SolarPACES 2023, 29th 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.v2i.784

Published: 15 Oct. 2024

Analysis of CSP/PV Hybrid Power Plants in High Latitude Regions

José A. López-Álvarez [1], Miguel Larrañeta [1], Elena Pérez-Aparicio [1], Sara Moreno-Tejera [1], Manuel A. Silva-Pérez [1], and Isidoro Lillo-Bravo [1]

[1] Dpt. Of Energy Engineering, University of Seville. Spain

*Correspondence: López-Álvarez, José A., jlopez1@us.es

Abstract. This study aims to explore the potential of combined CSP and PV systems in high latitude areas. Several performance metrics are evaluated and compared with standalone CSP or PV plants to identify the benefits and challenges of deploying such hybrid plants. Six different sites have been selected and the ASDELSOL hybrid power plant simulation tool, developed by the Thermodynamics and Renewable Energies Group at the University of Seville, has been used. This simulation tool allows performing dynamic performance simulations of hybrid solar plants under various operation strategies, along with conducting economic evaluations. We have analyzed a hybrid solar plant composed of 50 MW PTC and 75 MW PV, with 10 hours of TES and a 15 MW electric heater to transfer excess PV energy to the TES tanks in a 50 MW base load operation strategy, where the main objective of the PV plant is to cover the self-consumption of the PTC plant. Results obtained show that PV/PTC hybridization reduces LCOE and increases CF compared to standalone PV or PTC plants. These improvements are more pronounced in regions where the contribution of PTC plants is lower. In high latitude regions, an N-S orientation of PTC fields achieves higher production than an E-W orientation. However, a combination of both orientations can optimize their production and performance. Finally, it is concluded that it is necessary to carry out feasibility studies in high latitude locations before dismissing them outright, as it has been observed that, in certain regions, hybrid PV/PTC solar plants can offer an effective alternative.

Keywords: Hybrid CSP/PV, Simulation Tool, Prefeasibility

1. Introduction

In recent decades, the growing concern about climate change and the need to reduce greenhouse gas emissions have driven the development and adoption of renewable energy technologies worldwide. The most significant case among all types of renewable energy is solar energy, with an increase in global installed capacity of 649.5 % since 2014 [1]. Traditionally, Concentrated Solar Power (CSP) plants have been located in regions with high levels of direct solar radiation, typically at low latitudes near the solar belt [2]. However, photovoltaic (PV) plants have been developed in a wider range of locations, as they take advantage of scattered sunlight (diffuse solar radiation) available, including higher latitudes and farther from the solar belt. As solar technology has matured and implementation costs have decreased, there has been a growing interest in exploring new frontiers for solar energy. In this regard, combined CSP and PV systems can be a promising solution to provide thermal storage capacity to these plants at a lower cost than batteries [3].

Higher latitude regions present unique challenges for solar energy generation due to their specific climatic characteristics. In these areas, the availability of direct solar radiation is lower and there are significant variations during the day and solar radiation throughout the year. Despite these challenges, the potential advantages of implementing hybrid CSP/PV plants at high latitudes are considerable. The combination of both technologies can leverage their strengths to achieve more stable and efficient electricity generation. The thermal generation of CSP plants can compensate for the inherent variability of PV generation since thermal energy stored in heat-transfer fluids (mainly molten salts) allows continuous electricity production even during hours of reduced solar radiation. At the same time, PV panels can contribute to electricity production during daylight hours with higher solar intensity, thereby enhancing efficiency and total production capacity of the hybrid plant at a lower cost.

This work will explore the advantages and challenges of implementing Parabolic Trough Collectors (PTC) and PV hybrid plants at high latitudes, highlighting their role in the transition towards a more sustainable energy system. Additionally, the performance of integrated PTC/PV hybrid plants in high latitude regions will be evaluated. To do this, we have selected five different locations and used the ASDELSOL hybrid power plant simulation tool developed by the Thermodynamics and Renewable Energies Group (GTER) at the University of Seville [4-5].

