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Analysis and Simulation of CSP and Hybridized Systems

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Performance and Parametric Studies of a Non-Compact Hybrid PV-CSP Power Plant Integrated by a Supercritical Rankine Cycle and an Electric Heater in Series

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Abstract This study focuses on performing a parametric analysis of the non-compact concentrated solar power (CSP)-photovoltaic (PV) hybrid plant combined with an electric heater (EH) and a Supercritical Rankine Cycle as well as a multi-objective optimization of different technologies. The power plant sizing is evaluated in a baseload dispatch scenario of 165 MWe for a location in Seville and considering combinations of the PV installed power, CSP solar multiple (SM), thermal energy storage (TES) capacity and EH power. Studied parametric combinations are optimized for minimizing the Levelized Cost of Electricity (LCOE) and maximizing the capacity factor (CF), with the ultimate goal of achieving the Pareto front. The results of the study show that certain combinations, such as PV=450 MWe, SM=2, EH=250 MW, and TES=12 h, have a favourable balance between the LCOE and the CF (LCOE=0.0979 €/kWh, CF=0.702). In addition, the results obtained through the optimization process, in particular by considering the Pareto frontier, indicate that among the different technologies, the CSP-PV-TES-EH configuration has the lowest LCOE and the highest FC.

Keywords: Hybrid PV-CSP-TES-EH Plant, Supercritical Rankine Cycle, Techno-Economic Assessment, Multi-Objective Optimization

1. Introduction

There is an international consensus, confirmed by the Paris Agreement, to keep global warming below 1.5°C. This has led to a shift in energy policies worldwide, most notably the "Green Deal" implemented in Europe, with an emphasis on increasing the share of renewable energy sources within the energy mix [1]. CSP-PV hybrid systems have been recognized as a promising solution and a feasible means to reduce the LCOE of the CSP plants while maintaining the adaptability and increased capacity factors offered by the TES [2]. Numerous authors have conducted a performance assessment of the hybrid CSP-PV plants [3–5]. Furthermore, the integration of the EH with the PV-CSP-TES systems can improve the cost competitiveness of the hybrid plants by increasing their flexibility and CF [6]. The assessment of the net value of a generation system is determined through the use of the LCOE, which quantifies the mean cost of electricity over its lifetime and allows the comparison of novel technologies with state-of-the-art approaches.

Previous studies have investigated various aspects of the CSP-PV hybrid plants such as the study by Parrado et al. [7], which evaluated the LCOE for 50 MW CSP-PV power plants with 15 hours of the TES system or the work done by Ullah et al. [8] that presented a comprehensive comparative technical-economic evaluation of solar CSP-PV systems for different climate zones. However, there is a significant lack of research regarding the design parameter evaluation and multi-objective optimization of the non-compact CSP-PV-TES plants in combination with a Supercritical Rankine Cycle and an EH in series. In addition, there is a notable gap in understanding how simulation strategies affect the optimal configurations of these storage-integrated technologies, particularly in a baseload dispatch scenario where an EH in series is used. Therefore, this study aims to fill a research gap by providing parametric analysis, techno-economic assessment, simulation, and multi-objective optimization of a non-compact PV-CSP system with molten salts (MS) as TES fluid, an EH in series with the CSP, and a Supercritical Rankine Cycle. This research study is organized as follows: first, we will provide a detailed description of the hybrid configuration that will be subjected to investigation for analysis. We will then examine parametric performance and plant design assessments. Finally, we will compare different CSP and/or PV technologies in terms of the LCOE and the CF along the Pareto frontier.

2. Methodology

2.1. Description of the hybrid PV-CSP-TES-EH system

The presented hybrid PV-CSP-TES-EH power plant scheme is shown in Figure 1. The system under study consists of a CSP plant equipped with a Linear Fresnel Reflector (LFR) solar field using thermal oil as a heat transfer fluid (HTF), a supercritical Rankine power block (PB), based on [9], PV plant with a single-axis tracking system, an EH in series, and an indirect MS TES system consisting of three storage tanks with hot, medium, and cold temperatures.

