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

Solar Industrial Process Heat and Thermal Desalination

https://doi.org/10.52825/solarpaces.v3i.2317

Published: 22 Oct. 2025

Factor Estimation for Accounting Dynamic Start-Up Effects in Solar Heat Plants Using Quasi-Static Modeling.

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Abstract. Solar heat plants represent a promising solution to decarbonize the industry. However, the industry is reluctant to adopt this technology, largely due to concerns regarding the variability of solar resources. Early-stage projects rely heavily on annual simulation models to inform decision-making processes, underscoring the critical need for accurate predictions of solar plant energy yield. To address this, a methodology has been developed to enhance the precision of heat production estimates in annual steady-state modelling by integrating dynamic effects through the introduction of a heat-up factor. This heat-up factor will be dependent on the initial temperature, the DNI conditions, the heat capacitance of the installation, and the chosen control strategy. The findings demonstrate a significant enhancement in the accuracy of steady-state model simulations with the inclusion of the heat-up factor, effectively capturing the dynamic influence on energy consumption during start-up.

Keywords: Solar Heat for Process, Modelling, Transient Analysis

1. Introduction

Approximately 37% of the world's greenhouse gas emissions come from industry [1]. A recent study [2] has concluded that the combination of solar thermal, storage, and electric heating is economically viable to replace fossil fuels from the industry sector in the short term. Solar thermal energy represents a promising solution to industry decarbonisation, although some technological challenges persist, primarily due to the diurnal cycle of solar irradiance.

The daily irradiance cycle implies daily start-ups, where the solar field is preheated until it reaches the operational temperature. The energy consumption during start-up has a significant impact on the annual yield of energy. If this is not considered, the start-up energy could be overestimated by 18 % of the total annual energy. Moreover, the energy expenditure during start-up is contingent upon meteorological conditions, the thermal inertia of the solar plant, and the control strategy [3]. Consequently, solar heat plants installed in locations with lower direct normal irradiance (DNI) may exhibit longer start-up times with distinct characteristics from ideal start-up times, which would result in a reduction in the total amount of heat produced.

The objective of this investigation is to identify a method for incorporating the reduction in energy caused by dynamic effects during start-up of solar fields into steady-state annual simulations applied to heat production for the process industry in regions of high latitude. The study proposes the addition of a heat-up factor in a quasi-static modelling approach to account for the dynamic effects. Consequently, a simulation of a reference solar heat plant located in central Europe will be conducted with a dynamic model. The dynamic simulation was carried out with a DLR in-house tool, called Virtual Solar Field, VSF, which employs a high temporal and spatial resolution to simulate the solar field control strategy and obtain realistic results [4].

Secondly, a methodology for estimating the heat-up factor for the quasi-static model is presented. The quasi-static model is simulated in a DLR in-house tool called Yield Assessment Calculation and Optimization Program (YACOP) [5]. The two models will be applied to the same case of study: a process heat plant with the weather conditions in Jülich, Germany. The location was selected due to the availability of weather measurements for the VSF software, namely spatially resolved irradiation information from all sky imager (ASI) systems. Finally, the use of the heat-up factor in the steady-state model notably improved the accuracy of the simulations, accounting for the dynamic influence on energy consumption during start-up.

1.1 Reference solar heat plant.

The solar field comprises four loops with four solar collector assemblies (SCA) each, resulting in a total reflective area of 13,848 m^2 and a nominal power of 1.5 MW. The solar collector selected is a parabolic trough collector (PTC), called EuroTrough [6]. Each SCA is comprised by 10 units EuroTrough collectors, with an aperture wide of 5.77 m, an SCA length of 150 m, and a net peak optical efficiency of 0.75, with a PTR70 (Schott) of 66 mm of inner diameter. *Figure 1* depicts a diagram of the reference solar field, while *Table 1* presents the dimensions of the piping of the solar field and the nominal mass flow. The piping was designed to achieve a heat transfer fluid (HTF) velocity of 2 m/s. The HTF used is a silicone oil with a product named Helisol XLP, with an operative range between 51 °C and 425 °C. The outlet temperature of the solar field was set to 380 °C, while the inlet temperature was set to 280 °C, resulting in a temperature difference of 100 K between inlet and outlet. The analysis did not include thermal energy storage, as the objective was to focus on the solar field.

