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Application of Molten Salt Electrical Heaters to Increase the Flexibility of CSP Plants' Power Block

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Abstract. The transforming grid profiles require concentrated solar power (CSP) plants to operate in a dispatchable and flexible manner; however, the allowable minimum load of the power block exerts a limitation on the operation range. This study proposes using molten salt electrical heaters to lower the minimum electricity output of CSP plants. In this regard, three configurations of the molten salt electrical heaters, 1) in parallel to the receiver, 2) in parallel to the hot tank, and 3) in series to the receiver, are investigated with six grid and three revenue scenarios. The system is assessed for Fuerteventura. The findings validate that the application of the molten salt electrical heaters, particularly through Configurations 1 and 3, enhances a) the flexibility characteristics of the CSP plant with up to a 10.2% increase in demand coverage factor, an 84.6% decrease in start-up instances, and a 41.4% increase in operating hours; and b) economic performance with up to a 35.7% increase in gross profit.

Keywords: Molten Salt Electrical Heaters, Flexibility, Power Block, CSP, Load-Following

1. Introduction

The electricity generation profiles and, subsequently, the grid requirements have transformed significantly with the increased penetration of renewables to the grid. To accommodate the fluctuating nature of renewables, dispatchable electricity generation has become vital. However, dispatchability of the concentrated solar power (CSP) plants should be accompanied by "flexibility" to timely and accurately respond to the mismatch of electricity demand and supply.

Central receiver with molten salt thermal energy storage (TES) is the most promising CSP technology for electricity production on a commercial scale due to its operating temperature and associated energy conversion efficiency. Associatively, Steam Rankine Cycle is the conventional power cycle for commercial central receiver systems [1]. Expanding the load range of the CSP power block is crucial to improve its flexibility characteristics as the minimum allowable load of the steam turbine exerts a limitation on the operational range of the CSP plant.

Kosman et al. [2] analyzed the integration of a molten salt TES system with a molten salt electrical heater (MSEH) in a conventional power plant to lower the minimum load of the cycle. By the authors of the present study, this is regarded as an even more promising solution for CSP plants as the molten salt is already utilized as the heat transfer and storage medium in commercial plants. Besides, the already existing molten salt system allows more configuration options for molten salt electrical heaters for the CSP plants, as demonstrated in [3].

Therefore, this study aims to analyze different integration schemes of molten salt electrical heaters in central receiver CSP plants to increase the load range of the power block by decreasing the minimum power output fed to the grid through the techno-economical assessment of the CSP plant in load-following operation with different grid and revenue scenarios.

2. Methodology

This study investigates three integration options of a molten salt electrical heater powered by excess electricity into the CSP central receiver system under six grid and three revenue scenarios. The term "*excess electricity*" used in this paper particularly corresponds to surplus electricity generation which occurs when the grid demand is lower than the minimum allowed load of the steam turbine.

As the reference case, a commercial scale central receiver CSP plant is modeled and simulated without any MSEH integration and referred as "*reference*" throughout this paper. The proposed MSEH integration options are presented in Figure 1 and summarized as

- Configuration 1: MSEH in parallel to the receiver,
- Configuration 2: MSEH in parallel to the hot tank,
- Configuration 3: MSEH in series to the receiver.

When the grid demand falls below the minimum allowed load of the steam turbine, the power block is kept in operation, and the excess electricity is fed to the MSEH. Therefore, the allowed range for electricity production of the CSP plant is expanded with the application of MSEH, leading to a more flexible operation.

