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Johannes Christoph Sattler, Ricardo Alexander Chico Caminos, Vikrama Atti, Nicolas Ürlings, Siddharth Dutta, Victor Ruiz, Soteris Kalogirou, Panayiotis Ktistis, Rafaela Agathokleous, Spiros Alexopoulos, Cristiano Teixeira Boura, Ulf Herrmann, et al.

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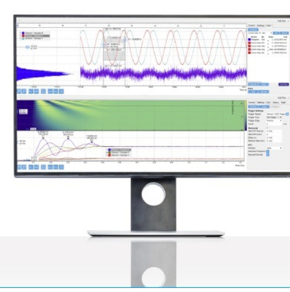

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Dynamic Simulation Tool for a Performance Evaluation and Sensitivity Study of a Parabolic Trough Collector System with Concrete Thermal Energy Storage

Johannes Christoph Sattler[1, a)], Ricardo Alexander Chico Caminos[1], Vikrama Atti[1], Nicolas Ürlings[2], Siddharth Dutta[2], Victor Ruiz[3], Soteris Kalogirou[4], Panayiotis Ktistis[4], Rafaela Agathokleous[4], Spiros Alexopoulos[1], Cristiano Teixeira Boura[1], Ulf Herrmann[1]

[1]Solar-Institut Jülich of the Aachen University of Applied Sciences (SIJ), Heinrich-Mussmann-Str. 5, 52428 Jülich, Germany
[2]Protarget AG, Zeissstrasse 5, 50859 Cologne, Germany
[3]CADE Soluciones de Ingeniería, S.L., Parque Científico y Tecnológico, Paseo de la Innovación, 3, 02006 Albacete, Spain
[4]Cyprus University of Technology, 30 Arch. Kyprianos Str., 3036 Limassol, Cyprus

[a)]Corresponding author: sattler@sij.fh-aachen.de

Abstract. Plant developers of parabolic trough collector (PTC) systems for industrial steam generation face various challenges. Some of the main challenges are availability of land, buildings in the vicinity of the plant that cast shadows on the collectors as well as land restrictions. The typical north-south collector axis alignment in many cases may not be possible due to limits of available ground. These were challenges that were faced in the planning phase for installing a PTC plant on the premises of the KEAN Soft Drinks Ltd factory in Limassol, Cyprus. As these issues cannot be avoided they must be accounted for by the plant developer, especially when a performance guarantee is given. This work presents, amongst other things, factors that should be analysed in order to predict the energy yield in the planning phase as best as possible by using a simulation model. In the sensitivity study presented in this paper, several effects on the energy yield were investigated theoretically. These effects include: Tracking inaccuracy, non-parallel collector row axis orientations as well as north-south vs. east-west collector alignment. A dynamic simulation model developed by the Solar-Institut Jülich (SIJ) [1] was further developed and used for the analysis. The simulation model features a deviation between the measured and simulated oil temperature at the collector outlet of only 1.5 K (rms). The findings are presented in this paper and give an insight into the effectiveness of mid-sized PTC systems for the industry sector.

INTRODUCTION

In Limassol, Cyprus, a concentrating solar thermal (CST) plant consisting of a mid-sized parabolic trough collector (PTC) system (145 kW_{th} nominal power, aperture about 3 m), a 600 kWh concrete thermal energy storage (C-TES) and boiler was installed and is in operation on the premises of KEAN Soft Drinks Ltd for the generation of process steam [1]. The work presented here is part of an international research project called EDITOR. The PTC system is manufactured by Protarget AG from Germany and the C-TES by CADE Soluciones de Ingeniería, S.L. from Spain. As presented in [1], a comprehensive simulation tool was developed by the Solar-Institut Jülich (SIJ) that accurately simulates the PTC and C-TES system at KEAN Soft Drinks Ltd. Since the publication, the simulation model has been further refined and optimised. A performance analysis and sensitivity study was carried out in order to obtain a better understanding both of the installed CST system but also for future plant installations.

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The main components of the CST plant are a PTC field with two rows, a two-module C-TES, a kettle-type boiler and a thermal oil pump. Figure 1(a) shows the installed CST system at the consumer's site. Figure 1(b) shows the schematic of the plant. As can be seen in Fig. 1(c), the factory buildings and trees are close to the plant which leads to shadows cast onto the collector and weather station at low sun angles in the evening. The axis direction of the CST plant at KEAN Soft Drinks Ltd deviates by −23.7° from north.

