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Analysis and Simulation of CSP and Hybridized Systems

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Comparative Techno-Economic Analysis of Different Parabolic Trough CSP Plants for the Italian Market

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Abstract. The objective of this study is to present updated estimates of the cost of concentrated solar power (CSP) projects that are relevant for the current Italian market. To this end, a comparative techno-economic analysis of different CSP plant types based on parabolic trough (PT) collectors was conducted, considering various scenarios with respect to heat transfer fluids, location and storage size. The scenarios were defined in accordance with a number of requirements, including the utilization of technologies produced in Europe (in alignment with the EU's Net-Zero Industry Act), the availability of performance and cost data from existing literature, and/or the authors' own experience, as well as the eligibility for incentives according to the initial drafts of the new support measure. The analysis employed two distinct modelling tools, developed by ENEA and DLR, respectively. These offered varying levels of detail in the description of the plant behavior. Thus, cross-checking of the results was enabled. Additionally, insights were gained concerning the impact of the chosen modelling approach on performance assessment.

Keywords: CSP, LCOE, Parabolic Trough, Molten Salt

1. Introduction

With regard to the Italian market, CSP systems are best suited for medium/large scale plants located in areas with high direct insolation and land availability that is not attractive for alternative uses. From the perspective of resource availability, suitable sites for the installation of these thermoelectric plants are those where the average annual direct solar radiation is higher than 1,800 kWh/m^2 [1]. By limiting our analysis to sites with an annual direct normal irradiance (DNI) of at least 2000 kWh/m^2, we can identify a potential area of 210 km^2 in Italy that could be allocated to CSP. However, geological, orographic, environmental and landscape constraints limit the effective extension of this area.

The Italian National Integrated Energy and Climate Plan (PNIEC) [2] identified molten salts CSP as a technology with significant innovative potential. It is, however, still uneconomic in the Italian context, and thus merits inclusion in incentive schemes based on certain considerations. These include the level of technological development, the potential for cost reductions, exploitable resources, potential contribution to targets and compatibility with cost containment in bills.

The same plan suggests that, for CSP technology to contribute effectively to the energy transition process, further research and development is necessary to reduce the cost of energy generation and to develop technical solutions to enhance performance and reduce the levelized cost of energy (LCOE). At the time of writing, a new ministerial decree is currently being drafted with the intention of providing an incentive scheme for CSP systems for the period between 2024-2028 [3]. Despite favorable conditions for the revival of the Italian CSP supply chain, the inflationary process observed in the years following the pandemic and the Italian supply chain's (due to delays accumulated in previous years) lack of industrialization, which hinders economies of scale, could impede the construction of CSP plants in Italy.

In this context, the scope of this study is to provide updated cost estimates for CSP relevant to the current Italian market. To this end, a comparative techno-economic analysis of different types of CSP plants based on parabolic trough (PT) collectors has been conducted, with consideration given to a range of scenarios in terms of HTF, location, storage capacity and storage size. The scenarios were defined in accordance with several requirements, including the utilization of technology manufactured in Europe (in compliance with the EU's Net-Zero Industry Act), the accessibility of performance and cost data from published sources and/or the authors' own expertise, and eligibility for incentives according to the initial versions of the new support scheme.

Two distinct modelling tools, developed by ENEA and DLR, respectively, were employed in the analysis, differing in their degree of system behavior delineation. This enabled cross-validation of outcomes and insight into the influence of the selected modelling approach on performance evaluation. The principal differentiation amongst the plant varieties lies in the type of HTF employed, namely: a conventional diphenyl oxide – biphenyl thermal oil (Therminol VP1), a ternary molten salt mixture (NaKCa-NO_3, YARA-MOST) and Solar Salt (KNO_3-$NaNO_3$). For each plant type, an investigation was carried out for a variety of potential scenarios. The locations of Gela, and Montalto di Castro were selected as reference plant locations in the south and center of Italy, respectively. To analyze the impact of varying storage capacities, three different values for the thermal energy storage (TES) capacity were considered: 9, 12 and 15 full load hours.

