







Hybridization of Concentrated Solar Power With Wind and PV to Meet the Self-Consumption Requirements

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Abstract. This paper explores the hybridization of Concentrated Solar Power (CSP) plants with wind and photovoltaic (PV) technologies to meet self-consumption demands in two distinct locations: Calama (Chile) and San José del Valle (Spain). We evaluate various hybrid configurations under two primary scenarios: one where excess energy cannot be utilized or fed into the grid, and another where electric heaters are used to transfer excess energy to thermal storage systems. Our findings reveal that hybrid plants significantly reduce the LCOE and increase the Capacity Factor (CF) compared to standalone CSP plants, with optimal configurations varying by location due to differences in climatic conditions. In Calama, wind energy plays a crucial role, whereas in San José del Valle, a combination of PV and wind is more effective. Additionally, the use of electric heaters to store surplus energy enhances system efficiency. This study underscores the viability and efficiency of hybrid CSP plants, especially when adapting to regional climatic and geographic characteristics, providing a compelling case for their implementation in diverse locations.

Keywords: Hybrid Solar Plant, CSP's Self-Consumption, Wind Power

1. Introduction

In the context of a growing global demand for clean and sustainable energy sources, solar and wind energy emerge as prominent players, with an increase of 32% and 13% in installed capacity in 2023 compared to 2022, respectively [1]. The convergence of various technologies, such as CSP, PV energy, and wind energy, offers a synergy that capitalizes on the individual strengths of each (including the low costs of PV and wind technology [2], and the energy storage capacity through CSP thermal energy storage (TES) systems [3]).

The hybridization of CSP plants with PV plants has been extensively studied in the literature, demonstrating that these hybrid configurations are more competitive. Hybrid plants achieve better CF [4] and lower LCOE [5] compared to standalone plants. The literature also explores the integration of hybrid plants combining CSP, PV, and wind energy, aiming to achieve significant performance improvements over standalone plants. [6] highlights that integrating wind power, photovoltaic, and concentrating solar power with supercritical CO₂ Brayton

cycles significantly improves techno-economic performance, reducing LCOE by 13.81% and CO₂ emissions by 40.36%, while increasing system efficiency by 36.36%. [7] presents a novel algorithm that combines Power Pinch Analysis (PPA) and Modified Electrical System Cascade Analysis (MESCA) for optimizing the sizing of autonomous hybrid renewable energy systems, including PV panels, wind turbines, CSP, thermal storage, and batteries, achieving competitive leveled cost of electricity and high supply reliability in a Moroccan case study. [8] evaluates the technical and economic feasibility of a hybrid cogeneration system integrating CSP, PV, and wind with thermal and battery energy storage, finding that the thermal energy storage mode provides greater flexibility and stable energy output compared to the steam recovery mode, though it requires cost-effective storage solutions, and validates the system's viability for Xining, Qinghai by highlighting the need for optimal wind and solar integration.

Regarding the goal of using PV to meet the self-consumption needs of CSP plants to reduce their LCOE and enhance their attractiveness. [9] assesses the feasibility of retrofitting parabolic trough power plants (CSP) with integrated PV systems to improve efficiency and reduce costs. The study explores various configurations and hybridization scenarios to optimize the performance and economic viability of these hybrid plants. The results demonstrate that integrating PV can significantly reduce the LCOE, especially when electric heaters are used to harness the excess PV energy, providing a more competitive and efficient solution for self-consumption and grid integration.

This study focuses on evaluating CSP plants with grid connection points that impose restrictions on energy discharge from other sources, and their hybridization with PV and wind technologies to meet the self-consumption requirements of the CSP plant. We will consider two different scenarios: Scenario 1, where excess energy from PV and wind plants cannot be used nor delivered to the grid, and Scenario 2, where these surpluses are directed to electric heaters, allowing the energy to be transferred to storage tanks.

