SolarPACES 2024, 30th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Analysis and Simulation of CSP and Hybridized Systems

https://doi.org/10.52825/solarpaces.v3i.2313

Published: 25 Nov. 2025

Optimal Design of Hybrid Solar Power Systems: A Case Study in the Chinese Market

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Abstract. The global energy industry is shifting towards a net-zero energy system to achieve climate neutrality, leading to significant growth in distributed renewable energy generation. This reshapes market dynamics and presents challenges in balancing supply and demand, increasing the risk of midday oversupply and variability in renewable generation, potentially compromising grid reliability. Concentrated solar power (CSP) offers a viable solution for grid decarbonization by integrating large-scale renewables and providing ancillary services like peak shaving and load shifting, frequency control, and energy storage, complementing the intermittent supply of photovoltaics (PV). The synergy between low-cost PV and dispatchable CSP fosters a resilient and sustainable system. Demonstration projects, especially in China, emphasize the relevance of hybrid CSP systems. CSP plants are built alongside large-scale PV installations to address the growing challenges associated with the electrical grid. The study explores hybridizing high-performance collectors, specifically Ultimate Trough (UT) collectors using molten salt as a heat transfer fluid, with PV to identify optimal solar field sizing and operational strategies. The techno-economic optimization framework integrates in-house cost models with thermodynamic and optical models derived from the System Advisor Model (SAM). A case study in Shichengzi, China, evaluates a hybrid CSP + PV plant with integrated thermal storage. High-performance collectors and better synergy in UT and PV production profiles lead to a 17% and 35% reduction in the power purchase agreement (PPA) price compared to conventional large aperture troughs not optimized for molten salt operation and linear Fresnel devices. This research supports informed decision-making and design solutions for sustainable and economically viable renewable energy production.

Keywords: Concentrated Solar Power (CSP), Photovoltaic (PV), Hybrid Solar Power, Ultimate Trough, Molten Salt, Techno-Economic Optimization

1. Introduction

Solar energy is the largest energy source on Earth [1]. Yet, its intermittent nature challenges its contribution to the energy mix by making it difficult to match supply and demand [2], [3]. Advanced infrastructure is necessary to transport electricity from regions with abundant solar and wind resources to those with less favorable meteorological conditions. The ‘duck curve’ highlights the need for rapid adjustments in power generation due to steep ramps in residual load [4], [5]. This ‘duck curve’ through contribution of solar photovoltaic (PV) recently developed into the ‘canyon curve’ what even made the conditions tougher. The International Energy Agency (IEA) forecasts that the proportion of curtailed energy from PV and wind is rising as the share of variable renewable energy (VRE) sources increases across multiple markets [6]. This trend is particularly evident when investments in grid infrastructure do not keep up with the expansion of VRE capacity. Boosting solar energy penetration makes it necessary to increase the reliability and dispatchability of energy production.

Energy storage helps by shifting production to times of the day when the demand is peaking and VRE is limited. Concentrated solar power (CSP) with an integrated thermal energy storage system (TES) can play that role in the transition to a net-zero energy system because of its complementarity with PV [7]. Low-cost PV produces electricity during the day, while CSP can provide dispatchable electricity to meet the demand whenever the sun is not shining [8]. Hybrid operation of these technologies leads to cost-effective and firm electricity production, reducing PV-curtailed electricity [9].

Hybrid plants are being realized worldwide to explore optimal PV-to-CSP capacity ratios and address operational challenges linked with hybrid systems [10]. China is the primary geographical focus due to its significant increase in solar and wind penetration [11]. Similar trends are expected in Europe and the Middle East and North Africa (MENA) region, where the share of VRE is also growing [12], [13]. IEA forecasts that CSP will provide approximately 11% of the electricity mix in 2050 [14]. Currently, parabolic trough collectors (PTCs) are the most mature CSP technology on the market, constituting almost 77% of total CSP installations [11]. However, solar power tower (SPT) systems have emerged as a global technological trend, rapidly increasing their installed capacity, currently making up 65% of Chinese CSP projects [11]. Cost reductions are driven by high-efficiency solar fields and industrialization. To bridge the gap between PTC and SPT technologies, factors such as large aperture areas and employing molten salt as a heat transfer fluid (HTF) are essential for PTCs.