2. Methodology

This study aims to explore the potential of combined PTC and PV systems in regions with lower levels of solar radiation. By evaluating performance metrics and comparing them with standalone PTC or PV plants, we seek to determine the benefits and challenges of deploying such hybrid plants in high latitude areas. To achieve our goal, we carefully selected six locations for analysis, each representing distinct climatic conditions and solar irradiance levels. The ASDELSOL hybrid power plant simulation tool was used to carry out the study. In this section, we will detail the simulation parameters, the characteristics of the chosen locations, and the specific configurations of the integrated PTC/PV hybrid solar power plants.

2.1 Simulation Tool

The ASDELSOL hybrid power plant simulation tool allowed us to perform dynamic performance simulations of hybrid solar plants under various operation strategies, along with conducting economic evaluations. This tool uses a specific library to load a typical meteorological year (TMY), to determine the position of the sun as a function of the time of the year and the geographic coordinates of the considered location, and to calculate the Global Tilted Irradiation (GTI), a critical parameter for analyzing photovoltaic plants.

For PTC technology, ASDELSOL builds upon Solartherm [6], but incorporates a specific library for this technology and brings a different approach to define the thermal energy storage capacity based on equivalent storage hours.

For PV technology, ASDELSOL employs a mathematical model that realistically estimates energy production in PV systems, taking into account specific environmental factors, such as cell temperature and module efficiency. The tool enables the calculation of the power output of PV modules and the total power of the plant based on the number of modules.

To simulate the harnessing of excess energy from the PV plant, which cannot be fed back into the electrical grid at certain times, using electrical heaters, ASDELSOL also includes various libraries focused on the conversion of electrical energy to thermal energy as well as plant control.

2.2 Location Selection

In this study, six locations have been selected to implement a hybrid PTC/PV system. Each site has specific geographic characteristics and climatic conditions that influence the performance and efficiency of hybrid plants. Table 1 summarizes the main characteristics of these locations.

Table 1. *Main characteristics of the selected locations.*

Location	Latitude (º)	Longitude (º)	Köppen climate classification	Accumulated annual DNI (kWh/m^2)	Accumulated annual GHI (kWh/m^2)
Seville [7]	37.38	-5.97	Csa	2111	1847
Paris [8]	48.85	2.35	Cfb	1024	1162
Calgary [8]	51.05	-114.07	Dfc	1652	1337
Kennewick [8]	46.21	-119.12	BSk	1838	1535
Stockholm [8]	59.33	18.07	Dfb	1140	1013
Ushuaia [8]	-54.80	-68.30	ET	1050	1020

Each of these locations has been evaluated using the ASDELSOL tool. To better understand the variability and availability of solar resource, Figures 1 and 2 show the average hourly DNI and GHI for each hour and day of the year at the selected sites.