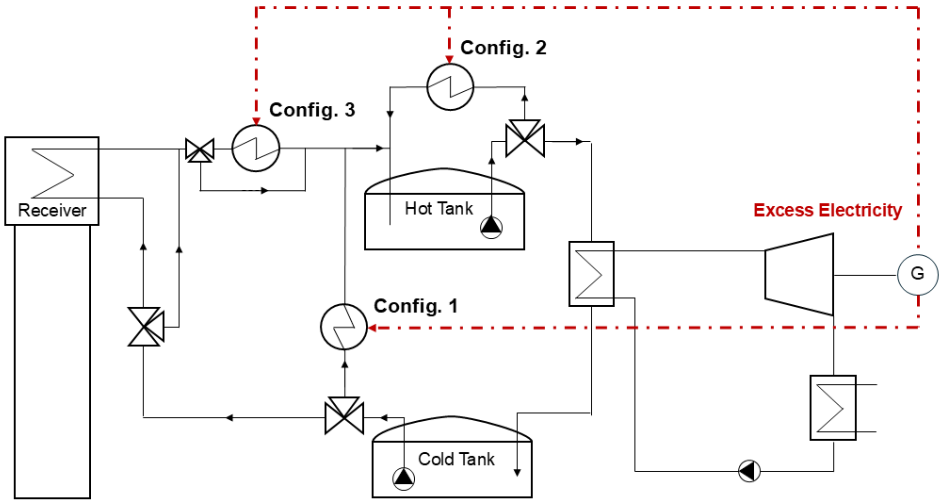

Figure 1. *Three integration options of the molten salt electrical heater into the central receiver CSP plant.*

The system is modeled as quasi-dynamic, where the start-ups of the receiver and the power block are accounted for by imposing time and energy penalties. The solar field and the associated efficiency matrix are generated using SolarPILOT 1.5.2, whereas EBSILON® Professional 16.04 is employed to simulate the power block and create the efficiency matrix as a function of molten salt temperature and load fraction. The efficiency matrices are imported to Python, where the overall modeling, simulation, and assessment of the CSP plant are conducted. Figure 2 presents the power block layout used in this study in accordance with the heat balance proposed in [4].

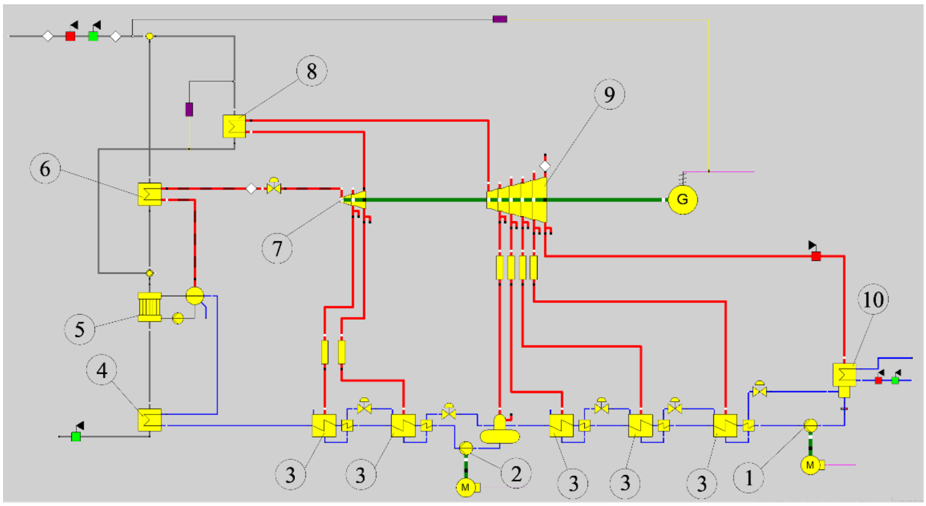

Figure 2. *Power block of the CSP plant modeled by EBSILON® Professional (1. Condensate pump, 2. Feedwater pump, 3. Regenerative feedwater heater, 4. Economizer, 5. Evaporator, 6. Superheater, 7. High pressure turbine, 8. Reheater, 9. Medium/Low pressure turbine, 10. Wet condenser).*

The system is assessed for Fuerteventura, Spain (28.44° N, 13.99° W), with an annual DNI of 2015.4 kWh m^{-2} [5]. The island is selected as a suitable candidate to study the proposed MSEH configurations due to its isolated grid structure, solar resources, renewable penetration, and demand profile. Accordingly, the configurations are analyzed under six energy system scenarios (referred as "*grid scenarios*"), as presented in Table 1, where Scenarios 1 and 2 represent the actual renewable energy (RE) capacity of Fuerteventura in 2019 and 2022, respectively. It is worth mentioning that the grid [6] and solar resource data [8] from 2019 are used as the base regardless of the analyzed scenario to maintain the real dependency between resource, demand, and generation profiles. The CSP plant design is parametrically determined based on Scenario 1, and the design decision is validated against the other scenarios. Hence, the resulting inputs are provided in Table 2, along with the other main technical inputs of the CSP plant.