2. Methodology

The primary objective of our study is to enhance the Self-Supply Ratio (SSR) [10] while reducing the LCOE and increasing the CF of CSP plants through their hybridization with PV and wind technologies. To achieve this, we use the ASDELSOL tool developed by GTER, incorporating a newly implemented library for modeling wind plants [9]. We have selected Calama (Chile) due to its high solar and wind potential (accumulated annual DNI is 2792.7 kWh/m² and the average wind speed is 7.4 m/s), and San José del Valle (Spain) with a lower potential (accumulated annual DNI is 1981.8 kWh/m² and the average wind speed is 2.5 m/s), to evaluate the performance of these plants in different locations and climates, as we can see in Figure 1.

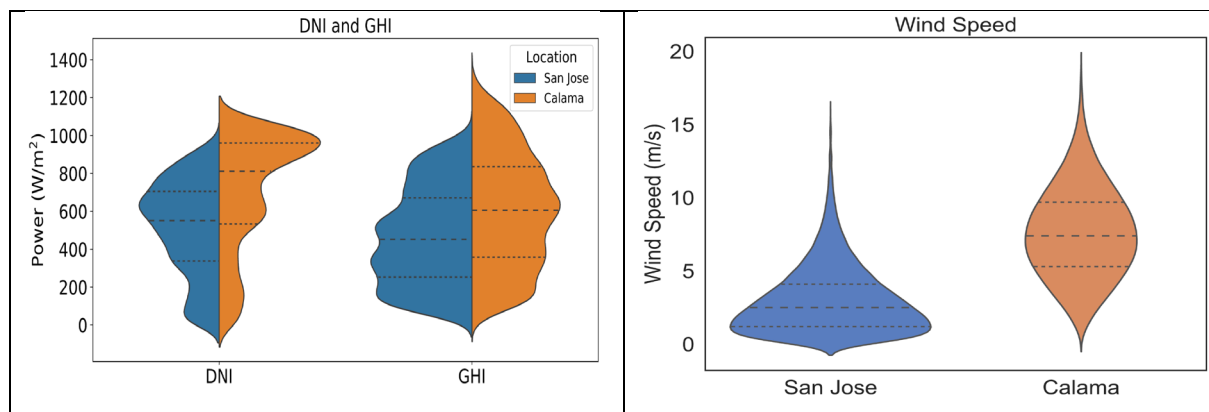


Figure 1. a) Solar resource in both location and b) Wind speed in both location

2.1 CSP plant configuration

To do this, we optimized a plant of 55 MW gross for 7.5 hours of storage, achieving an SM of 2.5. Table 1 presents the most significant parameters of the CSP plant analyzed for the two studied locations.

Table 1. Main Characteristics of CSP plant in both locations

Main Characteristics			
Gross Power (MW _e)		55	
SM (-)		2.5	
Storage time (h)		7.5	
Locations			
Calama		San José del Valle	
CF (%)	39.94	CF (%)	28.88
LCOE (€/kWh)	0.161	LCOE (€/kWh)	0.223

2.2 Wind Library

We developed a library in ASDELSOL for simulating a wind plant by modeling the Gamesa G126-2.5MW wind turbine using its power curve [11].

To determine the wind speed at the height of the wind turbine rotor, the Hellmann exponential law, also known as the Hellmann law, has been used. This law allows extrapolating the wind speed measured at a specific height to another height. The formula used is as follows:

$$\frac{v}{v_0} = \left(\frac{H}{H_0}\right)^\alpha \quad (1)$$

Where v represents the wind speed at height H , which is the height of the wind turbine rotor. v_0 is the wind speed at height H_0 , the measurement height, which in our case is 10 meters. The coefficient α , known as the friction coefficient or Hellmann exponent, varies depending on the terrain characteristics and is typically assumed to be 1/7 (approximately 0.14) for open land.

2.3 Hybrid plant configuration

We analyze two different hybrid plant configuration scenarios: Scenario 1, where the PV and wind plants satisfy the CSP plant's self-consumption requirements, but any excess energy is curtailed and lost, and Scenario 2, where an electric heater is introduced to utilize the excess energy from the PV and wind plants to heat salts in the TES system. Figure 2 illustrates the configurations for Scenario 1 and Scenario 2.