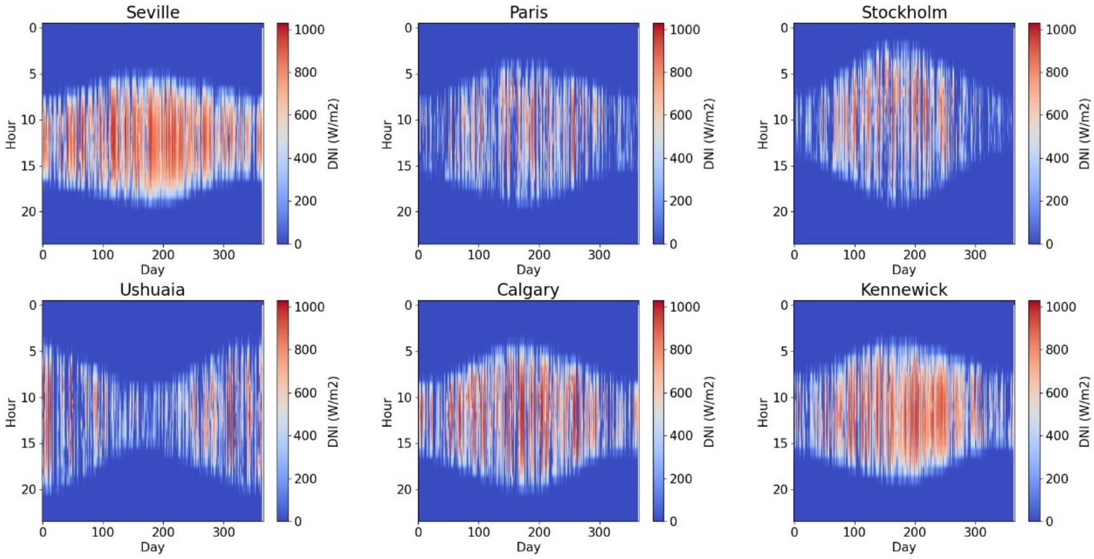

***Figure 1**. Average hourly DNI for each location.*

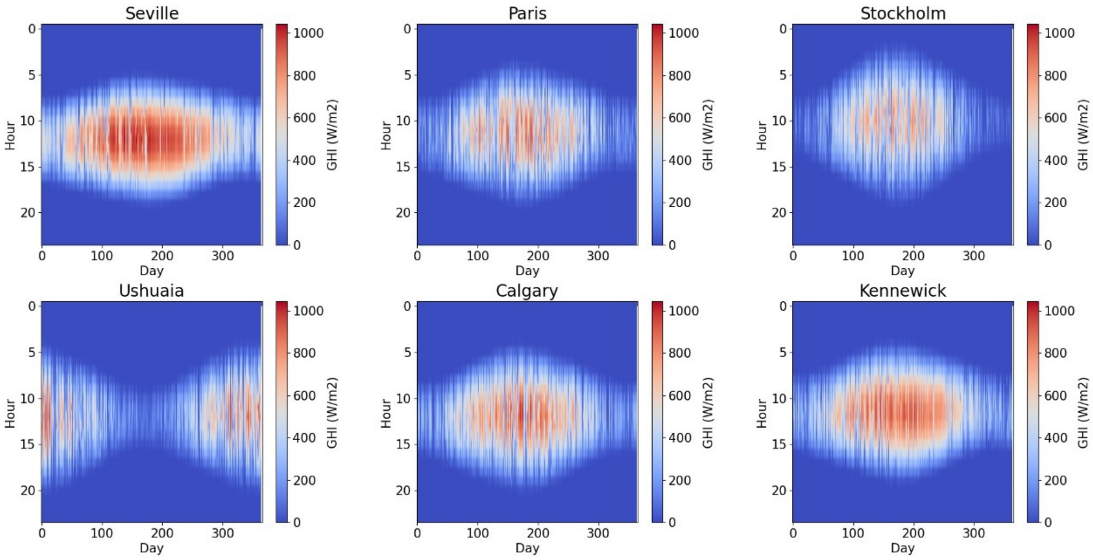

***Figure 2**. Average hourly GHI for each location.*

With this site selection and a comprehensive analysis of the solar resource available at each location, it will be possible to assess the expected performance and efficiency of PTC/PV hybrid plants. Additionally, specific challenges and opportunities related to the implementation of these systems in different latitudes and climatic conditions can be identified.

2.3 System Configuration

We have implemented a digital twin of a hybrid solar plant composed of 50 MW PTC and 75 MW PV, with 10 hours of Thermal Energy Storage (TES) and a 15 MW electric heater to transfer excess PV energy to the TES tanks in a 50 MW base load operation strategy, where the main objective of the PV plant is to cover the self-consumption of the PTC plant. Since the plants are located in high latitude regions, the analysis of east-west-orientated PTC plants will also be taken into account, in addition to the conventional north-south orientation used in most operational PTC plants.

The results of the plants operating in the selected locations will be compared with those operating in Seville, a well-known site for CSP plants with 11 PTC plants in operation [9]. Furthermore, we will compare a standalone 50 MW PV plant without BESS and a standalone 50 MW PTC plant with 10 hours of TES at each location to analyze the synergies of hybridizing solar thermal and photovoltaic technologies.