Table 1. *Six grid scenarios of Fuerteventura with varying RE capacities.*

Scenario	Description	Wind capacity	PV capacity
Scenario 1	RE capacity in 2019 [6]	28.7 MW	14.2 MW
Scenario 2	RE capacity in 2022 [7]	64.9 MW	38.2 MW
Scenario 3.1&3.2[a]	Hypothetical wind expansion	84.9&104.9 MW	38.2 MW
Scenario 4.1&4.2[b]	Hypothetical PV expansion	64.9 MW	58.2&78.2 MW

[a] Hypothetical increase of wind power capacity by 20.0 MW and 40.0 MW, compared to Scenario 2
[b] Hypothetical increase of PV capacity by 20.0 MW and 40.0 MW, compared to Scenario 2

Table 2. *Main technical inputs of the CSP plant.*

Parameter	Value
Design DNI (W m^{-2})	800
Solar Multiple	2.5
TES Size (h)	14
TES Hot & Cold Tank Design Temperature (°C)	565 & 290
Nominal Capacity (MW$_{el}$)	88
Allowed Load Range of Turbine (%)	30-100
Live Steam Temperature (°C)	540
Live Steam Pressure (MPa)	12.5
MSEH Outlet Temperature (°C)	575
MSEH Efficiency (%)	100

The power block shown in Figure 2 is simulated with the main inputs presented in Table 2 and [4] for molten salt temperatures from 525 °C to 575 °C with intervals of temperature of 5 °C and turbine load fraction of 0.1. The thermal efficiencies of the intermediate operating points are calculated using 2D linear interpolation. Figure 3 presents the thermal efficiency of the power block for the hot salt design temperature, 565 °C, as a function of load factor. It also shows the thermal efficiencies for the system at the allowed minimum and maximum hot salt temperature, 525 °C and 575 °C, respectively.

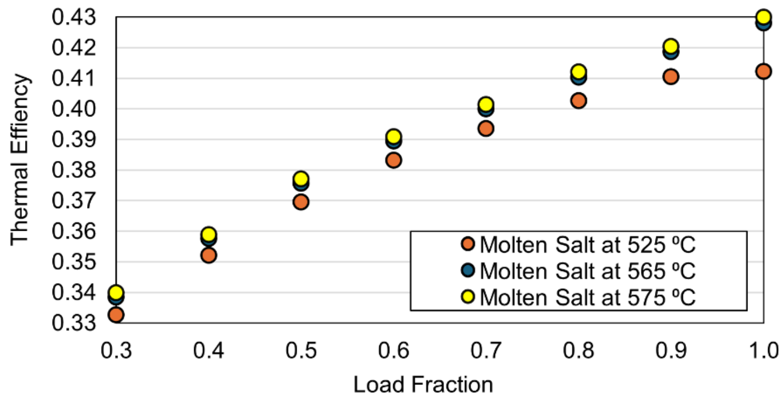

Figure 3. *The thermal efficiency of the power block as a function of molten salt temperature and load factor.*

The economic performance of the system is evaluated through the levelized cost of electricity (LCOE) and gross profit. Here, "*gross profit*" is defined as the discounted revenues for the lifetime of the plant minus the electricity production costs defined through LCOE. In this regard, three revenue scenarios are incorporated:

- Revenue 1 (Market Dependent): The electricity is sold at the Spanish day-ahead market with the feed-in-premium of 0.1 € kWh^{-1}. The price data of the Spanish market from 2019 [9] are adjusted based on [10] to reflect the projected European price trends.
- Revenue 2 (Market Independent): A constant feed-in-tariff is chosen as 0.15 € kWh^{-1} considering the yearly average day-ahead market price of the Spanish market in 2019 [9] and the electricity resale contract of eLLO power plant as referenced in a personal communication.
- Revenue 3 (Plant Dependent): The electricity is priced based on the thermal energy required to produce it. The price used in Revenue 2, 0.15 € kWh^{-1}, is chosen as the reference price at nominal load. The efficiency loss due to the partial load operation of the power block is projected by higher sale prices.

The remaining inputs of the economic analysis are given in Table 3.

Table 3. *Economic inputs of the CSP system (O&M: operation & maintenance, fix: fixed, var: variable).*

Parameter	Value	Parameter	Value
Lifetime	25 years	$OPEX_a$	O&M: 3.00% of CAPEX Insurance: 0.70% of CAPEX
Real Interest Rate	5%	$OPEX_b$	O&M: fix: 20.00 € kWh^{-1}, var: 0.01 € kWh^{-1} Insurance: included in O&M
$CAPEX_{min}$ $CAPEX_{min,MSEH}$ $CAPEX_{max}$ $CAPEX_{max,MSEH}$	369,221,809 € 371,667,505 € 657,148,544 € 660,010,009 €	$OPEX_c$	O&M: fix: 59.40 € kWh^{-1}, var: 0.03 € kWh^{-1} Insurance: 0.50% of CAPEX

As the cost of the CSP plants displays a wide range in the literature, the LCOE is calculated based on the maximum and minimum estimations of capital expenditures (CAPEX) and operational expenditures (OPEX), to the best knowledge of the authors [11-17].