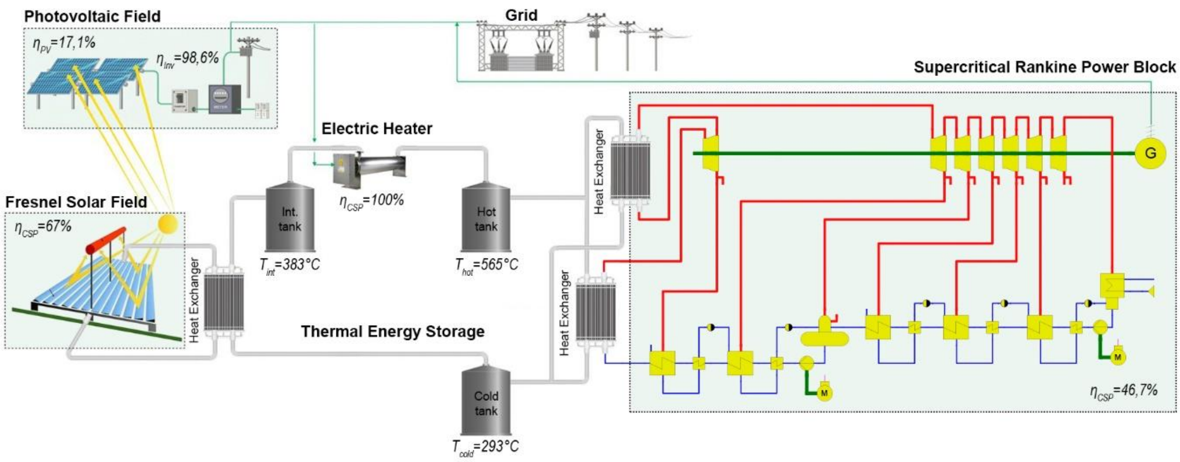

__Figure 1.__ Configuration of the CSP-PV-TES-EH plant.

2.1.1. CSP plant model

In this study, the CSP plant consists of an LFR solar field following specifications in [6], using Therminol VP-1 as HTF. Collectors have a north-south oriented solar tracking system and a single-tube vacuum receiver with a secondary concentrator. The nominal optical efficiency of the collector under normal incidence and ideal conditions is 0.67. The solar field forms an "H" shape, increasing thermal oil temperature from 310 to 393°C. The LFR system elevates solar salt temperature from 293°C to 383°C in an intermediate tank. The EH in series with the system further raises the salt temperature to 565°C, where a third storage unit is situated.

2.1.2. PV plant model

The PV field comprises a single-axis tracking system inclined in a north–south direction with an inclination of 30°. Monocrystalline silicon modules are used, more precisely the "Yingli Panda YL280C-30b" with a power of 280 Wp, as well as an inverter "SMA MVPS 2500" with a nominal power AC of 200 kVA. Both have an efficiency of 0.171 and 0.986, respectively, under rated conditions. The PV system is designed to be expandable in regards to the number of systems (modules and inverters) to achieve the nominal PV capacity while maintaining a fixed AC/DC ratio of 1.22.

2.1.3. TES model

In this study, a flexible storage system with three tanks is proposed to provide greater versatility to the hybrid plant system. MS was chosen as the storage medium because it is extensively used in TES systems for high-temperature, large-scale applications [8]. In this particular case, the widely used solar salt is chosen (60 wt% $NaNO_3$ and 40 wt% KNO_3), a mixture known for its greater thermal stability and lower cost [10]. Its operating range is between the freezing point and the decomposition temperature of 290°C and 565°C, respectively.