2.4 Key Performance Indicators (KPIs)

The analysis of the hybrid plant was based on the evaluation of several key performance indicators (KPIs). Two of the KPIs used were the Capacity Factor (CF) and the Levelized Cost of Electricity (LCOE). The CF provides a measure of efficiency by calculating the ratio of the generated energy to the maximum theoretical capacity of the plant over a given period. It is calculated as the annual energy yield divided by the maximum energy the hybrid plant can produce during the year with its nominal power of 50 MW. The LCOE is a financial indicator that allows for comparing the cost of electricity generated by the plant over its lifetime, considering both investment costs and operational and maintenance costs. In addition to these well-known KPIs, an additional indicator defined as Self Supply Ratio (SSR) was introduced. The SSR quantifies the proportion of the CSP plant's self-consumption needs that can be covered using the energy generated by the PV. By evaluating the KPIs, valuable information can be obtained regarding the energy balance between the PTC and PV plants, as well as the potential to reduce dependence on external energy sources in the operation of the hybrid plant.

These indicators provide a comprehensive view of the performance, efficiency, and profitability of the PTC/PV hybrid plant in high latitude regions.

3. Results

When comparing the annual production of hybrid power plants in the five selected locations with predetermined field directions, a number of similar behaviors are observed between them, as shown in Figure 3. In the northern hemisphere, the east-west (E-W) orientation of the PTC plant favors production in the months closest to the winter solstice, while the north-south (N-S) orientation favors electricity production for the rest of the year [10].