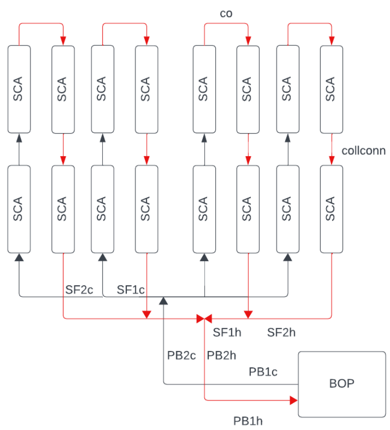

Figure 1. *Diagram of the reference solar field.*

Table 1. *Dimensions of the piping of the reference solar field.*

Line	D_i / mm	t / mm	L / m	$\dot{m}_{nom}$ / kg/s
PB1c	148.0	11.0	15	21.28
PB1h	148.0	11.0	10	21.28
PB2c- PB2h	148.0	11.0	20	21.28
SF1c- SF1h	99.2	8.8	12	10.64
SF2c- SF2h	76.1	7.11	18	5.32
CO	76.1	7.11	12	5.32
collConn	76.1	7.11	1.5	5.32

2. Methodology

A set of 12 days was selected from the available ASI data obtained at the DLR solar tower facility in Jülich, Germany. The ASI based method enables the provision of precise information regarding local clouds that could be affecting only specific SCAs of the solar field. This data is employed in VSF, which considers this spatially inhomogeneous DNI information, with 30 seconds temporal resolution and 23x23 m special resolution, by simulating the transient effect in flow maldistribution and potential defocusing of some SCAs [7].

The results of YACOP(quasi-dynamic) simulation tool is be compared in terms of start-up duration and start-up energy with VSF (fully dynamic model). The aim is to investigate how the dynamic effects can be considered in the quasi-dynamic model by the implementation of a correction factor, called the heat-up factor (f_{hu}). It is expected that the heat-up factor will be dependent on the DNI situation. Previous studies found higher inertia effects during cloudy days [3,8]. Therefore, the days are classified according to their temporal variability in DNI [9]. For this analysis, only three indicators are used: the mean, the standard deviation, and the maximum value of the absolute difference between consecutive DNI data from a minute step (t) and the previous step (t-1). The indicators are evaluated over the time duration of the start-up. Based on the three indicators, the days are divided into two categories: Clouds and High DNI and low variability (HDNILV). No clear sky days were available in the ASI data recorded. The ranges for the category distribution of the indexes are illustrated in *Table 2*.

Table 2. *Variability indicator for the classification of the days in temporal variability of DNI.*

Categories	ΔDNI_{avg}	ΔDNI_{std}	ΔDNI_{max}
HDNILV	2 – 21	1 – 34	3.6 - 137
Clouds	40 – 114	36.6 – 118	137 - 424

The initial temperature of the solar field may vary from day to day depending on the performance of the previous day. In the simulation, the initial temperature was varied between 130, 180, 230, and 280 °C to ascertain its impact influence on the heat-up factor calculation.

2.1 Dynamic simulation

VSF is a tool designed to study transient events in solar thermal power plants, providing information about the temperatures and flow distribution in each pipeline and loop as illustrated in *Figure 1*. Moreover, the operation of the solar plant can be simulated using different controllers' strategies. The solar plant can be operated in different modes, including anti-freeze, recirculation, start-up, normal operation and dumping. In the anti-freeze and the recirculation mode, the mass flow is recirculated within the solar field.

The maximum recirculation temperature has been set equal to the design inlet solar field temperature of 280 °C. Upon reaching this temperature, the operation mode is changed to the start-up mode. The solar field no longer recirculates the mass flow, and the inlet temperature of the solar field is now constant at 280 °C. Finally, when the outlet temperature reaches a value of 15 °C below the operation setpoint temperature of 380 °C, the normal operation mode is set.