2.1.4. Power block model

The PB of this study consists of a supercritical Rankine cycle with a nominal electric power of 165 MWe and a nominal efficiency of 0.467. It is a regenerative cycle with 6 extractions, steam reheat, and a water-cooled condenser. It operates with a maximum temperature of 555°C. The minimum turbine load was set at 20% of the gross power. The CSP-PV-TES-EH hybrid power plant is designed to meet a base load of 165 MWe required by the grid. Figure 2 shows a simplified representation of the iterative process involved in determining the operating modes. The operational mode prioritizes directing electrical power to the EH (1) to increase the temperature of the MS at the solar field outlet to match that of the hottest tank. This quantity will depend on the CSP field generation and the state of charge (SOC) of the three tanks. Following this primary objective, the surplus energy is harnessed to fulfil the power demands associated with auxiliary or parasitic loads within the solar field, the PV plant, the TES system, and the PB (2). Ultimately, any surplus electricity exceeding these requirements may be directed to the electrical grid to contribute to the base load (3). In the event of an electrical surplus that remains unutilized, it goes to waste (4).

The Fresnel field receives information about the remaining power to meet the demand from the grid. Part of this power will be directed to the TES system via the heat exchanger (5) to heat the MS to the temperature of the intermediate tank, while any excess power not accommodated by the tank state will be wasted through defocusing of the field panels (6). If the SOC of the hot tank is sufficient, the PB will be activated (7), initially to cover the remaining parasitic loads (8) and then the grid demand (9)

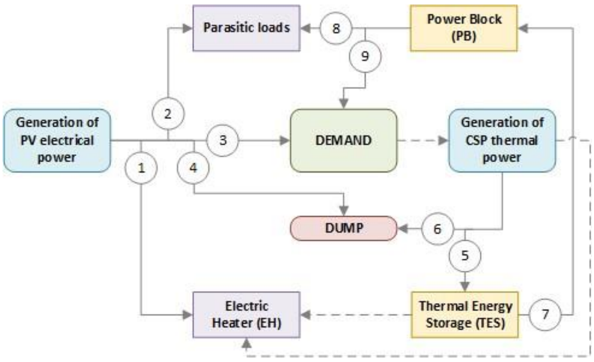

Figure 2. *Conceptual priority framework for meeting the base load of the grid.*

2.2. Simulation and parametric evaluation

In this study, Greenius software was utilized to simulate the hybrid PV-CSP plant integrated with an EH in series, while the simulation of the PB was implemented in Ebsilon software. Figure 3 presents a conceptual depiction of the methodology, outlining the softwares employed at each stage of this study.

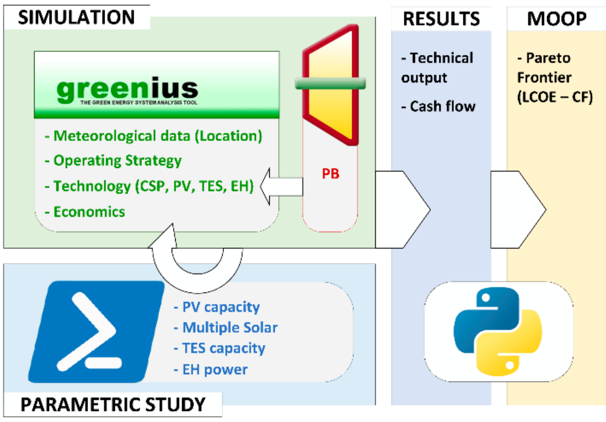

Figure 3. *Schematic representation of the methodology employed.*

The hybrid plant is situated in Seville, Spain. Table 1 provides a comprehensive depiction of the geographical coordinates and meteorological records associated with this location.

Table 1. *Geographical location and meteorological data of Seville, Spain*

Parameters	Values	Units
Altitude	11	m
Latitude	37.42	°N
Length	-5.90	°E
Average DNI	2089.40	kWh/(m^2·year)
Average GHI	1786	kWh/(m^2·year)

A parametric analysis was done considering the variables of the system including PV nominal power, SM, EH nominal power, and TES capacity. The parameter adjustments were automated using PowerShell software. The simulation employed limit values and step sizes for each of the variables, which are presented in Table 2.

Table 2. *Analyzed range for the design parameters*

Parameters	Lower limit	Upper limit	Step	Unit
PV nominal power	200	700	125	MWe
SM	0.2	2.9	0.45	-
TES capacity	3	21	4.5	h
EH nominal power	50	450	100	MW

The economic evaluation was conducted by calculating the LCOE for the hybrid power system. The cost breakdown for this study is presented in Table 3.

