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COMPARATIVE TECHNO-ECONOMIC ANALYSIS OF MOLTEN SALT VERSUS PARTICLE-BASED HYBRID PV-CSP PLANTS WITH ELECTRIC HEATERS AND SCO_2 POWER BLOCKS

Salvatore Guccione[1*], and Rafael Guedez[1]

[1] Department of Energy Technology, KTH Royal Institute of Technology, 100 44, Stockholm, Sweden.
E-mail: guccione@kth.se

Summary

This work presents a techno-economic comparison between two advanced hybrid PV-CSP systems integrating supercritical CO_2 (sCO_2) power cycles: one based on molten salt and the other on solid particles. Both use electric heaters to store excess PV electricity as thermal energy in CSP storage, enhancing system flexibility and dispatchability. The molten salt system operates at a maximum temperatures of 565 °C using a simple recuperated sCO_2 Brayton cycle, while the particle-based system reaches temperatures up to 780 °C and employs optimized sCO_2 layouts with recompression and intercooling. Optimization targets minimizing the levelized cost of electricity (LCOE), with additional KPIs including energy yield, and capacity factor. Results show that hybridization reduces LCOE by up to 14% for molten salt and 15% for particles compared to standalone CSP. PV-TES and hybrid systems significantly outperform PV-BESS at higher capacity factors, showing the role of thermal storage and efficient power blocks in cost-effective renewable energy.

Keywords: CSP, PV, Modeling Tool, Techno-economic Optimization

1. Introduction

The added value of the Concentrating Solar Power technology is the integration of a Thermal Energy Storage (TES) that increases the system stability, dispatchability, and the duration of energy output. Hybridization of CSP with PV has gained market traction and interest provided by the rapid decline of costs in PV installations, the need for storage in the system, and the geographical conditions compatibility for both technologies. Depending on the hybridization strategy, the costs of a hybrid CSP-PV facility could be 25% lower than an equivalent-sized CSP-only plant. Other hybrid configurations could be destined towards integrating PV for enhancing the firmness and capacity factor of the CSP plant (Zurita et al., 2018). In this context, the development of highly efficient and reliable electric heaters represents a stepping-stone toward more competitive CSP-PV hybrid systems, leveraging all existing benefits but further enabling other flexibility aspects. The integration of a compact and high efficient supercritical CO_2 (sCO_2) power block can boost the CSP deployment by increasing the overall thermal efficiency driving toward lower costs of electricity production. Most conclude that sCO2 cycles can indeed enhance the overall performance of CSP plants, particularly when considering more complex power block layouts operating at Turbine Inlet Temperatures (TITs) of 700 °C. New heat transfer fluids (HTFs) and TES media, among which solid particles are often proposed to reach such operating conditions. The present work proposed a techno-economic comparison between a molten salt-based hybrid PV-CSP plant with a sCO2 cycle and a novel particle-driven CSP plant with a direct TES and a sCO_2 power block actively hybridized with a state-of-the-art PV plant.

2. Methodology

The proposed layouts for the hybrid PV-CSP plant in this study are shown in Figure 1. The layout utilizing molten salt is illustrated in Figure 1 (left), while the particle-based layout is displayed in Figure 1 (right). The CSP plant comprises a direct two-tank TES and a sCO_2 power block, actively hybridized with a state-of-the-art PV plant through the utilization of an electric heater. The heater is placed parallel to the solar receiver so that it allows storing the electricity produced in excess by the PV field as thermal energy in the cost-effective

CSP storage. Considering its flexibility, fast response, and low cost, the electric heater could also be exploited with possible hybridization with the grid, allowing a smart and bilateral interconnection between the grid and the solar power plant. On the molten salt side the maximum receiver and electric heater operating temperatures is equal to 565 °C, thus the maximum TIT at the design point has been set to 565 °C. A simple recuperated Brayton cycle with dry cooling has been considered as the sCO_2 power cycle for the molten salt system. For the particle system, the HTF operating temperatures range between 600 and 800 °C (González-portillo et al., 2021), guaranteeing a TIT of 780 °C. Thus, an optimization on the sCO2 cycle layout has been performed to select the most suitable layout among eight different power block configurations. These layouts have been outlined modifying the simple recuperated sCO_2 Brayton cycle, including intercooling, reheating, and recompression. The techno-economic performance of the hybrid solar plants have been assessed by using MoSES (Modeling of Sustainable Energy Systems), a Python-based tool developed in KTH, coupled with a CoolProp environment (Bell et al., 2014) and the NREL-PySAM wrapper for System Advisor Model (SAM) (Gilman et al., 2019). Figure 2 shows the methodology flowchart. The design of the plant had been defined as solving an optimization problem aiming at minimizing the LCOE of the plant.

