Hybrid PV-CSP-sCO_2 Plant based on Molten Salt Parabolic Trough with Energy Storage and Electric Heater System – A Techno-economic analysis

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1. Introduction

Concentrating Solar Power (CSP) plants represent a promising technology for decarbonizing the electricity grid due to their ability to integrate cost-effective thermal energy storage (TES) [1]. The development of this technology is limited mainly because its Levelized Cost of Electricity (LCOE) is still higher compared to other energy sources [2]. On one hand, the sCO_2 cycle has been identified as the leading power block candidate to lower the LCOE of CSP systems due to the higher thermal efficiencies and compactness compared to traditional steam Rankine cycles [3]. On the other hand, hybrid systems including connection with solar photovoltaic (PV) have been identified as a viable solution to reduce the LCOE of CSP plants while maintaining the flexibility and high-capacity factors granted by the TES unit. The costs of a hybrid CSP-PV facility could be 25% lower than an equivalent-sized CSP-only plant [4], [5]. 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 present work aims to introduce and assess the techno-economic potential of a novel molten salt-driven parabolic trough CSP plant with a direct TES and a sCO_2 power block actively hybridized with a state-of-the-art PV plant.

2. System Description

The introduced hybrid PV-CSP plant scheme is presented in Figure 1. The plant under investigation is characterized by a state-of-the-art PV plant hybridized with a molten salt-driven parabolic through CSP plant with a two-tank TES system and a simple recuperated sCO_2 Brayton power cycle. In the CSP plant, molten salt flows in the Solar Collector Assemblies (SCAs) to extract the power collected by the solar field with operating temperatures ranging between 295 and 565 °C. The molten salts are directly stored in a two-tanks TES. Electric heat tracing is considered the main freeze protection system so that the molten salts stay above the solidification point during low irradiance periods. The TES decouples the sCO_2 power block electricity production from the intermittent solar-based heat production. During the discharge phase, the molten salts flow in a molten salt-to-sCO2 heat exchanger, guaranteeing a Turbine Inlet Temperature (TIT) of 550 °C. The hybridization between the two plants is realized by employing a molten salt electrical heater that allows storing the electricity produced in excess by the PV field as thermal energy. The electric heater can be placed both in parallel to the solar field - bypassing the solar field - or in series - to boost the receiver outlet temperature. The control strategy has been outlined based on two main constraints: the non-dispatchable PV production is always prioritized, and the maximum power that can be injected into the grid is equal to the power block capacity ($P_{max} = P_{CSP}$). If the electric power produced by the PV plant is above P_{max}, the excess electric power is used to charge the TES through the electric heater and the sCO_2 power block is in stand-by mode. Otherwise, the power block is operated to compensate for the gap between the maximum power and the PV production. The control logic adopted to manage the hybrid solar power plant depends on the actual DNI, the TES state of charge (SOC), and the PV production.

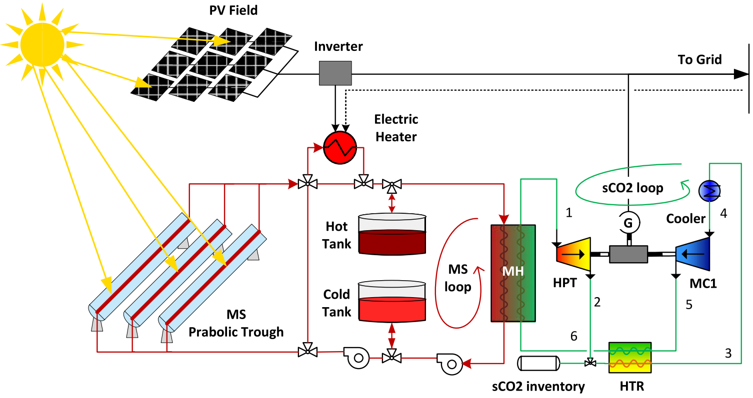

Figure 1: Layout schematic of the hybrid PV-CSP power plant.