Table 3. *Assumed investment and O&M costs*

Parameter	Investment Cost	O&M cost	Unit	Ref.
LFR solar field	170	4	€/m^2	[11]
EH	140	1	€/kW	[12]
TES	30	-	€/kWh	[13]
Supercritical Rankine PB	860	2.5	€/kWe	[13], [14]
PV plant	840	9.75	€/kWp	[11]
Replacement	-	0.2	%/year	[12]
Insurance	-	0.5	%/year	[12]
EPC	13	-	%	[12]
Contingencies	7	-	%	[12]

In addition, a discount rate of 5%, a 70% debt financing with an interest rate of 5.64%, and a lifetime of 25 years.

2.3. Multi-Objective Optimization

A Multi-Objective Optimization algorithm in Python (MOOP) was proposed to minimize the LCOE while simultaneously maximizing the CF. Specifically, an algorithm utilizing a brute-force approach with backtracking is employed to derive the Pareto front by evaluating all 875 simulation results. This entails systematically exploring every possible combination, incorporating the backtracking technique when it is determined that a previous choice does not lead to a valid solution. Initially, an array is initialized with all points considered part of the Pareto front, marked as true. The algorithm iterates over points marked as true, comparing them with each potential candidate to join the Pareto front. Candidates are eliminated if dominated (false) or retained as possible candidates if they are dominating (true). This evaluation aids in determining the relative superiority of each solution based on multiple objectives. Afterwards, the Pareto front obtained from this is compared to the results achieved using other technologies in the identical location.

3. Results

Figure 4 illustrates the trends in the LCOE as determined by our parametric analysis. Our findings reveal that at low PV capacities (200 MW), the LCOE is notably influenced by the EH capacity. The LCOE exhibits a downward trend as EH capacity decreases. This phenomenon is attributed to the fact that, at higher nominal EH capacities, a significant portion of the PV-generated power is allocated to elevating the temperature of the MS within the EH system. Consequently, integrating PV-generated power into the grid becomes a challenging task. To satisfy the base load, a large LFR and TES system would be necessary, which supposes high associated capital and operational expenses. As the installed PV capacity increases, the most economically efficient solution tends to involve a storage capacity of approximately 12 hours. The dependence on the EH system diminishes, and the optimal LCOE shifts towards higher

TES and EH capacities and lower SM. This trend is observed up to a certain elevated PV capacity, beyond which there is a general increase in LCOE across all configurations.

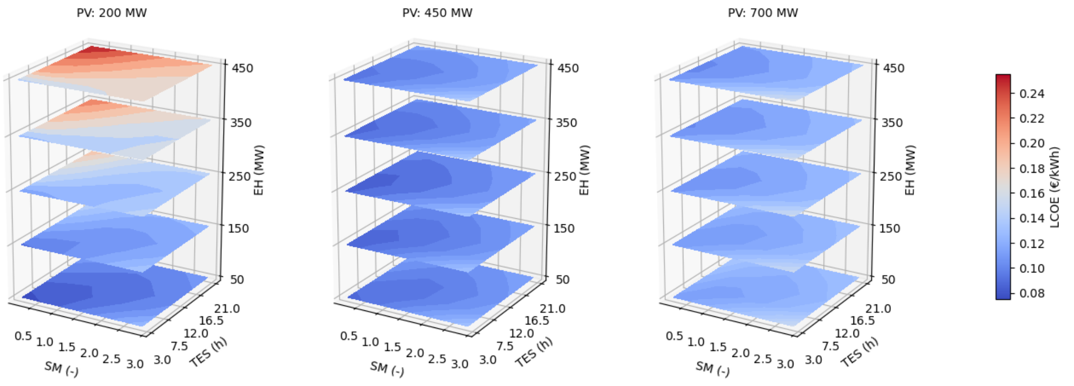

Figure 4. *Trends in the LCOE derived from the parametric analysis.*

Figure 5 shows the trends of the CF. In this case, our findings reveal that at low PV capacities (200 MW), there is limited reliance on TES capacity as the EH capacity also increases because the PV is unable to meet the base load requirements during the day, necessitating the use of the PB to fulfil this role and resulting in minimal energy storage for night time use. Lower EH values and higher SM values contribute to an increase in the CF. For higher PV capacities, the maximum CF shifts towards higher EH, with optimal values occurring at high SM and TES capacities, tending to a limit for the highest PV capacities (700 MW).