This study investigates the optimal design of hybrid CSP + PV + TES systems to minimize the power purchase agreement (PPA) price under a time-of-delivery (TOD) tariff structure. The optimal system design, using high-efficiency trough technology, such as Ultimate Trough (UT) collectors [15], is compared to conventional large aperture trough (LAT) not optimized for molten salt operation and linear Fresnel (LF) collectors. The modeling framework includes a CSP plant with UT collectors operating with molten salt, connected to a molten salt TES and a power block, a PV field, and an electric heater to heat the salt in the TES. The thermodynamic models of the modules are based on the System Advisor model (SAM) developed by the National Renewable Energy Laboratory (NREL). The optimization framework and the technology interactions within the hybrid system are implemented in a Python environment. A schematic of the optimization framework is given in **Figure 1**.

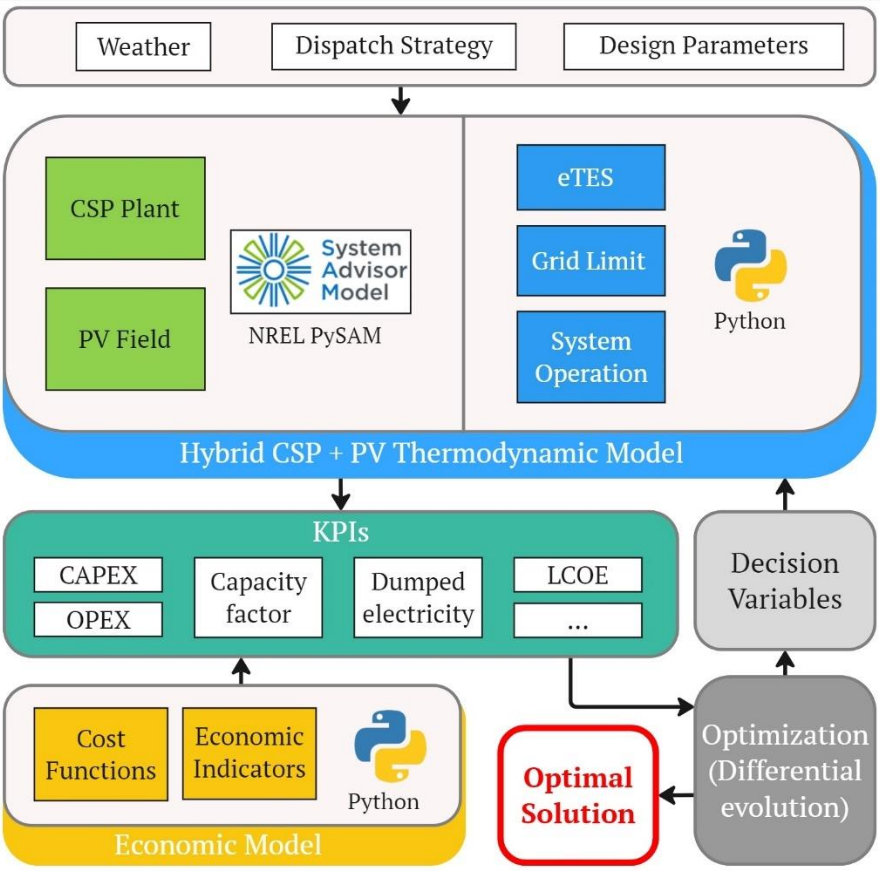

Figure 1. *Schematic of the optimization framework used in this study.*

The current case study for Shichengzi, China—an existing site for hybrid CSP and PV systems - analyzes the outcomes of the technology comparison. The main results and key findings are as follows:

- The optimal UT + PV plant design reduces PV dumped electricity by up to 19% compared to alternative line-focusing CSP technologies, while maintaining a capacity factor greater than 75%.
- UT technology combined with PV reduces PPA price by 35% compared to LF collectors, despite having 16% higher specific investment costs per aperture area.
- Employing high-efficiency collectors optimized for molten salt operation (UT) reduces aperture area by 7% compared to large aperture troughs and by 50% compared to linear Fresnel devices.

2. Methodology

2.1 Modeling framework

The hybrid power plant comprises various modules. The reference solar field in the CSP plant features UT collectors. These collectors use parabolic-shaped mirrors to focus direct normal irradiance (DNI) onto a tubular receiver with an outer diameter of 70 mm. These absorbers heat the HTF (molten Hitec Salt: 60% $NaNO_3$ and 40% KNO_3) to approximately 530 °C. The thermal power carried by the HTF is stored in the TES. Additionally, the PV field generates electricity, which is first used to cover the CSP parasitics, and then can either be injected into the grid or used to increase the heat stored in the TES via electrical heaters (eTES). A power block converts heat into electricity through a Rankine cycle. In the alternative scenarios, the

UT field is replaced by various collector technologies. Specifically, LATs not optimized for molten salt operation using an 88.9 mm receiver and LF collectors are considered. A schematic of the system is presented in **Figure 2**.