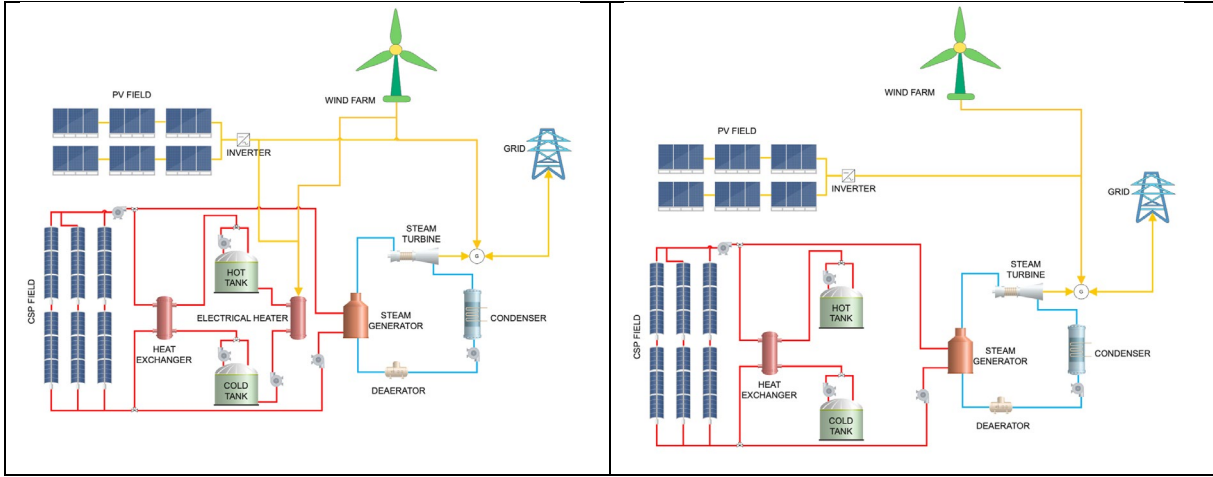


Figure 2. a) Hybrid plant configuration Scenario 1 and b) Hybrid plant configuration Scenario 2

2.4 Economic data

Table 2 summarizes the key economic parameters associated with the CSP, PV, and wind plants. The corresponding references are provided within the table.

Table 2. Main economic parameters

Parameter	Value	Unit
PV plant [12]		
CAPEX	1.20	€/W _p
O&M	20.95	€/KW _p -yr
CSP plant [13]		
Solar field	132	€/m ²
HTF system	52.80	€/m ²
TES system	54.56	€/kWh _t
Power block	800.8	€/kW
Auxiliary system	79.20	€/kW
O&M	60.06	€/kW-yr
Electrical heater [14]		
General cost	0.08	€/W
Wind Turbine [13]		
CAPEX	1.37	€/W
O&M	0.037	€/W

3. Results

We face a multi-objective optimization problem, as our goal is to minimize the LCOE while maximizing both the CF and SRR. To determine the optimal plant configuration, we employ Pareto curves. The variables used in the study, along with their ranges and increments for the simulations, are detailed in Table 1.

Table 3. Variables for sensitivity analysis for hybrid CSP-PV-Wind power plant

Variable (units)	Range	Step
PV ratio (%)	[0-40]	20
N° turbines (-)	[0-10]	2
Electrical heater ratio (%)	[80-100]	20

PV ratio represents the percentage of PV power relative to the fixed CSP power of 55 MW gross, and Electrical heater ratio (EH ratio) denotes the relative power of the electrical heater compared to the PV and wind plant.

3.1 Scenario 1

The economic optimum (Figure 3) for San José del Valle is achieved with a PV ratio of 20% and no wind turbines, while in Calama, it is achieved with a PV ratio of 20% and 2 wind turbines, reflecting a greater impact of wind energy in Calama. The optimal configuration in Calama reduces the LCOE by 7.4% compared to the standalone CSP plant, whereas in San José, the reduction is 6.05%. However, to maximize both SSR and CF, a compromise solution rather than the purely economic optimum is necessary. Therefore, we refer to the Pareto solutions (Figure 4).