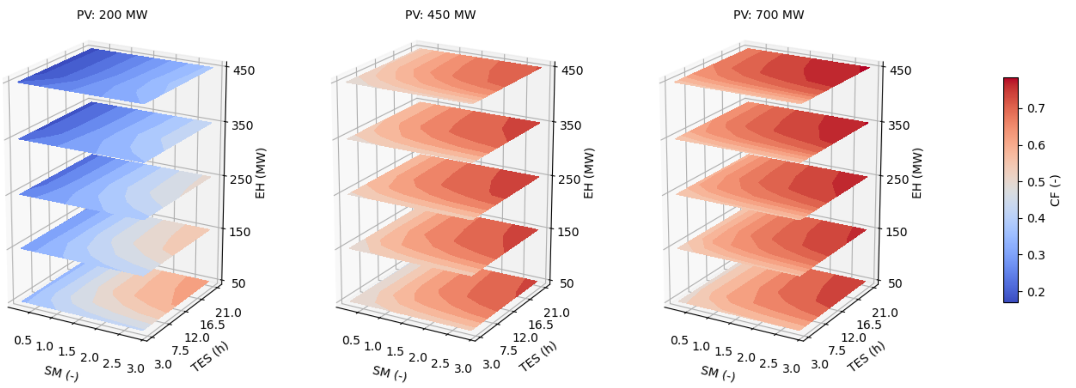

Figure 5. *Trends in the CF derived from the parametric analysis.*

Figure 6 shows the relationship between CF and LCOE for the 875 simulations performed. There is a specific region characterised by a low PV capacity of 200 MW, where the minimum LCOE decreases as the CF increases. The choice of EH, SM and TES leads to a wide range of potential LCOE values, ranging from 0.0742 €/kWh to 0.255 €/kWh. This particular pattern persists up to a specific CF of 0.45, beyond which both CF and LCOE increase. In this range, the LCOE values become narrower, ranging from 0.0742 €/kWh to 0.13 €/kWh, and experience a more significant increase as attempts are made to achieve higher CFs. A PV capacity of 325 MW emerges as the most optimal alternative in terms of LCOE, up to a CF of 0.65, at which point PV capacities of 450 MW become ideal. For higher CF values the ideal PV capacity keeps increasing as was commented above.

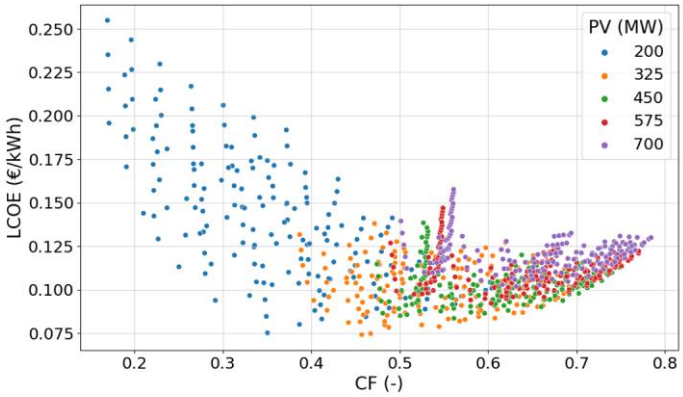

Figure 6. *LCOE and CF for different PV power levels.*

Combinations such as PV=450 MWe, SM=2, EH=250 MW, and TES=12 h, demonstrate a favourable balance between LCOE and CF (LCOE=0.0979 €/kWh, CF=0.702). However, the configuration is hindered by a considerable amount of PV dumping.