Two distinct controllers are employed in accordance with the operational mode. The initial controller, employed during the start-up phase, is designed to control the gradient temperature to 5 K/min by manipulating the mass flow of the solar field. The second controller, the normal operation controller, is responsible for 380 °C outlet temperature control of the solar field through mass flow manipulation. Finally, a defocus controller is employed to limit the maximum temperature of the solar field to 0.5 % above the collector setpoint. This is accomplished by partially defocusing the solar field. Regarding the start-up criteria, the start-up is considered as initiated when the gradient temperature of the solar field is positive, i.e. when the energy input into the system is positive. Subsequently, the start-up is considered complete when the outlet temperature set point has been achieved. The energy required for the start-up ($E_{start\text{-}up}$) is calculated by Equation 1, where Q_{abs} is the energy absorbed in the receiver (Equation 2), $Q_{loss,rec}$ is the thermal losses of the receiver, $Q_{loss,pipe}$ are the thermal losses in the piping and Δt is the simulation step of 2 seconds. If the solar field is in operation modes anti-freeze or recirculation the heat flux leaving the solar field is equal to zero (Q_{out}). Conversely, when the operation modes are start-up or normal operation, the inlet temperature is fixed at 280 °C and the outlet heat flow can be calculated using Equation 3. This equation requires the mass flow ($\dot{m}$) through the solar field, the specific heat capacity (Cp) of the HTF at the average temperature of the solar field, T_{out} the outlet temperature, and T_{in} the inlet temperature of the solar field. The thermal losses in the receiver are calculated using Equation 4, where T_{mean} is the average temperature in the solar field, L_{loop} is the length of the loop, and n_{loop} is the total number of loops. The header pipes' thermal losses in VSF are constant and are estimated to be 100 W/m in the cold header and 150 W/m in the hot header, which gives a total of 26,750 W.

$$E_{start-up,VSF} = \sum(Q_{abs} - Q_{loss,rec} - Q_{loss,pipe} - Q_{out}) \cdot \Delta t \quad (1)$$

$$Q_{abs} = DNI_{avg} \cdot IAM \cdot \cos(\varphi) \cdot A_{ref,tot} \cdot \eta_{opt} \quad (2)$$

$$Q_{out} = \dot{m} \cdot Cp \cdot (T_{out} - T_{in}) \quad (3)$$

$$Q_{loss,rec} = \left(6.48x10^{-9} \cdot {T_{mean}}^4 + 0.141 \cdot T_{mean}\right) \cdot L_{loop} \cdot n_{loop}. \quad (4)$$

2.2 Quasi -dynamic model

The reference solar field is modelled in the DLR in-house tool, called YACOP, which is a quasi-dynamic model developed in Python based on the SolarPACES Guideline for bankable STE Yield Assessment [10]. The solar field can be simulated in four distinct modes: operation, temperature hold, heat up and cool down, and forced defocus.

The “operation” mode is established when the mass flow is in the normal range and the outlet temperature is at the setpoint. In the event that the mass flow is below the minimum threshold, the operation modes may be either cool down or hold, depending if the heat available is higher than the thermal losses. Finally, the heat-up mode is initiated when the mass flow required is above the minimum but the temperature is below the setpoint. In the “operation” mode steady-state modelling is considered, whereas in the other modes quasi-dynamic model elements are considered as described for the start-up in the following.