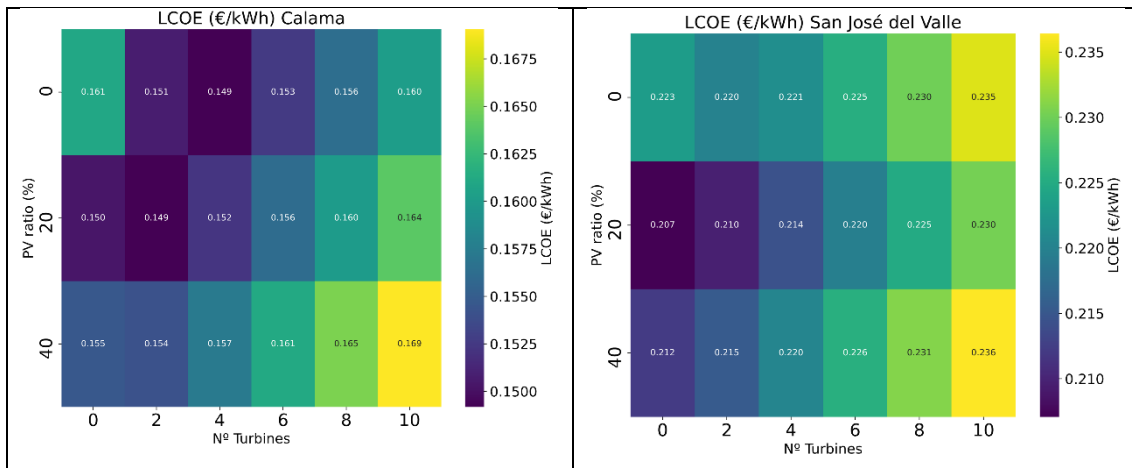


Figure 3. Economic optimization for Scenario 1

Optimal techno-economic solutions are among the Pareto solutions when optimizing CF and LCOE, with a CF increase of 14.1% in Calama compared to the CSP plant and 11.3% in San José del Valle. In San José del Valle, even with multiple wind turbines, the SSR remains below 60%, whereas in Calama, the SSR with only wind energy exceeds 80%. To achieve values above 80% in San José del Valle, a combination of a 20% PV ratio and 2 wind turbines is required, while in Calama, this configuration results in an SSR above 90%.