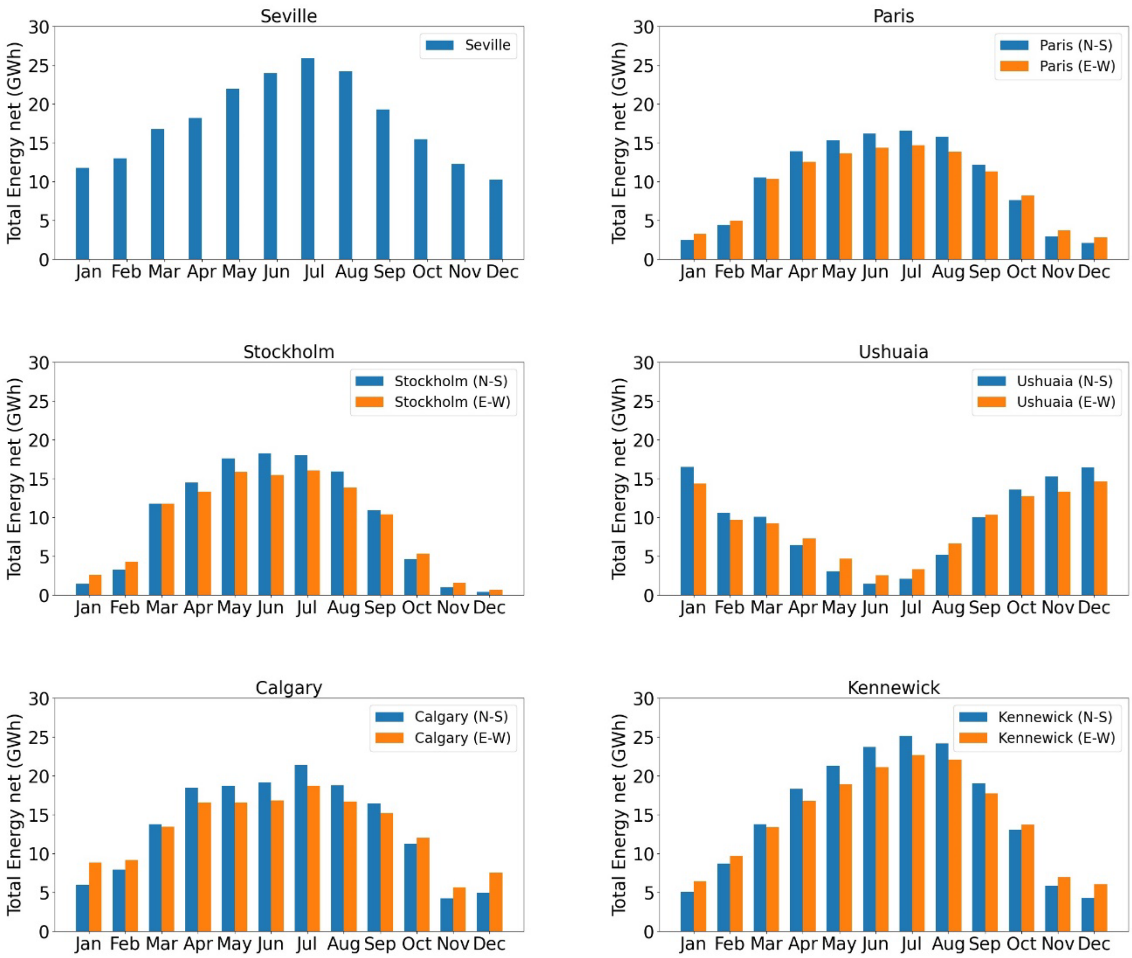

***Figure 3**. Annual energy production for different locations.*

Based on the obtained results, an optimization of the hybrid plant was implemented, allowing for the adjustment of the orientation of the parabolic solar collector (PTC) plant to maximize its monthly production. To achieve this, the plant orientation is adjusted monthly between the two considered orientations, selecting the one that yields the highest production based on the results depicted in Figure 3. The objective was to increase the Capacity Factor (CF) and reduce the Levelized Cost of Energy (LCOE), specifically in high latitude regions for hybrid plants. This phenomenon is depicted in Figure 4, where significant improvements are observed in Ushuaia and Calgary. It is noteworthy that Ushuaia experiences a 6.01% increase in CF and a corresponding 5.6% reduction in LCOE compared to the North-South configuration, while Calgary exhibits a 5.54% CF increase and a corresponding 5.2% reduction in LCOE compared to the same configuration.

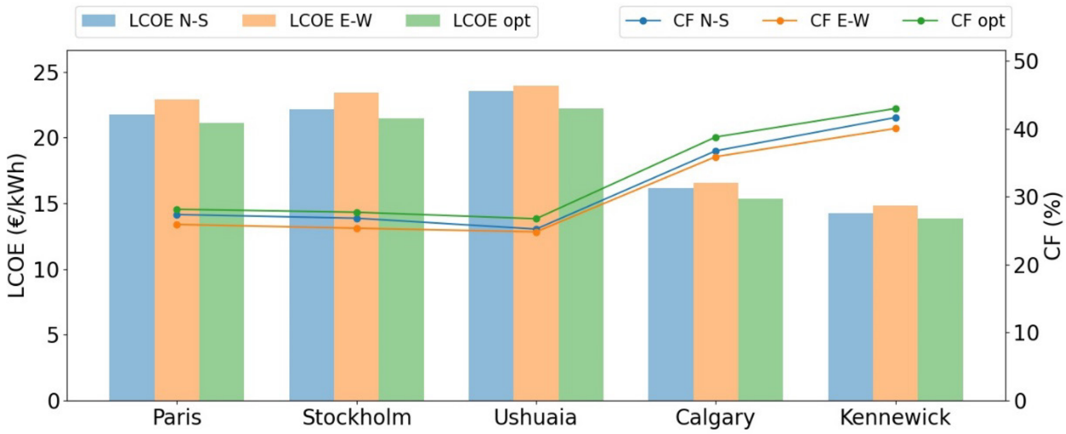

***Figure 4**. CF and LCOE for N-S, E-W and optimal (opt) configuration.*

The SSR indicator has been analyzed for all possible hybrid power plant configurations. Figure 5 shows that all configurations exhibit SSR values close to 50%, with lower values at optimal configurations. This is because a greater contribution from the PTC plant is also associated to a higher level of self-consumption, with a significant portion occurring during nighttime hours through the utilization of the TES, when the PV plant cannot contribute to meet such self-consumption needs.