During start-up, the thermal inertia of the solar field plays an important role. Therefore, in the heat-up mode, a quasi-dynamic approach is implemented to calculate the mean temperature of the solar field using Equation 5. This equation considers the HTF mass of the loops and the headers of the solar field (m_{tot}), m_s is the mass of the steel in the piping, cp_s is the heat capacitance of the steel and Q_{gain} accounts for the heat gains due to friction. The heat-up factor f_{hu} which accounts for the dynamic effects of the start-up, is introduced in this equation. The total mass can be estimated by two factors dependent on the total aperture area, shown in Equations 6,7 and 8. In this study, the factors were calculated with data from the reference solar field. The piping thermal losses are calculated with Equation 9, where A_{eff} is the aperture area of the solar field and K_{pipe} is a constant that has been estimated to match the VSF equation in a value of 0.00626889.

$$T_{mean,t} = T_{mean,t-1} + \frac{\Delta t}{(Cp \cdot m_{tot} + Cp_s m_s) \cdot f_{hu}} \cdot (Q_{abs,t} - Q_{loss,rec,t} - Q_{loss,pipe,} + Q_{gain,t}) \quad (5)$$

$$f_{htf\_to\_aperture} = \frac{m_{loop}}{A_{aperture}} = 0.35 \quad (6)$$

$$f_{to\_piping} = \frac{m_{tot}}{m_{loop}} = 1.26 \quad (7)$$

$$m_{tot} = f_{to\_piping} \cdot f_{htf\_to\_aperture} \cdot A_{aperture} \quad (8)$$

$$Q_{loss,pipe} = K_{pipe} \cdot A_{eff}.T_{mean} \quad (9)$$

The simulations in YACOP are started as soon as the gradient of temperature in VSF is positive. The initial temperature in YACOP is set to the value in VSF. The start-up period ends as soon as the temperature setpoint is achieved. The start-up energy is calculated using Equation 10, with a time step of one minute. The absorbed heat in the receiver is calculated using the same equation as that used for the receiver (Equation 2).

$$E_{start-up,yacop} = \sum(Q_{abs} - Q_{loss,rec} - Q_{loss,pipe} + Q_{gain}) \cdot \Delta t \quad (10)$$

3. Results and discussion

Simulation runs are conducted over 12 days and four different initial temperatures in VSF with a 2-second time step, utilizing data on DNI maps at a spatial resolution for each SCA as the inputs for the weather data. The time step in YACOP is one minute. Therefore, the spatial average of the DNI for the entire solar field was calculated for every two seconds and then the average in time for a minute step was obtained. A comparison in terms of start-up energy and duration is performed between the results of the two models. The difference between the start-up energy is calculated by Equation 10.

$$\Delta E = 1 - \frac{E_{yacop}}{E_{vsf}} \quad (11)$$

The difference for the 12 days and for the two temporal DNI categories, namely clouds (6 days), and HDNILV (6 days), is illustrated in *Figure 2.* It is observed that the start-up energy is consistently higher in the dynamic simulation. Additionally, the duration of the start-up is always longer in the VSF simulation. *Figure 3 (a)* shows the mean temperature profiles for a HDNILV day. During the recirculation period, the VSF temperature increase is slightly lower than the one in YACOP. This is mainly due to the VSF's controller, which limits the start-up temperature gradient. The behavior changes as soon as the recirculation mode is ended. The temperature rise in the VSF case is strongly reduced since thermal energy is extracted from the field. In contrast to that, the temperature rise in YACOP continues straight on since YACOP invests all solar energy collected into the start-up. The graph clearly demonstrates the principal difference between the models. Although the energy extracted from the field can be utilized for heating up other parts like storage or power block, it is not available for heating up the field. In consequence, the time and energy until the design conditions are reached differ strongly between the two model approaches. Since the main differences arise from the start-up phase with heat extraction, the ratio of start-up energies between VSF and YACOP is higher if this phase has a larger part. Whereas the ratio is about 10% for the initial temperature of 130 °C it is around 30% for an initial temperature of 280 °C where all of the start-up is in the extraction phase. The difference is significantly reduced when the Cloud days are distinguished from the HDNILV days as can be seen in Figure 2 (b) and (c). Since cloudy situation induce much higher controller and also defocusing activity especially when the design temperatures are reached, the energy finally required is higher. *Figure 3 (b)* shows the temperature profiles for a Clouds day.