2. Performance Model description

The simulations were conducted using a quasi-dynamic approach with a one-hour timestep, employing the Greenius software (version 4.11) [4],[5], developed by DLR, and a MATLAB (version 2023a) code developed by ENEA. Typical meteorological year (TMY) data for two installation sites (Gela, Sicily, in the south of Italy, and Montalto di Castro, Lazio, in the center) were generated by ENEA based on their own model for the radiation [6] and the values for ambient temperature and wind speed have been re-analyzed from [7]. The main meteorological data for the two sites are summarized in Table 1.

Table 1. *Meteorological data for the two installation sites.*

Parameters	Unit	Gela, Sicily	Montalto, Lazio
Latitude	[°] N	37.042	42.365
Longitude	[°] E	14.305	11.511
Altitude above sea level	[m]	12	1
DNI (yearly)	[kWh/m^2]	1968	1832
Ambient temp. (mean/ min/ max)	[°C]	18.2 / 6.8 / 35.4	17.2 / 8.6 / 31.7
Wind 10m (max)	[m/s]	9.98	11.05

In this paper, we refer to PT systems with a direct TES (Figure 1a), where the heat transfer fluid (HTF) and the heat storage media (HSM) are the same, that is YARA-MOST or Solar Salt, and PT systems with an indirect TES (Figure 1b), using VP1 as HTF and Solar Salt as HSM.

Every system can be described by separate and specific models for individual components: solar field, TES and power block. These component models are connected via an operating strategy defining primarily when the power block is operated and how the energy flow delivered by the solar field is spread between thermal storage and power block.

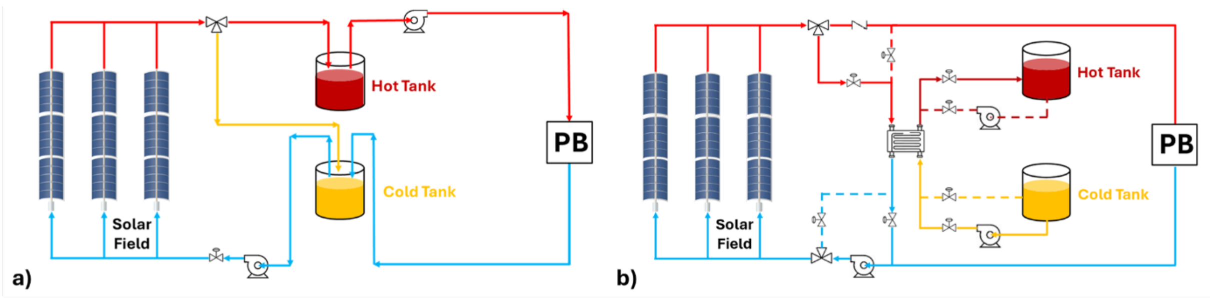

Figure 1. *CSP plant with a) direct storage system and b) diathermic oil as heat transfer fluid.*

For the solar field, the optical model simulates the solar concentrator for evaluating the power concentrated on the receiver, and with the thermal model it is possible to simulate the solar receiver to evaluate the thermal power produced by the solar field. Nominal optical efficiency depends on the optical characteristics of the collector, such as transmittance, reflectivity, absorbance, intercept factor and tracking error. The incidence angle of the beam solar radiation, θ, affects the optical parameters and the useful aperture area of the collector, A_{SF}. This effect is quantified by the incidence angle modifier, $IAM(\theta)$, which includes all optical and geometric losses in a PT collector due to an incidence angle. The effective optical efficiency is given by (1):

$$\eta_{optical}(\theta) = \eta_{optical,0}\, IAM(\theta) \tag{1}$$

Considering the shadowing, the end losses and cleanliness and indicating the DNI with E_b, the energy absorbed by the receiver tube is given by (2):

$$Q_{abs} = \eta_{optical,0}\, \eta_{shadow}\, \eta_{endloss}\, \eta_{clean} A_{SF} IAM(\theta) E_b \tag{2}$$