4. Multi-objective optimization

Figure 7 represents the Pareto front of the four technologies: standalone PV (accompanied by a battery storage system having an efficiency of 0.9 and a cost of 280 €/kWh, with a nominal capacity ranging from 0 to 1500 MWh), standalone CSP (consisting of an oil-salt indirect LFR system featuring two tanks priced at 25€ /kWh [13] and an 800 €/kWe subcritical Rankine PB [14] with a nominal efficiency of 0.387), a co-located PV-CSP system (incorporating both technologies operating independently and integrated into the grid, with the PV field excluding the batteries and the CSP system using oil-salt with two tanks and a subcritical Rankine PB), and the hybrid system under analysis. The remaining parameters retain the ranges and costs as presented in Table 2 and 3, respectively.

A summary of parameters and ranges used for the other configurations is shown in Table 4.

Table 4. *Parameters and ranges for other configurations*

Configuration	Parameters	Lower limit	Upper limit	Step	Unit
PV STANDALONE	PV nominal power	200	700	125	MWe
	BESS	0	1500	500	MWh
CSP STANDALONE	TES capacity	3	21	4.5	h
	SM	0.2	4.25	0.45	-
CO-LOCATED	PV nominal power	200	700	125	MWe
	SM	0.2	2.9	0.45	-
	TES capacity	3	21	4.5	h
HYBRID	PV nominal power	200	700	125	MWe
	SM	0.2	2.9	0.45	-
	TES capacity	3	21	4.5	h
	EH nominal power	50	450	100	MW

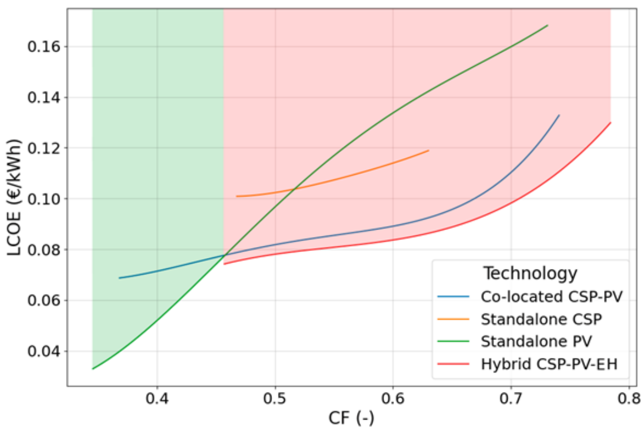

Figure 7. *Pareto front of different CSP-PV technologies.*

The results of Figure 7 illustrate that when the capacity factors are less than 0.45, PV technology proves to be the most economically feasible option in terms of the LCOE. However, to achieve higher capacity factor values, the cost of batteries remains unaffordable. On the other hand, when the capacity factor values exceed 0.45, the studied hybrid technology emerges as the optimal choice with the lowest LCOE, particularly at higher CF levels compared to the co-located plant.

5. Conclusions

A design parametric and performance assessment of the PV-CSP-TES-EH plant and a multi-objective optimization of different technologies were conducted for this study and the results of this research are outlined as follows:

- The increase in PV capacity has a positive effect on the CF while the effect on the LCOE varies depending on the range.
- The standalone PV system had the lowest LCOE for CFs below 0.45.
- For the capacity factors above 0.45, the hybrid CSP-PV-TES-EH plant had the lowest LCOE. Even better than the co-located CSP-PV plant.
- The region of particular interest lies in a CF range of 0.55 to 0.65, where the LCOE remains notably low. However, this scenario shifts swiftly as CF values increase.
- The proposed configuration has the potential to emerge as a favourable solution in a decarbonized scenario, emphasizing not only cost-effectiveness but also the crucial aspect of flexibility in meeting demand.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon a reasonable inquiry.

Author contributions

The authors declare that Rubén Barbero and Rafael Fornés contributed to the conceptualization and formal analysis of the study and collaborated with Imán Golpour and Mercedes Ibarra with the writing, editing and reviewing part while Antonio Rovira contributed to the supervision of the study.

Competing interests

The authors declare that they have no competing interests.

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