A heat-up factor is introduced in the YACOP model accounting for the transient effects during the start-up. The effect of the heat-up factor in the quasi-dynamic simulation is shown in *Figure 4*, where the start-up energy and the accumulated start-energy are plotted for a Clouds day for a heat-up factor of 1 versus 1.23. The YACOP simulation with the heat-up factor is still faster than the VSF simulation but the total accumulated energy is now the same. Appropriate heat-up factors for all simulation runs are identified in the same way. *Figure 5* illustrates the resulting factors. It is noticed that the Clouds days require a larger coefficient and the variance between the coefficients is also higher. With the factor applied the difference between the two models evaluated over all the simulations is reduced to a low value of 0.06. The heat-up factor needed to equal the start-up energy between VSF and YACOP cab be adjusted with Equation 11. This equation fits well to HDNILV and for the Cloud days with an initial temperature lower than 180 °C. However, for the Cloud days with initial temperatures above 230 °C the heat-up factor calculated by Equation 11 does not adjust with the factor needed to have an equal result between YACOP and VSF. In some cases, an additional increase over this factor, between 0 and 13%, is required, and for the 280 °C 17% may be needed.

$$f_{hu} = 1 + \frac{E_{yacop}}{E_{vsf}} \tag{12}$$

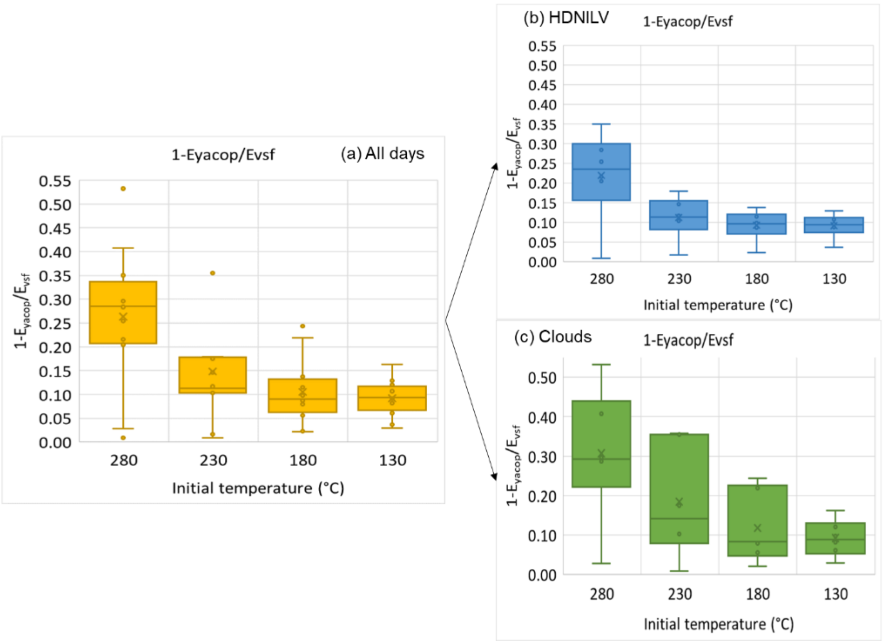

Figure 2. *Difference of the energy start-up in the VSF (dynamic) and YACOP (quasi-dynamic) model, (a) 12 days, (b) HDNILV days only (6 days), and (d) cloud days only (6 days).*