For the thermal model, losses are due to radiative, convective, and conductive heat losses from the receiver tube to the environment. The heat losses can be experimentally determined by operating the collector under real conditions at several temperatures. These experimental results can be formulated as in (3) and in (4) as a function of the temperature difference ΔT between mean steel temperature and ambient temperature in [K]:

$$q_{loss} = a_1 \Delta T + a_2 \Delta T^2 + a_3 \Delta T^3 + a_4 \Delta T^4 \tag{3}$$

$$Q_{loss,HCE} = q_{loss} A_{SF} \tag{4}$$

To evaluate the effective thermal power delivered to the TES, heat losses in piping are also considered:

$$Q_{loss,pipe} = h_{loss,pipe}\, A_{SF} \Delta T \tag{5}$$

Through the model for the thermal storage and the power block model, the actual thermal power supplied to the power block and the electric power produced, respectively, can be estimated. The power block has been modelled in EBSILON Professional (version 16.0, [8]) to calculate its part load behavior, auxiliary consumption, and the impact of nominal live steam temperature on design efficiency. The same relative part load curve was used for all power blocks considered in this study, only the nominal gross efficiency of the power block was varied as shown in Table 2. Part load behavior of the power block is of lower importance since the operating scheme assumed requires full load operation for almost all time steps.

The overall plant efficiency can be expressed by considering the efficiency of individual components (6) or by the ratio between the electric power produced and the solar power (7):

$$\eta_{plant} = \eta_{optical}\,\eta_{thermal}\,\eta_{piping}\,\eta_{storage}\,\eta_{power\ block} \tag{6}$$

$$\eta_{plant} = \frac{P_{el}}{P_{sun}} \tag{7}$$

An important aspect of the PT plants using molten salt as HTF is the amount of energy needed for freeze protection. As shown in Table 2, the minimal accepted temperature for the ternary salt mixture is 170 °C and for Solar Salt 270 °C. This is above theoretical freezing temperatures but in an operating power plant a kind of safety margin is required to avoid freezing in cold spots. Once the temperature in the solar field reaches this minimum temperature, the models consider antifreeze operation mode, which means that heat must be introduced to the system. This heat may be taken from thermal storage or supplied by an external heater fired with natural gas or a green fuel.

2.1 ENEA Performance Model specificities

In ENEA Performance Model, the sun position is calculated using the algorithm proposed by Grena in [9]. Based on the model proposed by Forristal [10], operation maps for thermal efficiency, mass flow rate, heat losses and HTF outlet temperature were generated as a function of HTF inlet temperature, Aperture Normal Irradiance (ANI), ambient temperature and wind speed. Figure 2 shows the overall solar field efficiency (a) and mass flow rate (b) as a function of HTF inlet temperature and ANI, in the case of Solar Salt. For the TES model, the mass and energy balance equations of the two tanks were implemented for each step and the thermal losses were evaluated as a function of actual fluid temperatures in the tanks. In ENEA Performance Model, the heat for the freeze protection has been supplied by an external gas-fired heater.