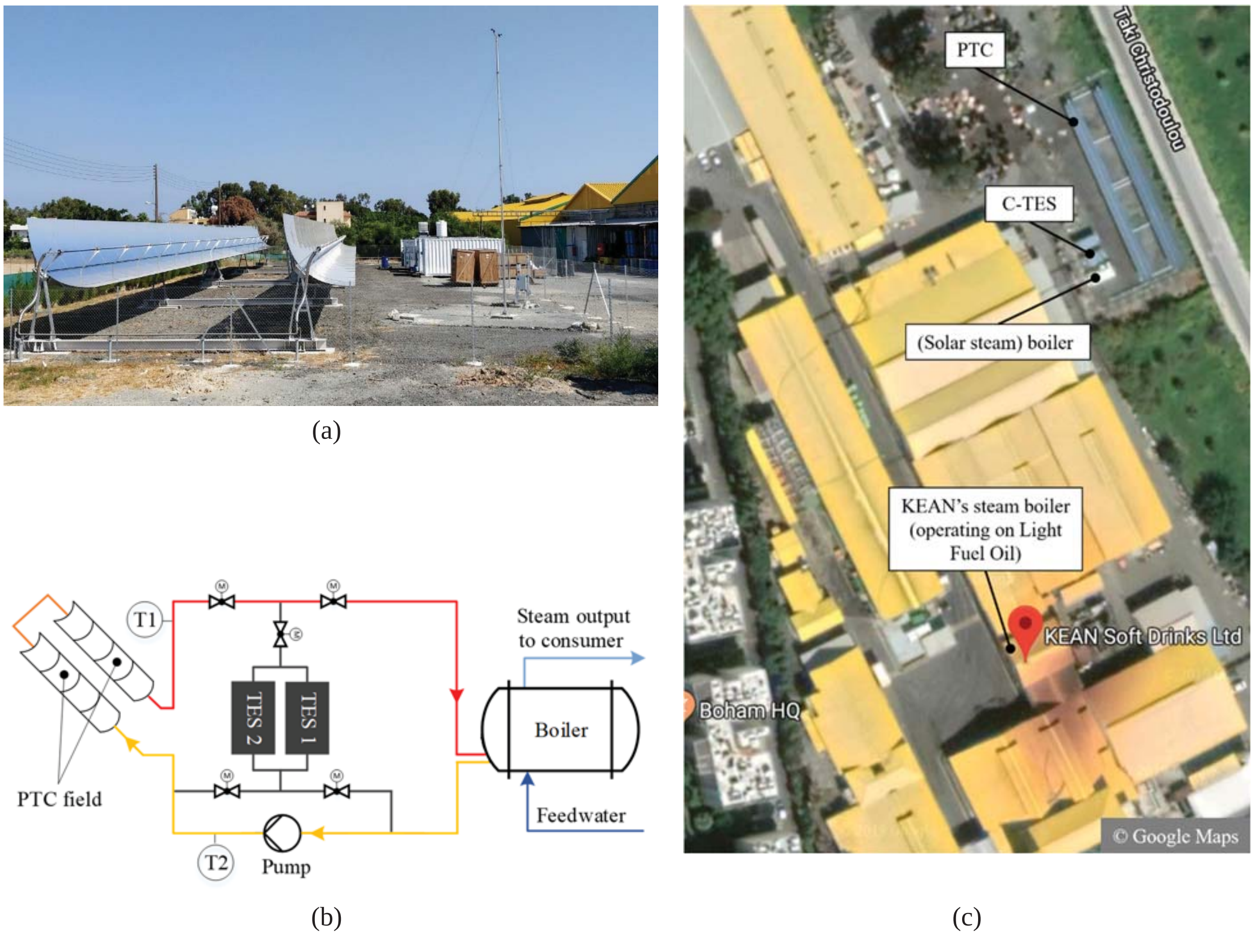

FIGURE 1. (a) Photo of the two-row PTC system, weather station as well as three shipping containers accommodating the C- TES and boiler (Photo provided by and © Protarget). (b) Schematic representation of the PTC system with C-TES (modules installed in parallel). (c) Aerial view of the KEAN factory including the installed solar system © Google Maps.