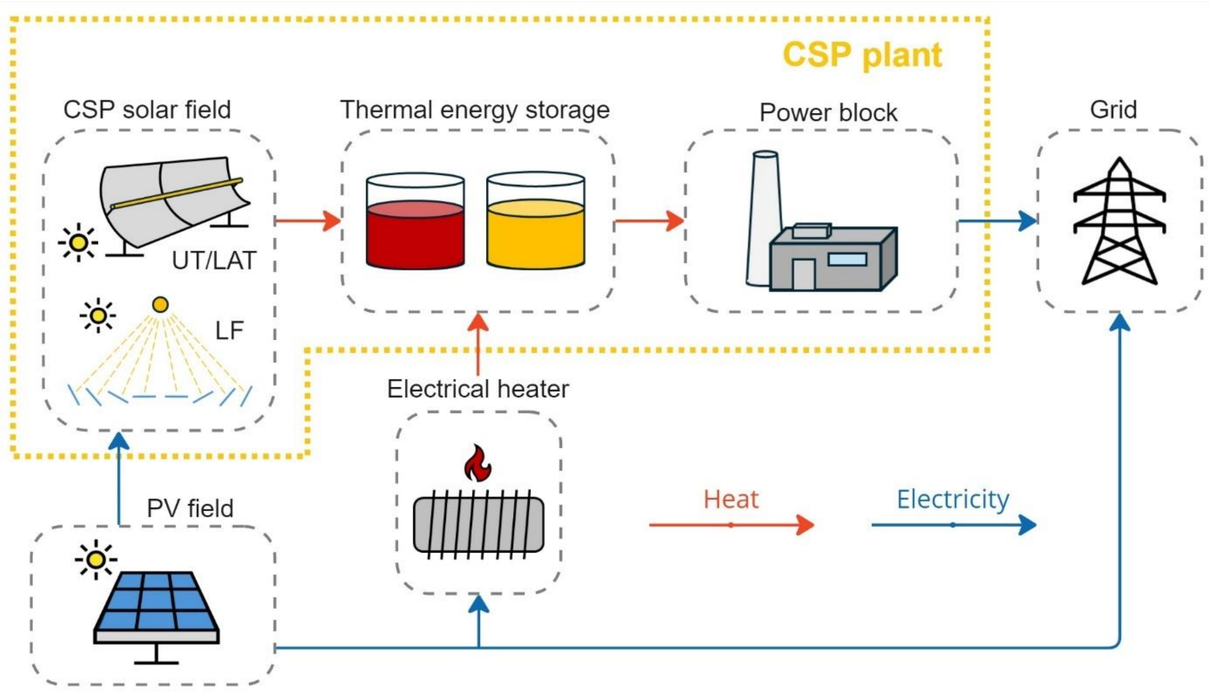

Figure 2. *Schematic of the modeling framework used in this study. The arrows represent energy flows.*

The main modeling assumptions are:

- Dynamic model formulation, accounting for transient fluctuations in the thermal resource.
- A grid limit enforces an upper bound on the electricity that can be accepted by the grid.
- The dispatch strategy for the CSP plant is optimized to leverage the TOD tariff structure, with the minimum turbine operation set at 20% of its nominal power to ensure rapid electricity dispatch when needed.
- Electricity is curtailed whenever the PV-generated electricity cannot be injected into the grid due to reaching the grid's capacity limit, nor stored via eTES because the TES is full or the electricity exceeds the heater's rated power.
- CAPEX and OPEX cost functions for the CSP plant components are based on in-house cost models, and scale with capacity according to concave functions.
- CAPEX for the PV system is based on in-house cost models, and scales with capacity according to a concave function.
- OPEX for the PV system scales linearly with the investment cost.

These assumptions introduce specific limitations to the modeling, and therefore, should be applied within a similar context. The model uses hourly discretization, as the purpose of the work is to provide high-level sizing information about the system. This approach could reduce the precision of the results and potentially yield suboptimal outcomes regarding the interaction between components in the hybrid system. While a finer discretization would produce more precise results, it would also require a greater computational effort.