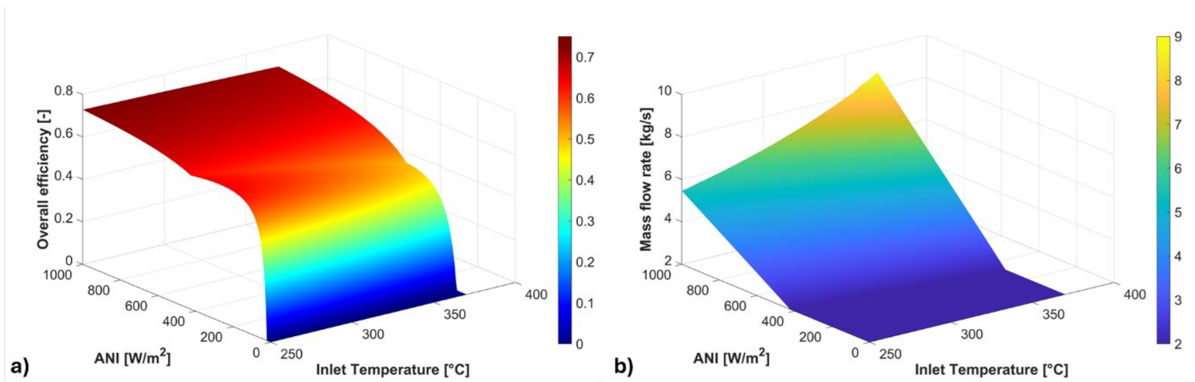

Figure 2. *Solar field operation maps showing a) overall efficiency and b) mass flow rate values in the solar field as a function of HTF inlet temperature and ANI, in the case of Solar Salt.*

2.2 Greenius specificities

In Greenius, the sun position is calculated using the SOLPOS algorithm of NREL [11]. The net heat output delivered by the solar field is calculated from:

$$Q_{net} = Q_{abs} - Q_{loss,HCE} - Q_{loss,pipe} - \left(m_{HTF}c_{HTF} + m_{pipe}c_{pipe}\right)(T_i - T_{i-1}) \tag{8}$$

The last term of equation (8) considers the thermal inertia of the solar field, which is used to model the heat-up and cool down: this term is zero during steady-state operation of the solar field. From this equation it is obvious that the solar field’s net heat output can be negative when the heat loss terms are higher than the absorbed heat. In these cases, Q_{net} is set to zero and equation (8) is used to calculate the solar field temperature of the current time step (T_i). All temperature-dependent calculations in the solar field model are done using the arithmetic mean temperature between solar field inlet and outlet temperature at each hour.

The two-tank molten salt thermal storage is modelled as an energy accumulator with a constant heat loss, independent of the state-of-charge. In Greenius, freeze protection is done primarily by using solar heat from the thermal storage, which is the most ecological and often also the most economical solution. Due to this assumption, freeze protection reduces the electricity output of the plants but the utilization of natural gas or green fuels is minimized. Anyhow, there are periods with low irradiation for several days when the solar field delivers hardly any thermal net output and freeze protection from auxiliary heating is required.

3. Simulation

It is assumed that all the plants are charging the storage tanks during daylight hours, electricity is produced as soon as TES capacity allows power block operation. The operation strategy foresees that with sunrise, the solar field is focused and started up, the energy will be conveyed to the TES system and the power block is started-up when TES is sufficiently filled to do start-up procedure. The power block runs until the TES is empty. The study was carried out by analyzing the three different plant configurations, for the two different installation sites, Gela and Montalto di Castro. For each scenario, three storage sizes (9,12 and 15 h) were considered. Validated solar collector systems were selected as references, including an ENEA-developed collector designed for Solar Salt and the HelioTrough system, which can use VP1 and YARA-MOST. The main parameters of the plants used in the simulations are shown in Table 2. For the economic assessment, the LCOE is evaluated through the relationship (9):

$$LCOE = \frac{\sum_{t=1}^{N} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+r)^t}} \quad (9)$$

where I_t are the expenses for investment, M_t the expenses for operation and maintenance, F_t the expenses for fuel, all referring to year t; E_t is the electric energy generated at year t, r the real discount rate at year t and N is the useful life of the plant. The costs used for the evaluation of LCOE (retrieved from [12], [13] and [14]) are shown in Table 3.

