cost values for the economic study are shown in Table 2. The cost of the heliostat field, CST receiver and TES were considered for the Low-Cost scenario by 2030 reported by Zurita et al. [9]. A discount rate of 5 % [10], an EPC and contingency of 18 % [9], and a system lifespan of 20 years were used. Data of the Spanish day-ahead market of 2023 was considered [11].

Table 2. *Cost data of the CSP plant and CPV receiver.*

Component	Unit	Cost
Heliostat field	€/m^2	90 [9]
CST receiver	€/kW$_t$	81 [9]
Tower	€/m	13,500 (1)
TES	€/KW$_{h\text{-}t}$	13.5 [9]
CPV receiver	€/m^2	63,875
BoP & power block	€/kW$_e$	850 [9]
Fixed O&M	€/kW-year	6.2 [12]
Variable O&M	€/MWh	2 [12]

(1): calculated based on the reference cost provided by SAM [13] and an assumed tower height of a CSP commercial plant of 200 m. The additional construction cost of having a combined tower (with two receivers) has been neglected.

The cost estimation of the CPV receiver includes the costs of the following components: 1. The CPV cells, 2. Cooling plate of the CPV cells, 3. Components of the hydraulic circuit, 4. Water-air heat exchanger, 5. Inverter, 6. DC-DC converter. The costs were obtained from available commercial products for the corresponding power ratings or sizes required for a 4 m² (1 MW$_{el}$ nominal power) CPV receiver. Regarding the cost of CPV cells, a 25% reduction was considered due to economies of scale compared to the current cell price [14].

4. Results and discussion

4.1 General results

In this study, the techno-economic analysis of a multi-tower plant that combined two types of concentrating technology was carried out. The results of the parametric study show that minimum LCOE and COVE were obtained for the minimum studied size of power block: 12.5 MW$_e$. Table 3 shows the results of all the studied configurations with a power block of 12.5 MW$_e$.

Table 3. *Techno-economic results for a plant with a power block of 12.5 MW_e.*

TES size [h]	TES size [MWh]	Solar field size [m^2]	LCOE [EUR/MWh]	COVE [EUR/MWh]
4	172.4	4000	83.6	85.1
8	344.8	4000	90.2	84.2
12	517.2	4000	95.3	85.1
4	172.4	6000	65.3	68.5
8	344.8	6000	70.0	68.3
12	517.2	6000	73.7	69.0
4	172.4	8000	57.3	61.3
8	344.8	8000	61.1	61.1
12	517.2	8000	64.0	61.9
4	172.4	12000	56.8	61.6
8	344.8	12000	60.0	61.2
12	517.2	12000	62.5	61.7

The results indicate that the optimal hybrid system configuration obtained a LCOE and COVE of 56.8 €/MWh and 61.9 €/MWh, respectively. Nevertheless, the optimal system configuration differs for each of the two optimal performance indicators. Specifically, the storage size that minimizes the COVE is two times larger than the size that maximizes the LCOE. This difference arises because the COVE accounts for electricity prices, making it more cost-effective to store additional thermal energy for electricity generation during periods of higher market prices. In contrast, the LCOE considers only the amount of electricity generated, not its price. Consequently, since storing energy for dispatch during periods of high electricity prices is not economically rewarded, utilizing a larger storage system is not cost-effective. Hence, the LCOE is minimized for a system with smaller thermal storage and extended operating hours of the CPV receiver.

With regard to the solar field, the LCOE and COVE improve significantly for system configurations with solar field sizes of 8,000 and 12,000 m². Smaller sizes of solar fields (4,000, and 6,000 m²) do not send enough solar flux to the receivers, preventing the full utilization of the investment made in a multi-receiver system. Despite both, LCOE and COVE were used to identify the optimal system configuration, the authors of this study think that optimal CSP plant configuration should be determined in the future based on the minimum COVE rather than minimum LCOE, since it allows the added value of storage to be reflected in the electricity selling price and maximizes profits.

Furthermore, for comparison purpose, the same parametric study was performed assuming only a CSP plant. The results indicated minimum LCOE and COVE of 106.05 €/MWh, and 90.27 €/MWh, respectively. That is to say, the proposed system improved the key performance indicators by 87 % and 46 %, respectively, with respect to a conventional CSP plant with a power block of 12.5 MW_e, 12 hours of TES and a solar field of 8,000 m^2.

4.2 System operation

Optimal system configuration in terms of COVE can be explained by analyzing the DNI, spot prices and system operations shown in Figure 2 and Figure 3, respectively. During the central hours of July 29 and 30, when the electricity sale price was low and solar resource availability was high, the control system sent the solar resource to both receivers: 1. generating electricity with the CPV receiver, and 2. storing solar heat in the TES. The energy stored in the TES will be used when the energy price is high, which can be observed at the end of the day on July 29 and 30. On the other hand, on July 31, the electricity price remained relatively constant and high. For this reason, simultaneous charging and discharging of the TES occurred for a significant portion of the day.