3. Results

The model is validated against the System Advisor Model (SAM) with maximum power generation mode and without any MSEH application. The gross output of the turbine is found to be overestimated by 2.5% compared to SAM results, whereas the overall balance of electricity to/from the grid is found to deviate only by +0.6%. Hence, the model is concluded to be representative and accurate for this study.

Figure 4 presents the capacity factors of the turbine and the plant, and the demand coverage factor of the CSP plant for different MSEH configurations and grid scenarios. Here, the capacity factor of the turbine (CF_T) is defined as the ratio of the actual gross generation of the turbine over the generation that would be achieved by the nominal operation of the turbine throughout the year. For the capacity factor of the plant (CF_{CSP}), the numerator is changed to the electricity fed to the grid while the denominator is kept the same to account for gross-to-net efficiencies and the impact of the MSEH. As the capacity factor is not fully representative to capture the effect of the MSEH for the grid scenarios with varying amounts and trends of renewable penetration into the grid, a new metric, "*demand coverage factor*", is introduced. The demand coverage factor (DCF) is defined as the ratio of the net power block output to the residual load of the grid after the non-dispatchable renewable generation.

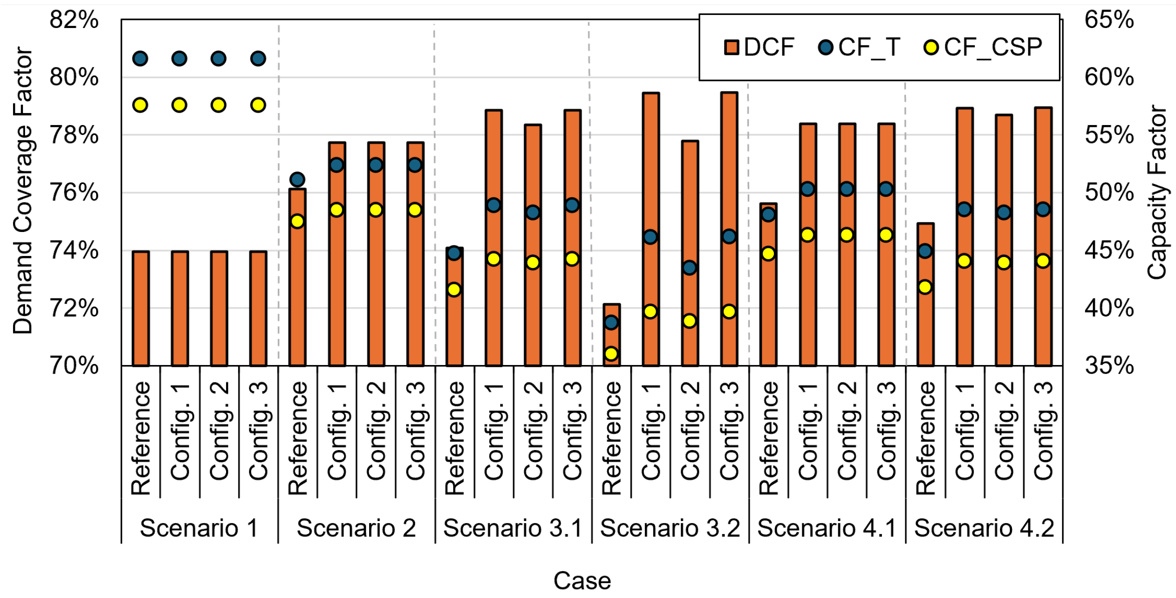

Figure 4. *The capacity factors and demand coverage factor of the CSP plant for different MSEH configurations and grid scenarios.*

As presented in Figure 4, the demand coverage factor and capacity factors do not show any difference between the configurations in Scenario 1, as the residual demand always remains above the minimum allowed load of the CSP plant, resulting in no MSEH operation. Therefore, Scenario 1 serves as the basis to explore the potential of MSEH application on the existing CSP plants in the grids with increasing renewable penetration where the CSP plants can be assigned the role of "load-following". Accordingly, the integration of the MSEH enhances the capacity factors and demand coverage factor in Scenarios 2, 3 and 4 regardless of the configuration, as presented in Figure 1. The effect of the MSEH becomes most significant in Scenario 3.2, where the highest increases in turbine capacity factor and demand coverage factor are observed, ranging from 12.23% to 19.25% and 7.86% to 10.18%, respectively.