Table 2. *Main parameters used in the simulations.*

	Unit	VP1	YARA-MOST	Solar Salt
Collector				
Collector type/name		HelioTrough	HelioTrough	ENEA
Aperture area	[m²]	1263	1263	566.4
Aperture width (gross)	[m]	6.77	6.77	5.9
Collector length (gross)	[m]	193	193	100
Mean cleanliness of collectors	[%]	97	97	97
HCE diameter (inner/ outer)	[mm]	84.6 / 89	75.6 / 80	64 / 70
Nominal optical efficiency	[%]	81.6 [1]	81.2	79.7
Solar Field				
Nominal outlet temperature	[°C]	393	500	550
Nominal inlet temperature	[°C]	298	290	290
Collectors per loop	[-]	4	6	6
Minimum temperature in plant (Antifreeze)	[°C]	60	170	270
Nominal operation SF parasitics for pumping	[W_{el}/ m^2_{ap}]	~6.3	~2.9	~1.4
Nominal operation SF parasitics for control and tracking	[W_{el}/ m^2_{ap}]	1.0	1.0	1.8
Storage System				
Storage type		2 Tank (indirect)	2 Tank (direct)	2 Tank (direct)
Storage medium		Solar Salt	YARA-MOST	Solar Salt
Nominal load operation hours		9, 12, 15	9, 12, 15	9, 12, 15
Nominal HTF temperature charge / discharge	[°C]	393 / 379	500 / 500	550 / 550
Nominal Temperature of storage medium (T_{hot}/T_{cold})	[°C]	386 / 285	500 / 290	550 /290
Power Block				
Nominal gross electrical Power	[MW_{el}]	50	50	50
Nominal live steam temperature	[°C]	386	490	540
Nominal PB gross efficiency	[%]	~39.0	~42.0	~43.5

Table 3. *Cost assumptions for the evaluation of the LCOE ([12], [13] and [14]).*

	Unit	VP1	YARA-MOST	Solar Salt
Specific price of solar field	[€/m^2_{ap}]	260	280	280
Specific price of TES	[€/kWh_{th}]	55	30	25
Cost of natural gas	[€/kWh_{th}]	0.11	0.11	0.11
Specific land price	[€/m²]	2	2	2
Surcharge for EPC, etc.	[%]	20	20	20
Interest rate	[%]	8	8	8
Lifetime	[a]	25	25	25
Annual insurance costs	[%]	0.7	0.7	0.7
Annual HTF replacement	[%/a]	1	0	0
Annual O&M costs	[%]	2	2	2
Electricity	[€/MWh]	88	88	88

4. Results and conclusions

A comparison of the results obtained from the two performance models in terms of electricity generation and LCOE was carried out, taking as reference the values resulting from Greenius

(Figure 3). Overall, the difference in electricity generated ranges from -7.7% to +3.2%: this gap is rather small in the case of Solar Salt (from -0.6 to +3.2%), while it is more pronounced in the case of VP1 (from -5.2 to -1.9%) and YARA-MOST (from -7.7 to -5.5%). This discrepancy is primarily attributable to the varied approach in modeling the solar field and the different methods of antifreeze protection implementation. This is reflected in the calculation of the LCOE, which is inversely proportional to electricity production. Figure 4 shows the values of LCOE and Capacity Factor (CF) in lines and bars, respectively. For both performance models, higher LCOE values are calculated for plants located in Montalto, as its annual DNI is lower than that of Gela. In addition, the plants with YARA-MOST show the lowest values: these results are interesting and promising even if there is fewer operating experience with the use of ternary salt compared to Solar Salt and VP1. Although the results of both models are very much aligned in the case of the Solar Salt, the conclusions that can be drawn are different for the VP1 systems. Indeed, according to the Greenius results, the LCOE values for VP1 plants are the highest ones, except for small TES sizes, where they are cheaper than Solar Salt. In contrast, from the ENEA results, the LCOE values for Solar Salt plants are the highest ones, except for large TES capacities, where they are cheaper than VP1. This discrepancy could be mainly due to heat accounting for the freeze protection: indeed, while the plants using VP1 or YARA-MOST need almost no external freeze protection, while Solar Salt plants do. Obviously, the solar field using Solar Salt needs the highest amount of freeze protection due to its high mean temperature and the elevated minimum temperature. In the explored set of conditions, the LCOE values are in the range 192-257 €/MWh, which is considerably higher than the prices announced for new CSP projects in the last years [15]. The analysis presented here uses conservative assumptions, considers the high energy costs in Italy and a lack of economy of scale in the supply chain, and already accounts for the inflation waves experienced after 2020. In addition, the selected sites are in the low range of annual DNI considered to be profitable [1]. If we use the specific costs (for collector, HTF, TES and land) for VP1 and Solar Salt systems presented in a pre-2019 paper [15], we obtain LCOE values in the range from 145 to 194 €/MWh.