A case study was conducted for Shichengzi, Xinjiang, China, to compare different CSP technologies in combination with a single-axis tracking PV, oriented North-South. The coordinates of the location are 40°30'0"N latitude and 91°5'60"E longitude. The annual DNI and GHI at the site are approximately 1830 kWh/m^2 and 1780 kWh/m^2, respectively. This location was selected because Xinjiang has the highest number of CSP plants under construction or planned in China at the end of 2023 [11]. The CSP plant has a fixed rated power of 100 MWe, a typical capacity in the market.

2.2 Optimization framework

The optimization problem is formulated as a nonlinear program (NLP). The objective function is the power purchase agreement (PPA) price [€/kWh] required to achieve a desired internal rate of return (IRR), calculated as the sum of the annualized CAPEX [€/y] and the OPEX [€/y], divided by the annual electricity production [kWh/y] scaled according to the TOD factors, as presented in Equation (1). This formulation assumes that the off-taker pays varying PPA prices based on the timing of electricity delivery. This approach is designed to reflect the dynamics of a grid with a high share of intermittent solar energy sources, as shown in **Figure 3**. By implementing TOD pricing, the power plant is incentivized to produce more electricity during high-demand periods, thereby contributing to grid stability and ensuring a reliable electricity supply. The fixed-charge rate (FCR), equal to 8.2%, annualizes the capital costs based on the weighted average cost of capital r = 6.5% and the lifetime of the system n = 25, as shown in Equation (2). The set of hourly time steps is denoted by $\mathbf{T}$, while $\mathbf{U}$ denotes the set of modules. The non-linearities come from the concavity of the cost functions and the performance equations in SAM.

$$\mathrm{PPA} = \frac{\mathrm{FCR} \cdot \sum_{u \in \mathbf{U}} \mathrm{CAPEX}_u \; + \; \sum_{u \in \mathbf{U}} \mathrm{OPEX}_u}{\sum_{t \in \mathbf{T}} \mathrm{E}_t \cdot \mathrm{TOD}_t} \quad (1)$$

$$\mathrm{FCR} = \frac{r \cdot (1+r)^n}{(1+r)^n - 1} \quad (2)$$

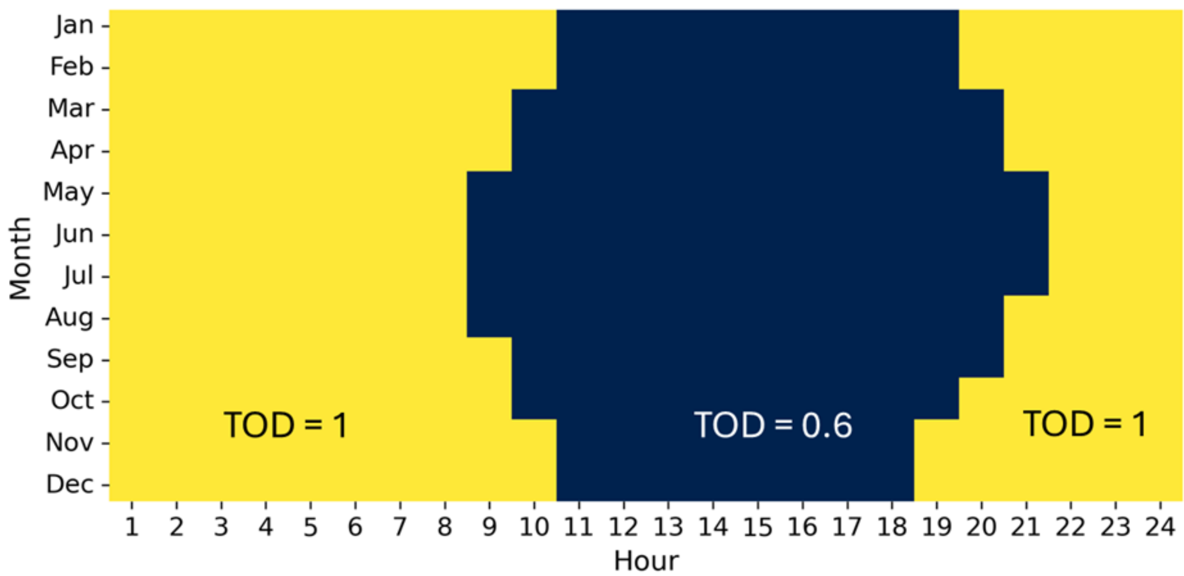

Figure 3. *TOD factors considered in the present study. The value of electricity injected into the grid at night is higher compared to that injected at midday, reflecting a grid with a high penetration of intermittent solar energy sources.*

The decision variables of the optimization problem are:

- Technology sizes, in terms of installed capacity, including the PV field peak power, the CSP solar field aperture area, the full load hours of TES, and the rated power of the electrical heater.