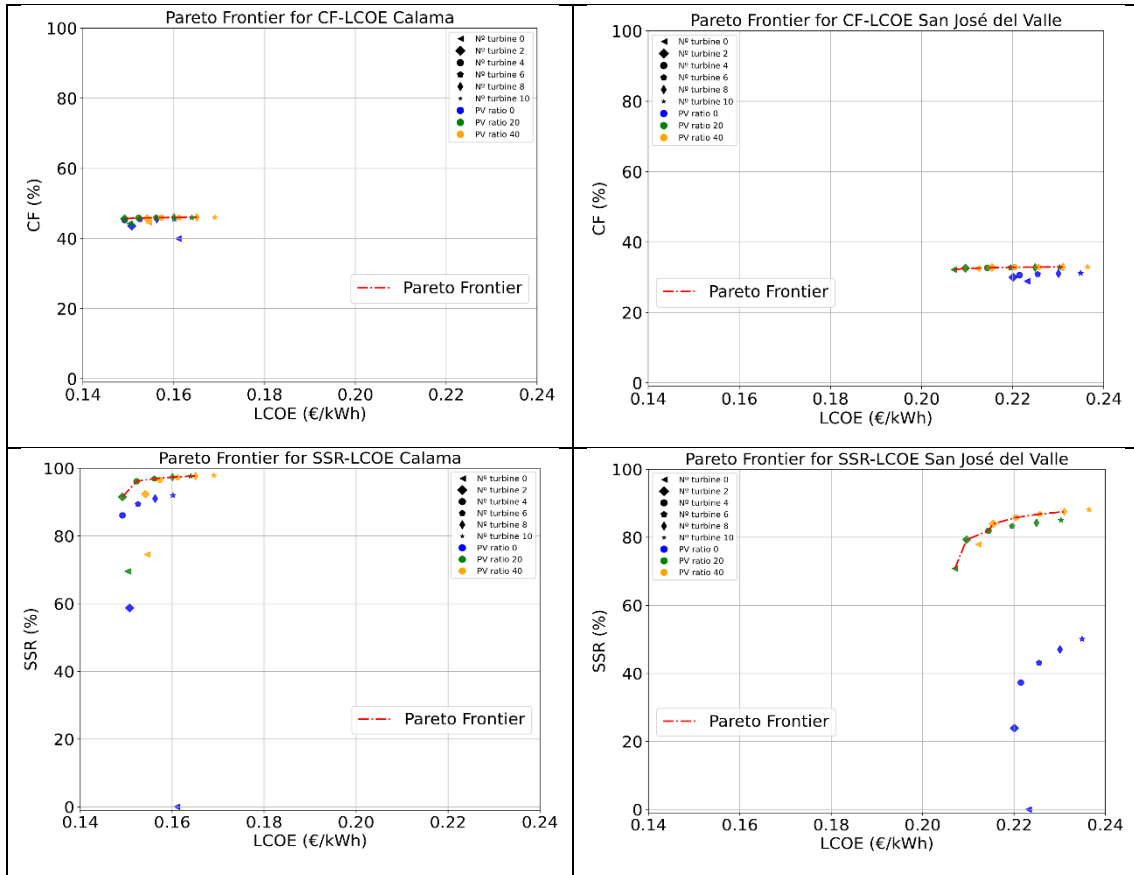


Figure 4. Pareto frontiers for Scenario 1

3.2 Scenario 2

Figure 5 shows the Pareto frontiers to San José del Valle for each EH ratio.