3. Methodology

The techno-economic performance of the hybrid solar plant has been analyzed by using MoSES (Modeling of Solar Energy Systems), a new tool developed in KTH. MoSES is Python-based, coupled with a CoolProp environment and the NREL-PySAM wrapper for System Advisor Model (SAM). 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 design of the plant had been defined as solving an optimization problem aiming at minimizing the LCOE and the CAPEX of the plant. The analysis focuses mainly on the hybridization between the two plants. The electric heater utilization modes, in series or parallel to the solar field has been considered part of the optimization problem, as well as the PV-CSP share of the installed capacity. Capacity Factor (CF) and the PV and CSP share of the Annual Energy Yield (AEY) have been adopted as auxiliary key performance indicators. First, the hybrid solar plant has been optimized for a European good solar resource location (Evora, Portugal) and considering a CSP capacity of 100 MWe. Then, the impact of the scale has been investigated by adopting a CSP capacity of 10 MWe.

3. Results

In this section, the preliminary results for the studied hybrid CSP-PV plant are presented. Figure 2 shows the LCOE and the CF for different PV/CSP capacity ratios and two different scales (10 and 100 MW_e). The integration of sCO_2 power blocks and the active hybridization with PV make CSP cost-competitive both at large (<70 EUR/MWh) and small scales (< 90 EUR/MWh). Figure 2 shows that the PV/CSP ratio that minimizes the LCOE of the plant ranges from 1.3 to 2 at a large scale, showing that the largest PV/CSP ratios lead to the highest CFs (>70 %), with a slight increase in the LCOE. On the other side, the smallest PV/CSP ratios lead to relatively low CFs and high LCOEs. At a small scale, the optimal configurations are characterized by large gaps between the PV and CSP capacities (PV/CSP>2.3). Similarly, Figure 3 shows the LCOE and CF as a function of the CSP fraction of AEY for the two different sizes under investigation. The optimal systems are characterized by CSP shares higher than 50 %, both for large- and small-scale systems, showing that the energy production of such hybrid plants is driven by the CSP. This emphasizes the importance of this active hybridization, in which the excess PV production contributes to the CSP electricity production. Low-cost PV systems make CSP more cost-competitive, but the dispatchability of CSP allows reaching high CFs and firm production.

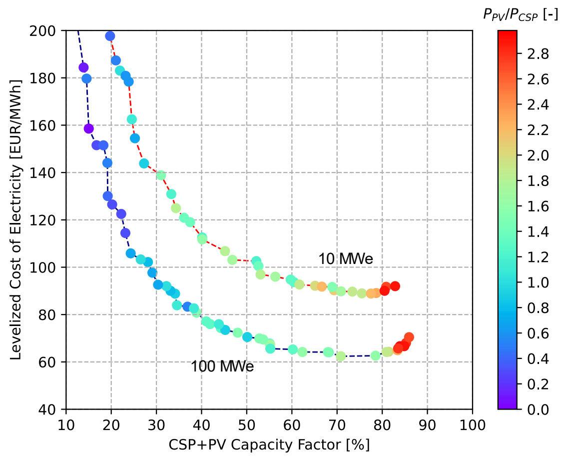

Figure 2: LCOE and CF as a function of the scale and the PV-CSP capacity ratio

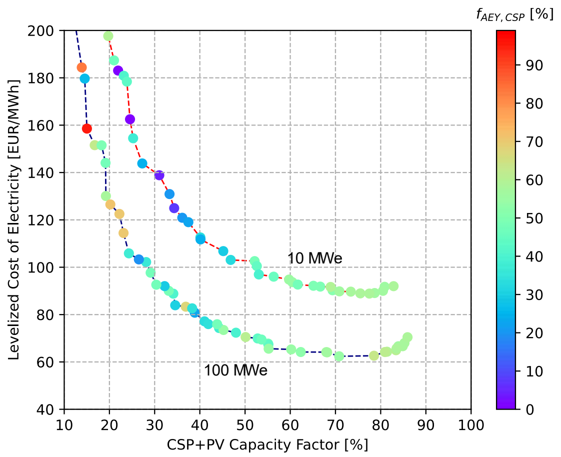

Figure 3: LCOE and CF as a function of the scale and the PV-CSP electricity production ratio

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