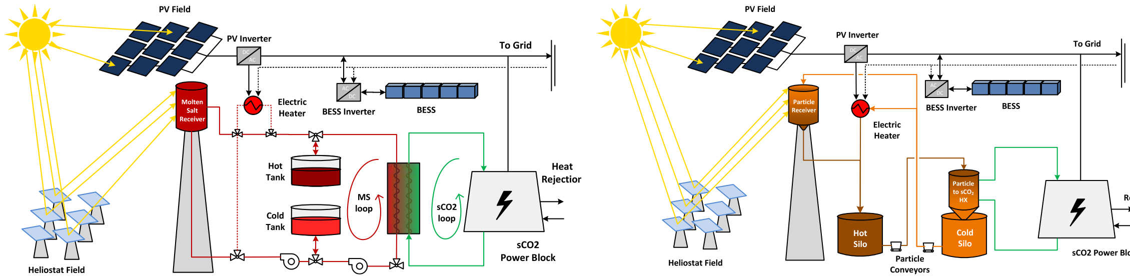

Figure 1: Schematic of the analyzed hybrid PV-CSP power plant

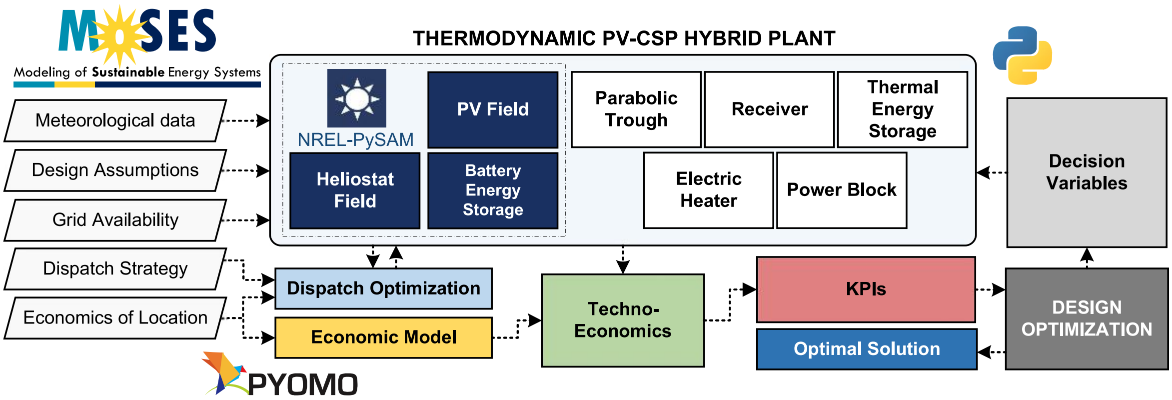

Figure 2: Methodology flowchart

Other key performance indicators are the Annual Energy Yield (AEY) and the share of PV and CSP, efficiency, Utilization Factor (UF), and the Capacity Factor (CF) in the different operation modes that were analyzed. The techno-economic indicators have been evaluated by coupling the thermodynamic performance - assessed by developing a quasi-steady-state model - with the economic model based on a bottom-up estimation method. The PV-CSP share of the installed capacity has been considered part of the optimization problem, as well as the solar multiple (1 - 3), and the TES hours (6 – 16 h). The hybrid solar plant has been optimized for a CSP capacity of 100 MWe, for a good solar resource in Europe (Evora, Portugal - 1800 kWh/m^2-yr).

3. Techno-economic optimization results

The preliminary results for the hybrid CSP-PV plant are presented in this section. Figure 3 shows Pareto-front resulting from minimizing the LCOE (on the y-axis) and maximizing the hybrid capacity factor (on the x-axis). Figure 3 (left) shows the results for the molten salt-based system, and it is possible to highlight that the hybrid PV-CSP plant with sCO_2 power cycle led to a 14% decrease in LCOE compared to the state-of-the-art standalone CSP system. Figure 3 shows that PV driven solutions (PV-BESS or Hybrid PV-CSP with SM = 0) prove to be the most suitable for CF below 60%. The value of CSP hybridization is emphasized as it provides greater dispatchability and serves as a more cost-effective alternative to achieve higher CF, extending up to

85%. Also noticeably, the best PV-only configurations were those consisting of PV coupled with TES options using electric heaters. This further underscores the value of TES as a standalone component. PV-only and PV-BESS alternatives (represented by the black dashed line) are economically viable choices only up to CFs below 35%, which corresponds to around 3–4 h of storage duration. Considering a particle-driven hybrid system, similar trends are obtained when adopting a sCO2 power cycle with recompression and intercooling. The LCOE values populating the Pareto front are shifted down by 15%, representing a more cost-competitive solution. However, a sensitivity on the cost assumptions will follow to discuss more in detail the preliminary results proposed.

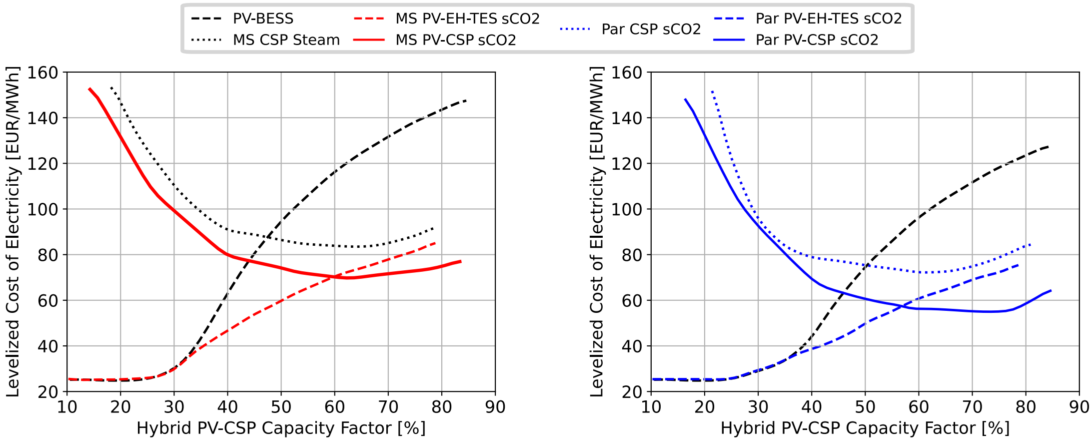

Figure 3: Comparative analysis for a solar power plant (left) molten salt-based and (right) particle-based

4. References

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