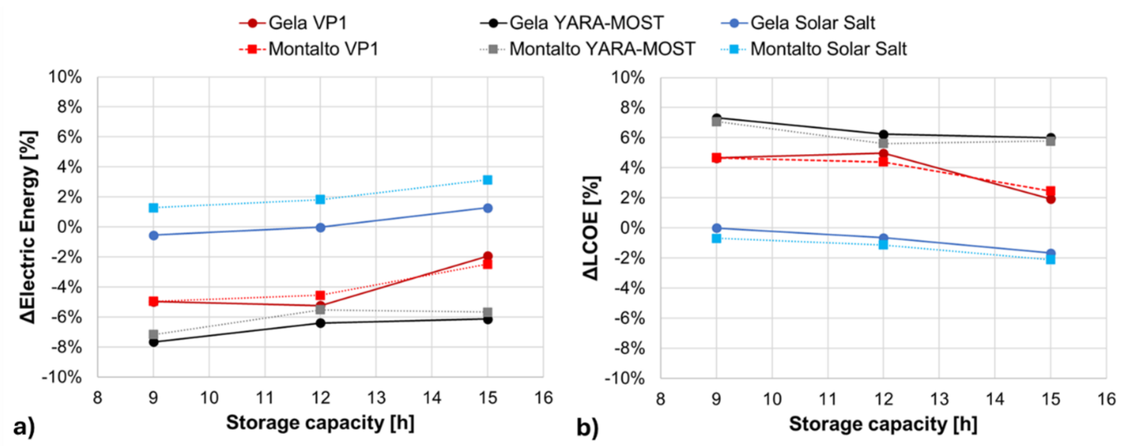

Figure 3. *Comparison between the two Performance Models in terms of a) produced electric energy and b) LCOE, both expressed as a percentage.*

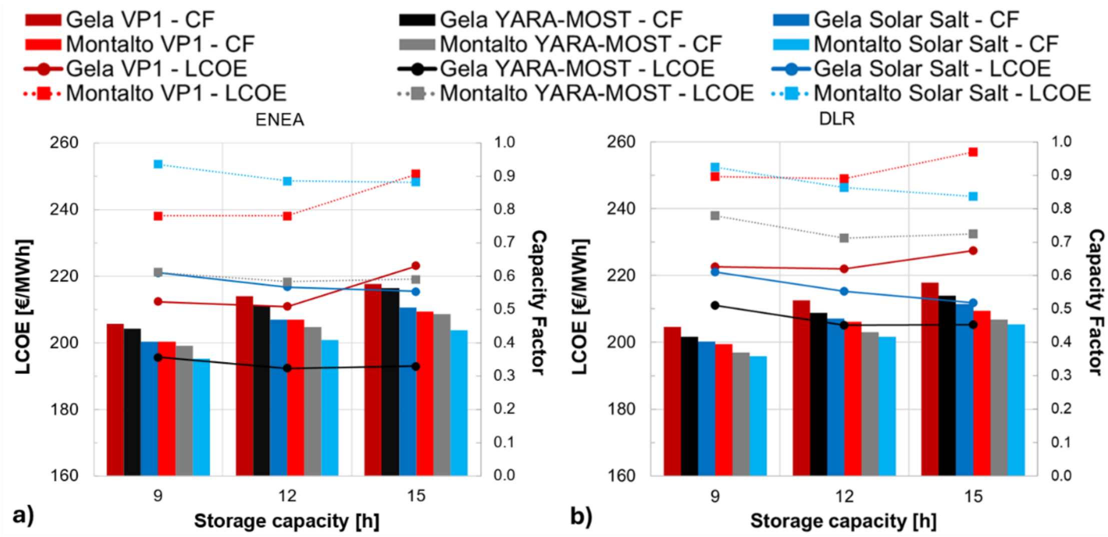

Figure 4. *LCOE and CF obtained with a) ENEA and b) Greenius simulations for all scenarios.*

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors on request.