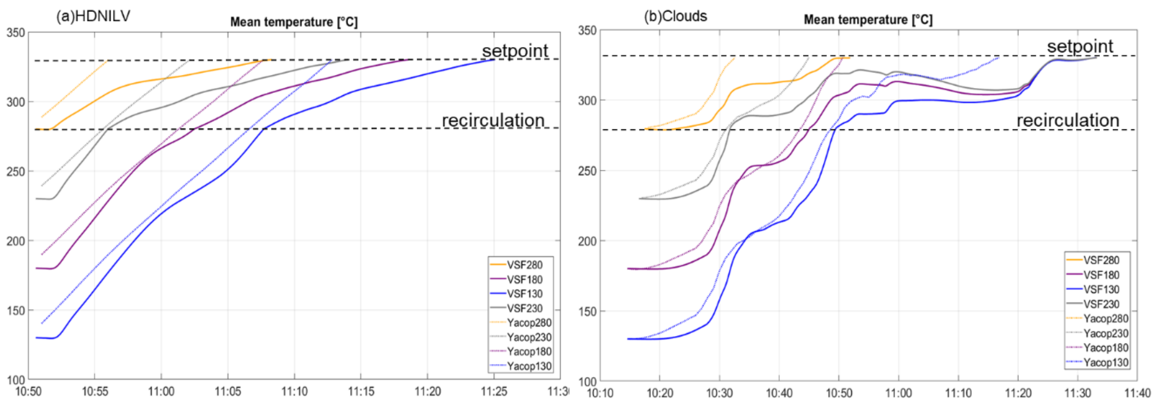

Figure 3. *Mean temperature profile in the solar field for the two models and the 4 initial temperatures for a HDNILV day (a) and a cloud day (b).*

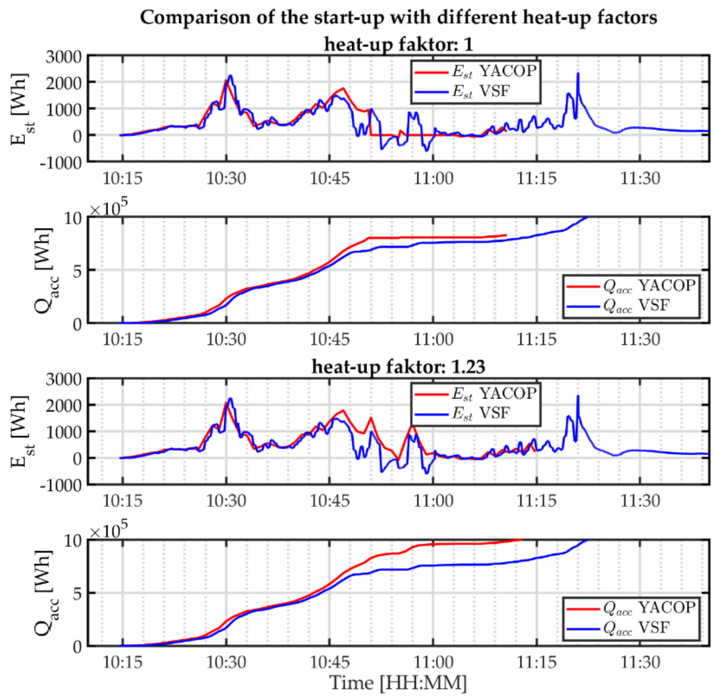

Figure 4. *Start-up energy (Est) and accumulated energy (Qacc) for heat-up factor of 1 vs 1.23 on a cloud day.*

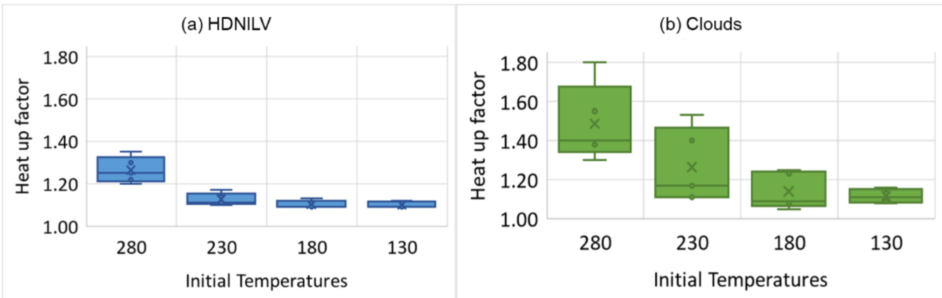

Figure 5. Heat-up factors for the two different DNI temporal classifications.