Other main calculated key performance indicators (KPIs) are:

- Total annualized cost (TAC), along with CAPEX and OPEX, and their breakdowns.
- Curtailed electricity.
- Hybrid system production profile.
- Hybrid system capacity factor (CF), defined as the sum of the useful CSP and PV net electricity production divided by the maximum electricity that can be injected into the grid:

$$\mathrm{CF} = \frac{\sum_{t\in\mathbf{T}}\left(\mathrm{E}_{\mathrm{CSP},t} + \mathrm{E}_{\mathrm{PV},t} - \mathrm{E}_{\mathrm{curtailed},t}\right)}{\sum_{t\in\mathbf{T}} \mathrm{E}_{\mathrm{load},t}} \tag{3}$$

The main model parameters are:

- Parameters related to the case study location, including latitude, longitude, elevation, and weather data.
- Grid limit of the case study location.
- TOD factors, used to account for the lower value of energy during low-demand hours and the higher value during peak demand periods.
- Dispatch strategy of CSP plant, defining the turbine output fraction at each time step.
- Parameters related to the thermal and optical properties of the technologies, including efficiencies and operating temperatures.
- Parameters related to system economics, including debt and equity fractions, loan rate, and desired IRR, needed to calculate the weighted average cost of capital.
- Lifetime of the system.

Notably, the dispatch strategy of the CSP plant prioritizes heat storage during the day and its delivery at night. Including the hourly dispatch as part of the decision variables would enhance the results by allowing the CSP to adjust the production profile for different days, thus optimizing performance. The optimization problem is solved using a differential evolution algorithm [16] due to its robustness and effectiveness in handling non-linearities.

3. Results

The annual electricity demand, defined by the load curve, is approximately 970 GWh. To ensure consistent production throughout the year and enhance the complementarity between PV and PTC production curves, the CSP solar field is oriented in the East-West direction. The maximum power that can be injected into the grid is limited to the maximum net power deliverable by the power block. This maximum is defined as the nominal power of the power block plus the maximum parasitic losses supplied by the PV field. An optimization run is performed on the system featuring UT collectors, and the sizes of the LAT and LF solar fields are scaled to match the same electricity production. The optimal hybrid system features a UT solar field aperture area of 1.05 km² and an integrated TES providing 14 full load hours of storage. The optimal PV field size is 260 MWac, and the electrical heater's rated power is 130 MWe. The required solar field areas to produce the same annual CSP electricity are 1.12 km² for LAT collectors and 2.10 km² for LF collectors. The design DNI of the CSP solar field is set as 900 W/m².

The TAC comparison for the CSP plant is shown in **Figure 4**, relative to UT values. For the same CSP annual electricity production, the TAC of UT collectors is significantly lower than LAT and LF collectors, with reductions of 23% and 34%, respectively. This occurs despite the specific cost per aperture area of the UT field being higher than that of the LF field, due to the UT collectors' higher optical and thermal efficiency. Specifically, the high intercept factor of UT

(97%) and the optimization of the heat collecting element (HCE) diameter for molten salt operation (reduced to 70 mm) contribute to these efficiencies. In all three scenarios, the solar field causes the primary costs. LF results in a similar CAPEX to LAT. This underscores the importance of optimizing collectors for molten salt operation, as the LAT experiences substantial thermal losses. However, the OPEX of the LF is considerably higher than that of the LAT due to the significantly larger aperture area required to produce the same amount of electricity.