It is also noteworthy that even though the same trends are observed for both capacity factors in all scenarios, the difference between CF_T and CF_{CSP} becomes more pronounced with increased MSEH operation due to the part load operation and the losses associated with MSEH, resulting in CF_{CSP} being 10.6%-14.1% lower than CF_T in Scenario 3.2.

Figure 5 presents the LCOE and gross profit of the CSP plant for different MSEH configurations, grid, and revenue scenarios. It should be noted that even though the LCOE is calculated and provided over a range, the gross profit is presented based on the most optimistic LCOE scenario. As expected, the increasing renewable capacity in the grid inevitably results in higher LCOE due to lower capacity factors of the CSP plant, already depicted in Figure 4. The application of the MSEH decreases the LCOE and increases the gross profit of the plant in all cases, showing the maximum impact with Scenario 3.2. In this scenario, the MSEH application boosts the gross profit by 26.66% to 35.69% compared to the reference case. It is also worth mentioning that the economic scenarios of Revenue 1 and Revenue 2 result in good compliance with a 3.56% deviation at most, suggesting that the determined electricity sale prices are consistent across the scenarios in this study. Conversely, even though Revenue 3 also fairly complies with Revenue 1 with a +5.90% difference in Scenario 1, higher discrepancies between Revenue 3, and Revenue 1 and/or Revenue 2 are observed in Scenarios 2, 3 and 4 as a result of the increased part load operation of the power block.

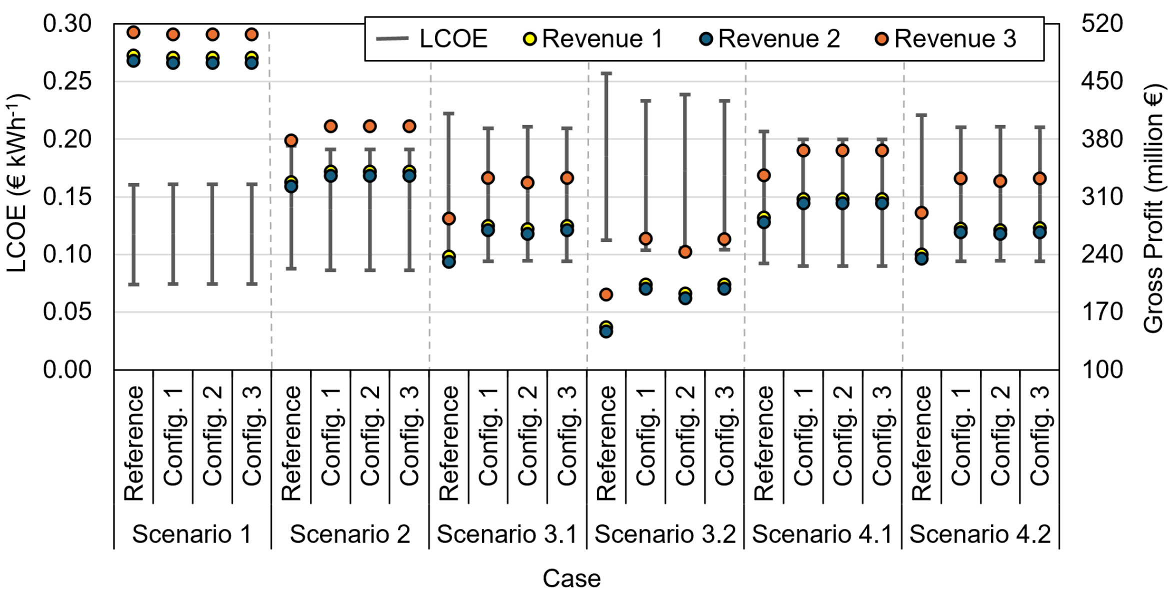

Figure 5. *The LCOE and gross profit of the CSP plant for different MSEH configurations, grid and revenue scenarios.*