Author contributions

Conceptualization, W.G., S.D., L.T., J.D., T.H., J.S., M.W.; **Methodology**, W.G., S.D., L.T., J.D.; **Software**, V.R., M.D., J.D.; **Validation**, W.G., S.D., L.T., J.D.; **Writing - original draft preparation**, W.G., V.R., M.D., J.D.; **Writing - review and editing**, W.G., V.R., M.D., S.D., L.T., J.D., J.S., M.W.; **Supervision**, W.G., S.D., L.T., J.S., M.W. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no competing interests.

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References

[1] G. Flamant, “Solar Power Plants: State of the Art” in Concentrating Solar Thermal Energy: Fundamentals and Applications, 1st ed., Wiley, 2022, ch. 1, pp. 1–43. DOI: https://doi.org/10.1002/9781394169702.ch1

[2] Ministry of the Environment and Energy Security, “Italian National Integrated Energy and Climate Plan”, June 2024.

[3] Ministry of the Environment and Energy Security, “Incentives for innovative or high-cost renewable source plants with innovative characteristics and low environmental and territorial impact”, Decree 19th June 2024.
[4] J. Dersch, K. Hennecke, V. Quaschning, “Free Greenius – New Options and Availability”, SolarPACES 2012 Conference, 11.-14. September 2012, Marrakech, Morocco.
[5] “Softwaretool greenius”. http://freegreenius.dlr.de (accessed: 03/04/2025)
[6] F. Spinelli, I. Balog, A. Benedetti, R. Siviero, G. Caputo, "Caratterizzazione dei potenziali siti di installazione di impianti solari dal punto di vista radiativo", Report RdS/ PTR(2019)/090.
[7] “Climate Data Store”. https://cds.climate.copernicus.eu/ (accessed: 03/04/2025)
[8] “EBSILON®Professional”. https://www.ebsilon.com/en/ (accessed: 03/04/2025)
[9] R. Grena, “Five new algorithms for the computation of sun position from 2010 to 2110”, J. Sol. Energy, vol. 86, no. 5, pp. 1323–1337, May, 2012. DOI: 10.1016/j.solener.2012.01.024
[10] R. Forristall, “Heat Transfer Analysis and Modeling of a Parabolic Trough Solar Receiver Implemented in Engineering Equation Solver”, Technical report-OSTI ID: 15004820; U.S. Department of Energy, Office of Scientific and Technical Information: Oak Ridge, TN, USA, 2003. DOI: https://doi.org/10.2172/15004820
[11] “Solar Position and Intensity”. https://www.nrel.gov/grid/solar-resource/solpos.html (accessed: 03/04/2025)
[12] C. Turchi, M. Boyd, D. Kesseli, P. Kurup, M. Mehos, T. Neises, P. Sharan, M. Wagner, T. Wendelin, “CSP Systems Analysis - Final Project Report2, NREL/TP-5500-72856, 2019. DOI: https://doi.org/10.2172/1513197
[13] J. Iñigo-Labairu, J. Dersch, L. Schomaker, “Integration of CSP and PV Power Plants: Investigations about Synergies by Close Coupling”, Energies, vol. 15, no. 19, p. 7103, 2022. DOI: https://doi.org/10.3390/en15197103
[14] MGP - Results - PUN INDEX GME. https://www.mercatoelettrico.org/en-us/Home/Results/Electricity/MGP/Results/PUN (accessed: 03/04/2025)
[15] C. A. Pan, R. Guédez, F. Dinter, T. M. Harms, “A techno-economic comparative analysis of thermal oil and molten salt parabolic trough power plants with molten salt solar towers”, SolarPACES 2018, AIP Conf. Proc. 2126, 2019.