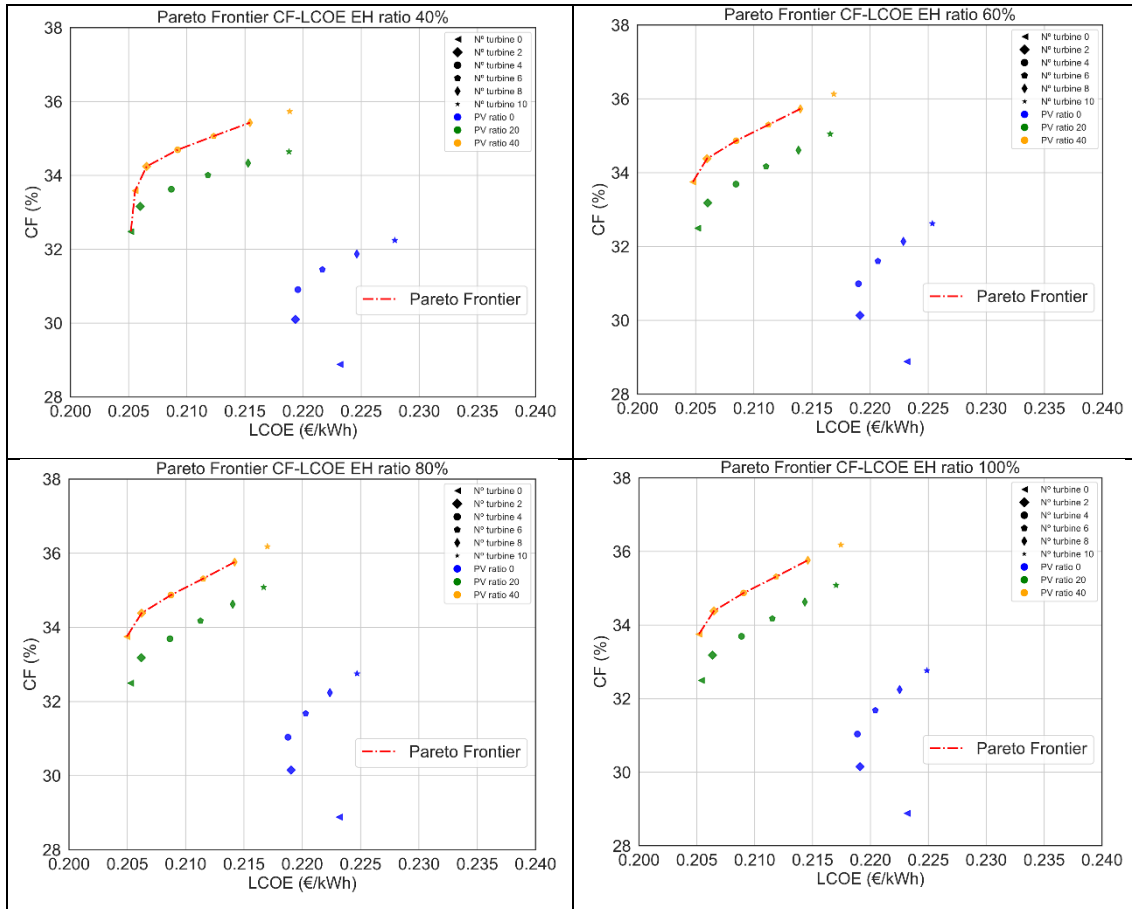


Figure 5. Pareto frontiers for San José del Valle in Scenario 2

The analysis indicates that for EH ratios of 60%, 80%, and 100%, the CF remains nearly constant, with only a slight increase compared to the 40% EH ratio. Although the LCOE is lower for a 40% PV ratio with no wind turbines, the CF is also lower, making the configuration with 2 wind turbines the optimal Pareto compromise. From an EH ratio of 60% onward, the CF stabilizes as the equipment can utilize 96% of the energy rejected by the auxiliary plant. The optimal EH size for the hybrid plant is 60% of the self-consumption capacity. Incorporating electric heaters allows excess energy to be used for heating salts, increasing plant output. Transitioning from the optimal Scenario 1 with a 20% PV ratio and no wind turbines to a 40% PV ratio with 2 wind turbines in San José del Valle results in a 0.53% reduction in LCOE and a 6.97% increase in CF. Electric heaters also reduce energy rejection from auxiliary plants, with the optimal Scenario 2 configuration utilizing 96% of excess energy, achieving an SSR above 80% in all configurations.

When seeking a balanced solution among the Pareto-optimal configurations for different EH ratios (Figure 6), the 60% EH ratio emerges as the best choice, as it significantly improves the capacity factor (CF) while only slightly increasing the LCOE compared to other configurations, with a PV ratio of 20% and 10 wind turbines. Specifically, this configuration results in a CF of 51.61% and an LCOE of 0.147 €/kWh and a SSR of 97.6%. Compared to the Scenario 1 configuration, this represents a 1.47% reduction in LCOE and a 13.18% increase in CF.