Finally, as the improvements anticipated by the integration of MSEH are expected to contribute to the stable power block operation, the annual power block start-up behavior and operating hours are analyzed for different MSEH configurations and grid scenarios, as shown in Figure 6. As presented in Figure 6, the intermittent power block operation becomes increasingly pronounced with expanded renewable installations; the effect is most severe in Scenario 3.2 for the reference configuration, where the operating hours of the power block decrease by 21.6% with an increase of start-up instances by 248.0%, compared to Scenario 1. Accordingly, the benefit of the MSEH integration is most notably seen in Scenario 3.2, with Configuration 1, where the number of start-ups decreases by 84.56% and the operating hours increase by 41.40%, both compared to the reference case. Overall, the MSEH integration with Configurations 1 and 3 is consistently found to improve power block operation with enhanced operating hours and reduced start-ups, and concluded to be more favorable than Configuration 2 for stable power block operation. The inferior performance of Configuration 2 is attributed to the capacity of the hot tank and associated operation limitations, revealing the need for further analysis and more sophisticated operation strategies for Configuration 2.

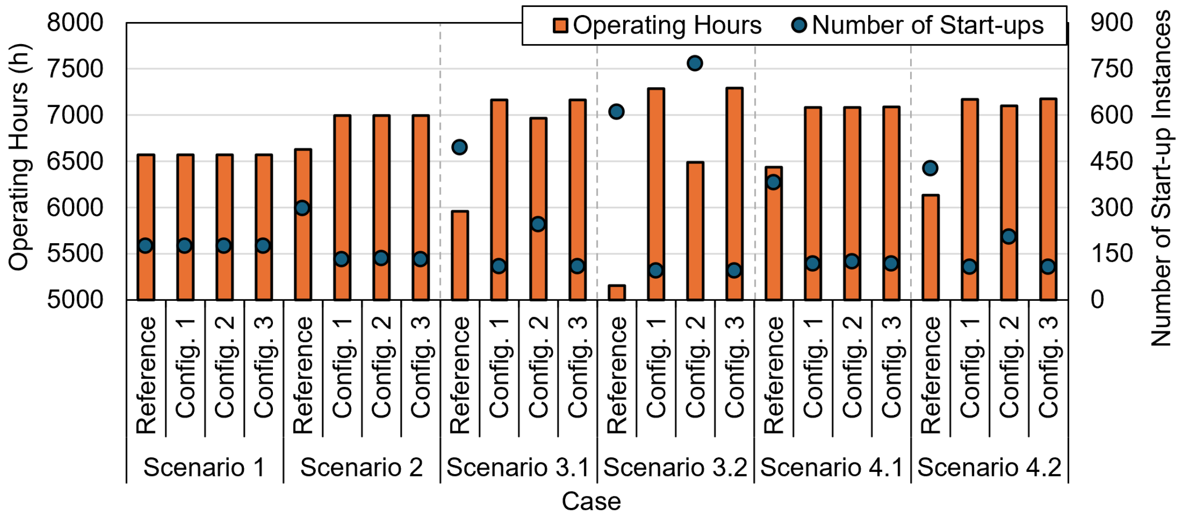

Figure 6. *The number of start-ups and operating hours for different MSEH configurations and grid scenarios.*

4. Conclusions

In this paper, three MSEH configurations proposed to decrease the minimum power output of CSP plants are analyzed with six different grid and three different revenue scenarios. It is demonstrated that the capacity factor is not a representative measure to evaluate the performance of load-following CSP plants; therefore, the demand coverage factor is introduced as a new metric. It is found that the MSEH integration increases the capacity factors and the demand coverage factor, and improves the economic performance of the CSP plant regardless of the integration scheme. Configuration 1, in parallel to the receiver, and Configuration 3, in series to the receiver, emerge as more favorable options than Configuration 2, in parallel to the hot tank, due to the superior flexibility improvements and techno-economic performance of the CSP plant. As the final remark, it should be noted that the design and operational aspects of MSEH integration remain unaddressed in this paper and require further analysis.

Data availability statement

The data supporting the findings of this study are available from the corresponding author upon request.

Author contributions

Eylül Gedik: Conceptualization, Methodology, Visualization, Writing - original draft, Writing – review & editing, Project administration; **Johannes Werner:** Methodology, Software, Formal analysis, Visualization, Writing – review & editing; **Manfred Wirsum:** Supervision, Funding acquisition.

Competing interests

The authors declare no competing interests.

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