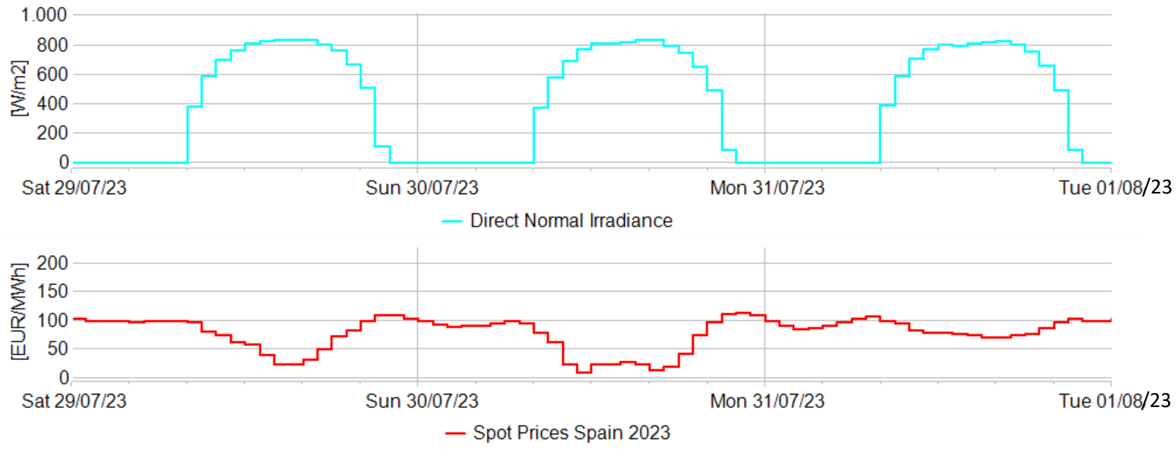

Figure 2. *Direct normal irradiation (DNI) and spot prices in Spain 2023 for the period 29/07/2023 to 01/08/23*

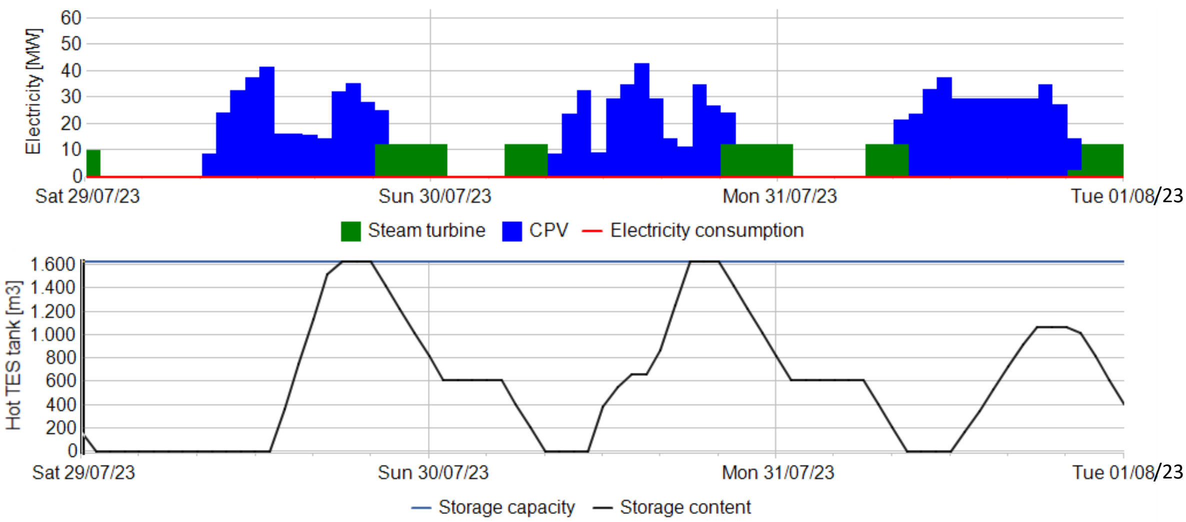

Figure 3. *System operation during the period 29/07/2023 to 01/08/23*

5. Conclusions

This study aimed at analysing the techno-economic viability of a multi-receiver and multi-tower concentrated solar plant. Each solar tower of the plant contains a cavity thermal receiver and a CPV receiver of 9 and 4 m^2, respectively. The performance of the hybrid system was analysed through numerical simulations performed in the commercial software energyPRO. Optimal system configurations obtained a LCOE and a COVE of 56.8 €/MWh and 61.9 €/MWh, respectively, promising values when compared to the values of LCOE and COVE (106.05 €/MWh, and 90.27 €/MWh) obtained for a CSP plant of similar characteristics. The obtained results provide evidence supporting the techno-economic viability of the proposed multi-receiver solar plant, which may encourage further interest and potential investment from stakeholders. It should be noted that some of the input parameters used in this techno-economic analysis are based on estimates from available literature or estimated by the authors considering assumptions (i.e. cost reduction due to economy of scale or neglect additional tower construction cost due to supporting two receivers). As such, the results are intended to provide insight under the given assumptions and should be interpreted accordingly.

Data availability statement

The data supporting the results of this study will be provided under request.

Author contributions

Conceptualization, J.B., and J.I.R; methodology, A.C., M.M., A.N.A. and M.F.; software, D.R., M.M., and M.F.; data curation, A.C., and M.M.; formal analysis, A.C.; investigation, A.C., and M.M.; resources, G.B, J.B, J.R., D.C.; writing—original draft preparation, A.C.; writing—review and editing, G.B., and J.B.; visualization, A.C.; supervision, J.B.; project administration, J.B and J.R.

Competing interests

The authors declare that they have no competing interests.

Funding

Funded by the European Union under the Horizon Europe Framework Programme (Project name: SOLARX; grant number: 101084158). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them. The project is also supported by the Swiss State Secretariat for Education, Research and Innovation (SERI).

Acknowledgement

The author Alicia Crespo is a Serra Húnter Fellow.

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