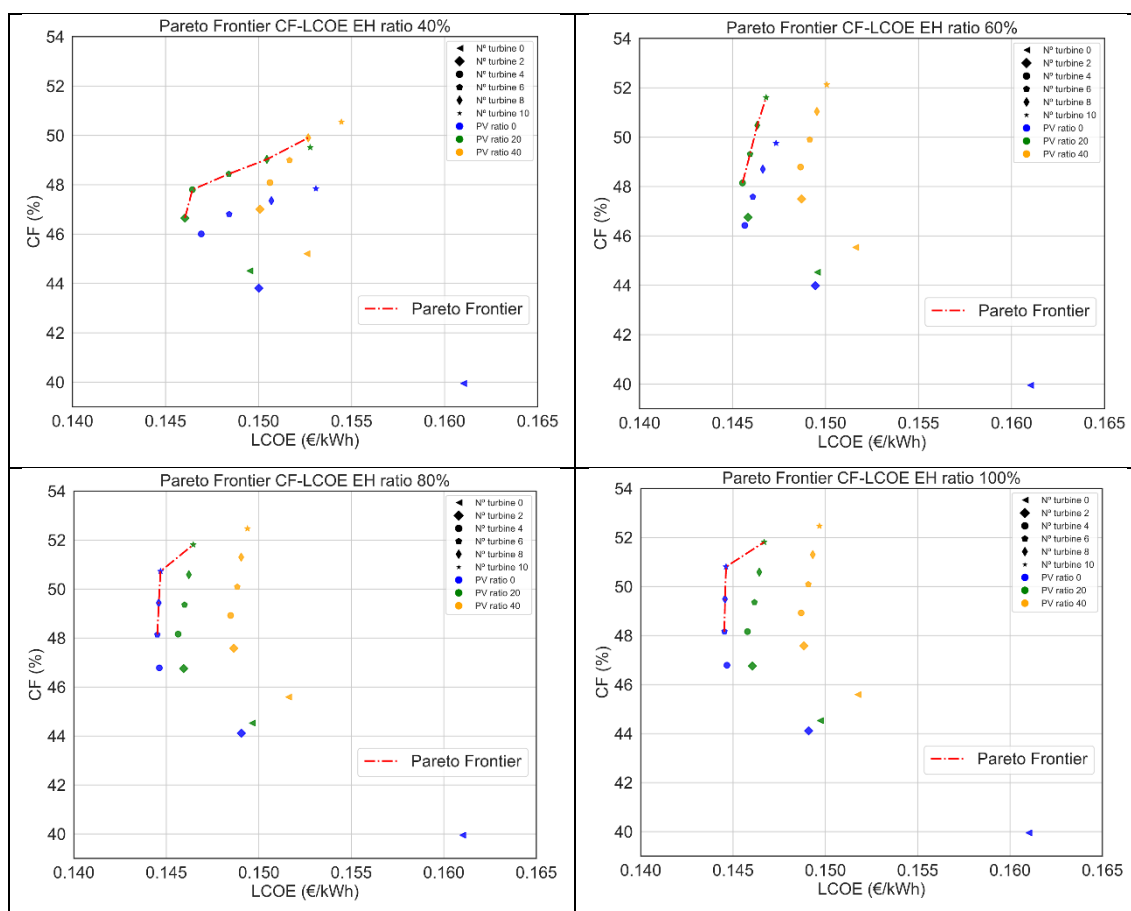


Figure 6. Pareto frontiers for Calama in Scenario 2

4. Conclusions

In Scenario 1, hybridizing CSP with PV and wind energy in Calama, with a 20% PV ratio and 2 wind turbines, achieved a 7.4% reduction in LCOE, a 14.1% increase in CF, and an SSR above 80%. In San José del Valle, the optimal configuration with a 20% PV ratio and no wind turbines lowered the LCOE by 6.05% but required wind turbines to boost the SSR above 60%. In Scenario 2, adding electric heaters in Calama allowed efficient use of excess energy, achieving an SSR of 97.6% with 20% PV and 10 wind turbines, resulting in a 51.61% CF and an LCOE of 0.147 €/kWh, which was a 13.18% improvement in CF and a 1.47% reduction in LCOE from Scenario 1. In San José del Valle, electric heaters with a 60% ratio and a 40% PV configuration plus 2 wind turbines improved CF by 6.97% and slightly reduced LCOE by 0.53%, though benefits were limited by local resource availability. Overall, Calama showed greater potential for CSP hybridization due to better solar and wind resources, while San José del Valle's results were less significant, emphasizing the need to tailor strategies to local conditions.

Author contributions

José A. López-Álvarez: Conceptualization, Methodology, Software, Visualization, Formal analysis, Writing – original draft.

Miguel Larrañeta: Conceptualization, Methodology, Validation, Visualization, Writing – review & editing.

Sara Moreno-Tejera: Conceptualization, Methodology, Writing – review & editing.

J.M. Delgado-Sanchez: Validation, Supervision.

Isidoro Lillo-Bravo: Validation, Supervision.

Manuel A. Silva-Pérez: Conceptualization, Methodology, Validation, Writing – review & editing.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

The data supporting the findings of this study are not publicly available but can be provided by the corresponding author upon reasonable request.

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