A dynamic simulation model of the CST plant was developed in the programming language Modelica® and validated with measurement data. The overall model is composed of a series of nested layers with classes depicting the physical component design and energy transfer mechanisms. The PTC model consists of three layers. The first layer depicts the PTC rows, whereas the second layer describes the individual collector consisting of a parabolic reflector and a heat collecting element (HCE). The HCE is modelled in a third layer and is mathematically described by three energy balances. The glass envelope temperature of the HCE is calculated with the first energy balance. The absorber tube temperature is determined with the second energy balance. A third energy balance is required to compute the temperature of the thermal oil flowing through the absorber tube. The complete model structure is explained further in [1]. Figure 2 shows the top layer class of the overall PTC system with C-TES, boiler and controller. Local weather and mirror reflectivity measurement data serve as input for the simulation model. The original purpose of the simulation model is to evaluate and improve the plant's controller, to simulate the system operating modes and to perform plant efficiency calculations for scaled-up plants.

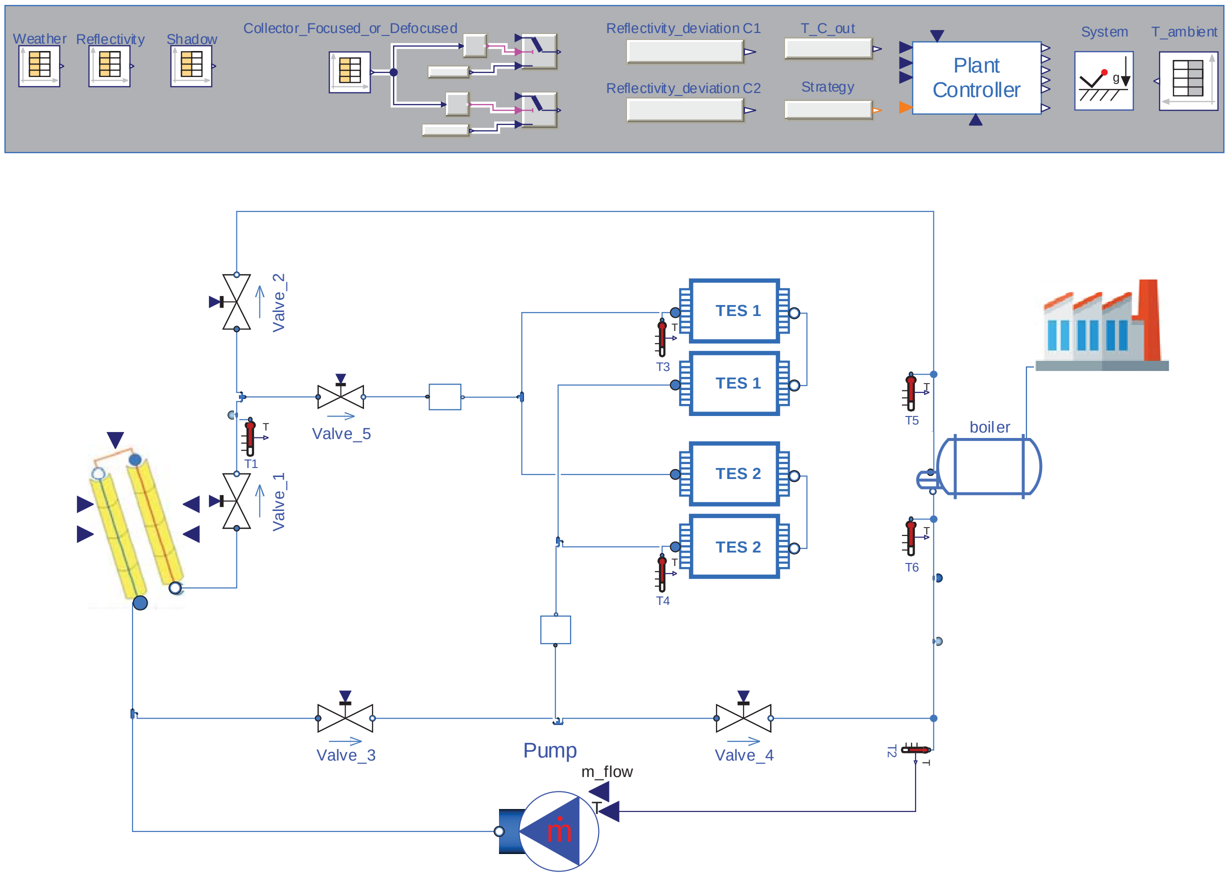

FIGURE 2. Top layer class of the CST plant model in Dymola® (© SIJ)

VALIDATION AND EVALUATION OF CST SIMULATION MODEL

To enhance the simulation accuracy, it is important to minimise uncertainties. One uncertainty in the simulation model that was identified, for example, is the glass envelope transmissivity, which is not measured directly at the KEAN plant. By approximating that soiling affects the glass envelope transmissivity in the same magnitude as the mirror reflectivity, the relative change of the glass envelope's transmissivity value in the simulation model is set to match the relative change in mirror reflectivity. Thermal losses of the oil loop piping are modelled in detail and were compared to measurement data. These adjustments along with additional optimisation measures led to an improvement of the PTC model accuracy.