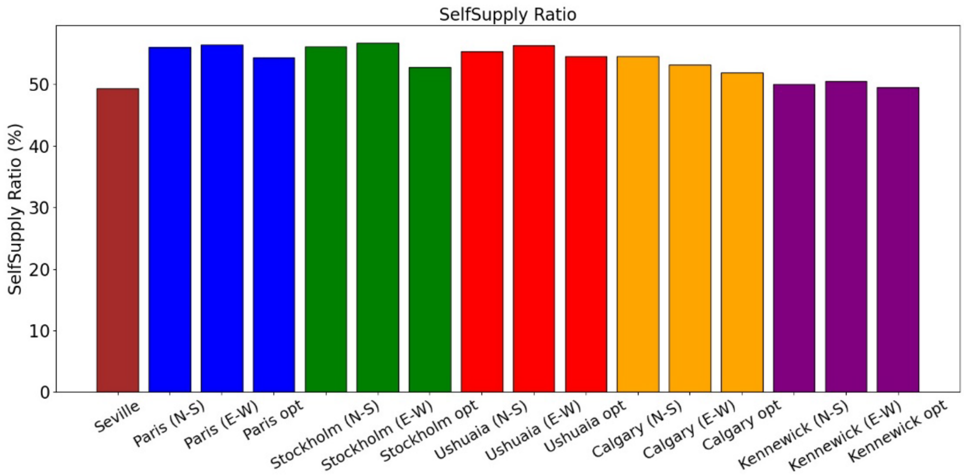

***Figure 5**. SelfSupply Ratio for each configuration.*

When comparing the LCOE and CF of standalone PV and PTC plants with hybrid plants, it is evident that all locations achieve an increase in CF and a reduction of the LCOE with respect to the stand lone PTC plant, as we can see in Figure 6. However, the most substantial LCOE reductions are observed in locations where standalone plants perform worse, such as Ushuaia, Paris, or Stockholm. These locations also experience a significant CF improvement in hybrid plants, reaching an increase of approximately 200%, from around 10% in standalone plants to 30% for hybrid plants. Calgary and Kennewick exhibit LCOE and CF values not too different to those of Seville, making them highly appealing options for these locations, despite their higher latitudes.

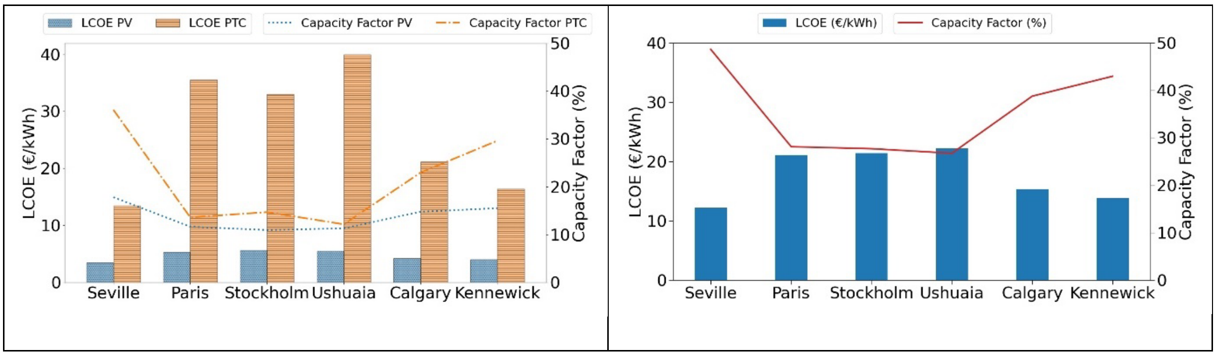

***Figure 6**. a) LCOE and CF for PTC and PV standalone plants and b) LCOE and CF for hybrid plants in optimal configuration.*

4. Conclusions

In high latitude regions, an N-S orientation of PTC fields achieves higher production compared to an E-W orientation. However, during the months near the winter solstice in the Northern Hemisphere (and vice versa in the Southern Hemisphere), the E-W configuration improves the production of hybrid plants. Therefore, a combination of both orientations can be an effective solution to increase the production and performance of these plants at high latitudes.

The SSR for all locations shows similar values to Seville, although somewhat higher due to the lower contribution of PTC plants to the total production in these high latitude areas. This highlights the importance of meeting the self-consumption requirements of PTC plants in these regions by incorporating PV energy.

The hybridization of PTC/PV plants demonstrates a successful reduction in LCOE compared to PTC plants and an increase in CF compared to PV plants in all examined locations. This achievement is particularly notable in places where standalone plants exhibit poor performance, characterized by higher LCOE values and lower CF values. Consequently, the concept of hybrid plants emerges as an appealing and viable solution for these locations, surpassing the capabilities of standalone plants.