4. Conclusions

By comparing results from a quasi-dynamic and a fully dynamic simulation model, it is found that significant differences in terms of start-up duration and required energy for the start-up occur. Main reasons are controller-induced limitation of temperature gradients and partial de-focusing events especially under cloudy conditions. The largest difference occurs when the solar field switches from recirculation mode into normal mode. Thermal energy leaving the field before the design operating temperature is reached is not usable for the remaining heat-up. This period thus gets significantly longer than in the quasi-dynamic model which uses all energy for the heat-up. In order to better represent the dynamic effects in typical quasi-dynamic tools used for yield prediction a heat-up facto approach is suggested. The factor corrects the energy effectively available for the start-up and thus slows down the heat-up in the quasi-dynamic model. Correction factors between 10% and up to 50% are found depending on the general DNI conditions and the solar field initial temperature. Another approach could be to adapt the quasi-dynamic model in a way that a heat extraction phase is explicitly considered. The heat extracted is not necessarily lost but can be utilized to pre-heat components outside the solar field. The investigation clearly shows the importance of correctly considering dynamic effects during start-up when calculating energy yields of parabolic trough fields. The investigation was carried out for a small size parabolic trough field in central European climate. The difference in heat-up factors between good and cloud situations is present. Nevertheless, the quantity does not indicate that start-ups are a principal hurdle when applying the technology in “medium” climates.

Data availability statement

Results are produced with DLR’s in-house simulation codes YACOP and VSF. Please contact us for the availability of tools and simulated data.

Author contributions

Magdalena Barnetche: Conceptualization, Methodology, Writing-Original Draft. **Tim Kotzab:** Conceptualization, Methodology, Writing-Review and Editing. **Tobias Hirsch**: Conceptualization, Methodology, Writing-Review and editing, Supervision. **Robert Pitz-Paal**: Supervision.

Competing interests

The authors declare no competing interest.

Funding

Special thanks to “Universidad Politécnica de Madrid”, which has given support to this research by means of ‘‘Programa Propio I+D+i’’ and ASTEP project has received funding from European Union’s Horizon 2020 research programme under grant agreement N◦884411. Funded by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) on the basis of a decision by the German Bundestag within the AuSeSol-AI project (Grant Agreement 67KI21007A)

References

[1] McKinsey & Company, “Net-Zero Europe,” pp. 1–204, 2020.
[2] R. Pitz-Paal *et al.*, “Decarbonizing the German industrial thermal energy use with solar, hydrogen, and other options–Recommendations for the world,” *Sol. Compass*, vol. 3–4, p. 100029, Sep. 2022, doi: 10.1016/J.SOLCOM.2022.100029.
[3] T. Hirsch, et al., “Start-up modeling for annual CSP yield calculations,” *J. Sol. Energy Eng. Trans. ASME*, vol. 134, no. 3, 2012, doi: 10.1115/1.4006268.
[4] Noureldin, K., et al. (2017). Virtual Solar Field - Validation of a detailed transient simulation tool for line focus STE fields with single phase heat transfer fluid. Solar Energy, 146, 131–140. https://doi.org/10.1016/j.solener.2017.02.028
[5] M. Loevenich, et al. Yield Assessment Calculation and Optimization Program (YACOP) – DLR internal Documentation; 2024
[6] Lüpfert, E., et al. (2003). EUROTROUGH collector qualification complete-performance test results from PSA.
[7] Nouri, B., et al. (2020). Optimization of parabolic trough power plant operations in variable irradiance conditions using all sky imagers. Solar Energy, 198, 434–453. https://doi.org/10.1016/j.solener.2020.01.045
[8] Barnetche, M., et al. (2023). Analysis of the thermal inertia of pipelines in SHIP. https://doi.org/10.1016/j.rineng.2023.100908
[9] Nouri, B., et al. (2019). Real-time uncertainty specification of all sky imager derived irradiance nowcasts. Remote Sensing, 11(9). https://doi.org/10.3390/rs11091059

[10] Hirsch, T., et al. (2017). SolarPACES guideline for bankable STE yield assessment. IEA-SolarPACES, 190.