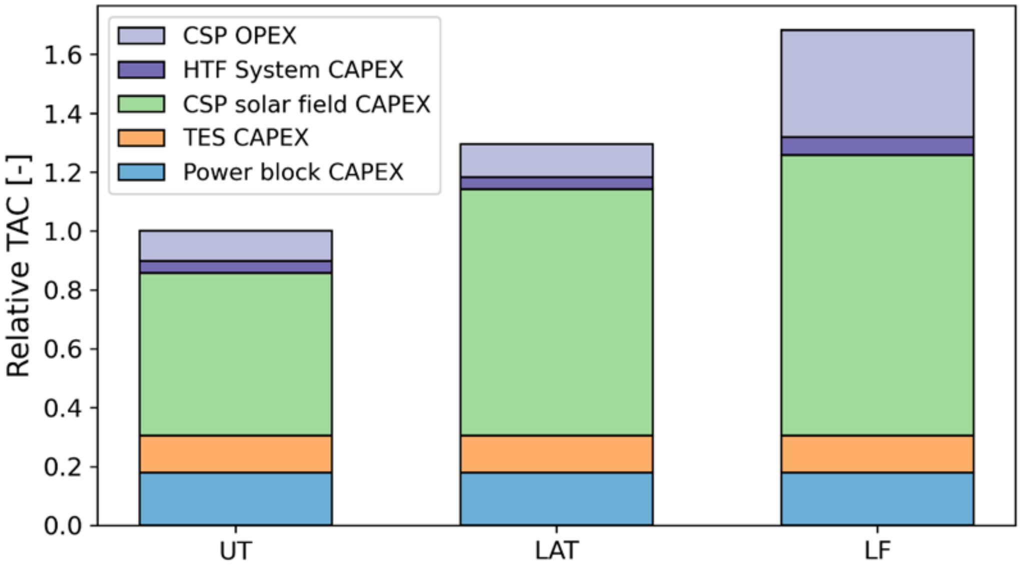

Figure 4. *TAC comparison for CSP variants delivering the same annual electricity, relative to UT.*

Figure 5 illustrates the breakdown of the monthly net electricity production from the power block and the PV field in the UT + PV hybrid configuration. PV low-cost electricity is directly injected into the grid whenever the sun is shining and partially stored for later use via eTES, minimizing dumped electricity. During the night hours or on low-irradiance days, the TES delivers thermal energy to the power block, ensuring a reliable supply. The integration of an electrical heater enhances the synergy between the technologies and allows the transfer of energy from the PV system to the TES. This strategy proves particularly effective during the winter months when the CSP solar field generates less thermal energy, allowing the TES capacity to be supplemented by electricity generated from the PV system. In the summer, while PV systems continue to contribute significantly by directly supplying electricity to the grid, CSP is prioritized for energy storage and subsequent use later in the day. The UT field offers better complementarity to the PV field in terms of production profile. The PV electricity curtailment is limited to the months between March and September, when the TES available capacity is lower. This results in a reduction of dumped electricity by up to 19%. Additionally, the high capacity factor (>75%) confirms the system's capability to maintain stable dispatch throughout the year, even under varying TOD conditions.