It is important to conduct studies of solar resources in high latitude locations before dismissing them outright, as it has been observed that in certain areas, hybrid PTC/PV solar plants can offer an effective solution to improve production, performance, and profitability compared to standalone plants. This makes them particularly attractive in locations such as Calgary or Kennewick, with latitude values of 51.05º and 46.21º, respectively.

Data availability statement

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

Author contributions

José A. López-Álvarez: Conceptualization, Methodology, Software, Formal analysis, Writing – Original Draft. Miguel Larrañeta: Resources, Investigation, Writing – Original Draft. E. Pérez-Aparicio: Resources, Formal analysis, Data curation. S. Moreno-Tejera: Validation, Writing - Review & Editing. M.A. Silva-Pérez: Conceptualization, Validation, Supervision. I. Lillo-Bravo: Conceptualization, Supervision.

Competing interests

The authors declare that they have no competing interests.

Acknowledgement

This work has been carried out within the framework of the project 'Exploitation of the synergies of thermosolar and photovoltaic technologies for the development of hybrid solar systems of electricity production (ASDELSOL)' funded by the Junta de Andalucía (Spain) in the frame of the Andalusian investigation development and innovation plan (PAIDI 2020).

This work was supported by Grant RYC2021-032300-I, funded by the Ministry of Science and Innovation/State Research Agency/10.13039/501100011033 and by the European Union "NextGenerationEU/Recovery, Transformation and Resilience Plan".

References

[1] IRENA, RENEWABLE CAPACITY STATISTICS 2023. Abu Dhabi: International Renewable Energy Agency, 2023.

[2] SolarPACES, "CSP Projects Around the World." https://www.solarpaces.org/csp-technologies/csp-projects-around-the-world/ (accessed Jul. 04, 2023).

[3] A. Zurita et al., "Techno-economic evaluation of a hybrid CSP + PV plant integrated with thermal energy storage and a large-scale battery energy storage system for base generation," Sol. Energy, vol. 173, no. July, pp. 1262–1277, 2018, doi: 10.1016/j.solener.2018.08.061.

[4] J. A. López-Álvarez, M. Larrañeta, E. Pérez-Aparicio, M. A. Silva-Pérez, and I. Lillo-Bravo, "An Approach to the Operation Modes and Strategies for Integrated Hybrid Parabolic Trough and Photovoltaic Solar Systems," Sustainability, vol. 13, no. 8, 2021, doi: 10.3390/su13084402.

[5] J. A. López-Álvarez, M. Larrañeta, E. Pérez-Aparico, P. Jiménez-Valero, and M. A. Silva-Pérez, "HERRAMIENTA PARA LA SIMULACIÓN DINÁMICA DE CENTRALES HÍBRIDAS SOLARES DE CANAL PARABÓLICO Y FOTOVOLTAICA. RESULTADOS PRELIMINARES DEL PROYECTO ASDELSOL," in XVIII Congreso Ibérico y XIV Congreso Iberoamericano de Energía Solar, 2022, p. p.201-209, [Online]. Available: https://owncloud.uib.es/index.php/s/tmkYMiGqZPeR8AT?dir=undefined&openfile=16318142, p.45-53.

[6] P. Scott, A. D. L. C. Alonso, J. T. Hinkley, and J. Pye, "SolarTherm: A flexible Modelica-based simulator for CSP systems," AIP Conf. Proc., vol. 1850, no. July 2019, 2017, doi: 10.1063/1.4984560.

[7] "UNE 206011:2014 'Solar Thermal Electric Plants. Procedure for Generating a Representative Solar Year.'" .

[8] Meteotest, "Meteonorm: Global meteorological database for engineers, planners, and architects," 2023. https://meteonorm.com/en/ (accessed Jul. 17, 2023).

[9] Protermosolar, "Protermosolar." https://www.protermosolar.com/proyectos-termosolares/mapa-de-proyectos-en-espana/ (accessed May 04, 2023).

[10] M. I. Alam, M. M. Nuhash, A. Zihad, T. H. Nakib, and M. M. Ehsan, "Conventional and Emerging CSP Technologies and Design Modifications: Research Status and Recent Advancements," Int. J. Thermofluids, vol. 20, no. June, p. 100406, 2023, doi: 10.1016/j.ijft.2023.100406.