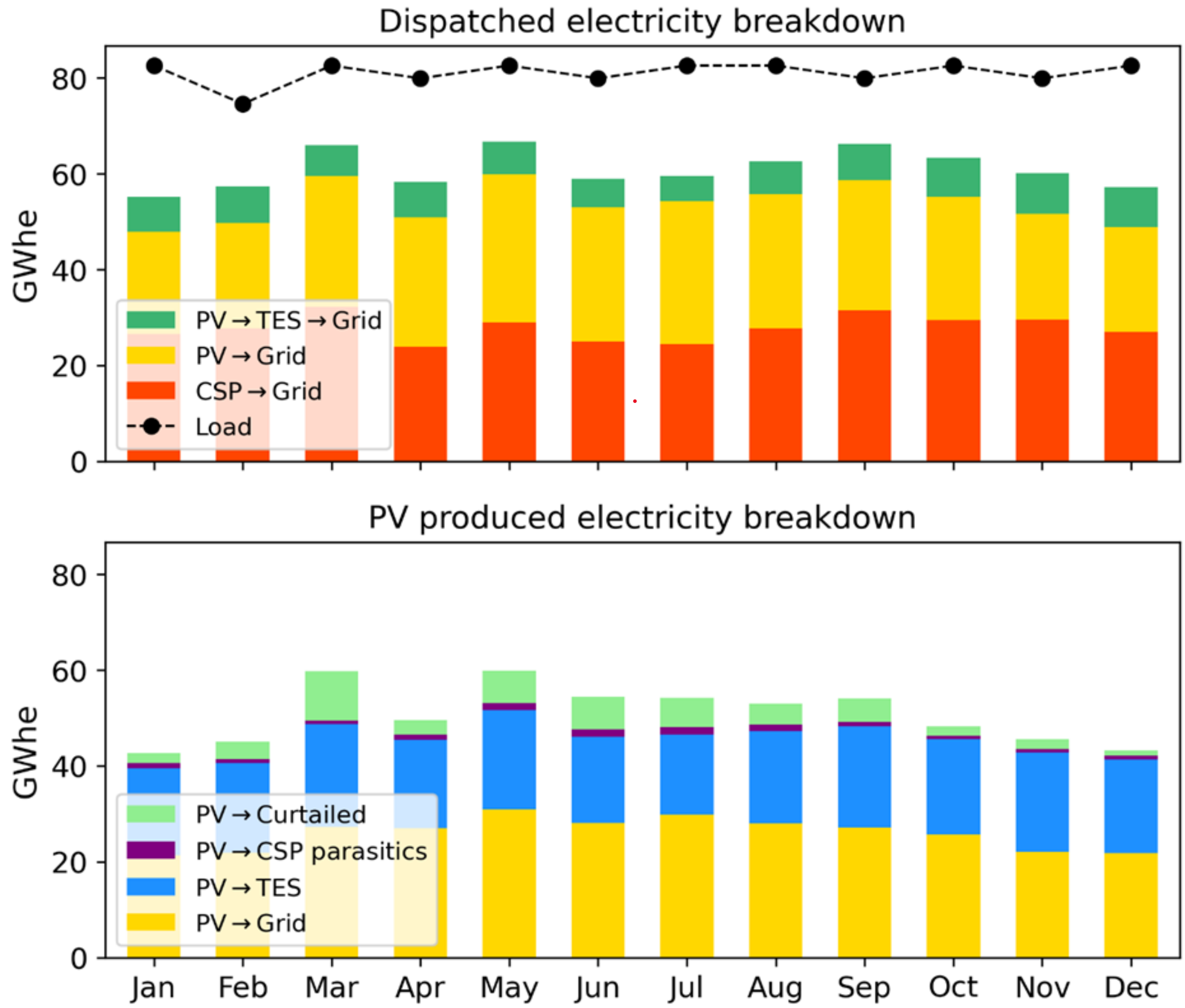

Figure 5. *Breakdown of monthly net electricity production for (a) overall hybrid system and (b) PV field in UT + PV hybrid configuration.*

4. Conclusions

This study investigated the performance of high-efficiency parabolic trough collectors, such as the Ultimate Trough (UT), which feature large apertures and use molten salt as the heat-transfer fluid, within a hybrid system configuration combined with photovoltaic (PV) technology. A comparison was conducted between conventional large aperture troughs (LATs), which are not optimized for molten salt operation, and linear Fresnel (LF) collectors. A case study in Shichengzi, China, demonstrated that the UT + PV scenario achieved a significant reduction in PPA price by 17% and 35% compared to the LAT + PV and LF + PV alternatives, respectively. This happens even if the specific investment cost per aperture area of UT is 16% higher than LF. The primary advantages of UT are its high optical and thermal efficiency, due to its high intercept factor of 97% and the optimization of the heat-collecting element diameter. These factors contribute to a production profile that is well-suited for combined operation with PV, thus reducing the amount of dumped electricity. This is a crucial necessity for a grid with an increasing share of intermittent renewables. Hence, this research facilitates informed decision-making regarding CSP and PV technologies, in a context where CSP's primary purpose is to stabilize the grid. Additionally, it provides design solutions considering the complex interactions between these technologies. This can contribute to sustainable, efficient, and economically viable renewable energy production.

Data availability statement

All the results in the paper are based on confidential data from commercial projects. This data was used for the development of the cost models as well as the modeling and optimization framework.

Author contributions

Gabriele Furlan: Data curation, Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Software, Conceptualization. **Axel Schweitzer:** Project administration, Writing – review & editing, Methodology, Investigation, Conceptualization. **Fabian Gross:** Project administration, Writing – review & editing, Methodology, Software, Investigation. **Alf Oschatz:** Project administration, Writing – review & editing, Resources.

Competing interests

The authors declare that they have no competing interests.

Funding

The study was internally funded.

Acknowledgement

We would like to acknowledge the National Renewable Energy Laboratory (NREL) for providing the System Advisor Model (SAM), which was instrumental in the analysis conducted in this study.

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