To demonstrate the quality of the simulation model, a simulation of a complete day with fluctuating direct normal irradiance (DNI) in March 2019 was carried out and compared to measurement data. The weather data, the oil temperature at the collector inlet, the thermal oil mass flow and mirror reflectivity data were used as input. The reflectivity is measured on-site in regular time intervals using a Condor® reflectometer from Abengoa Solar. The simulation model inputs DNI, wind speed and ambient temperature are recorded on-site with a MDI automatic weather station from CSP Services GmbH. The oil temperature at the collector inlet as well as the oil mass flow are inputs taken from the plant's logged data.

The oil temperature at the collector outlet was computed and compared to the measured oil temperature. Figure 3 shows that the simulated outlet oil temperature "T_c_oil,out [simulation]" and measured outlet oil temperature "T_c_oil,out [measured]" correspond accurately and deviate by only 1.5 K (rms), which is an improvement by 0.4 K compared to the model presented in [1]. The simulation model is reacting reliably even during times of strongly fluctuating DNI. During the operation of the plant until about 10:00 am (local time), the heat-up gradient of the oil temperature is low because only a single collector was set in tracking mode. After 10:00 am both collector rows are set to track the sun position leading to a steeper heat-up gradient.

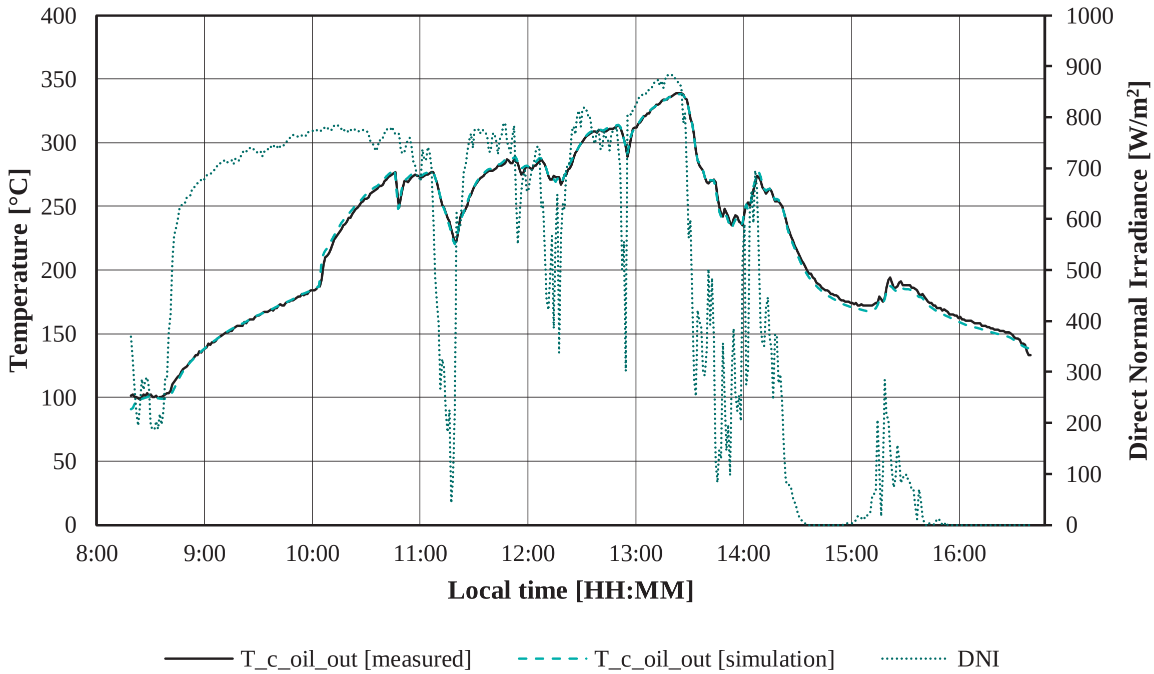

FIGURE 3. Comparison of measured vs simulated oil temperatures at the collector outlet

The storage model has also been validated and evaluated during storage charging operation. Figure 4 shows the simulated oil temperature “T_oil_out [simulation]” at the storage outlet compared with the measurement readings “T_oil_out [measured]”. The difference between the temperatures is 2.5 °K (rms). The simulation model of the storage will be optimised further.

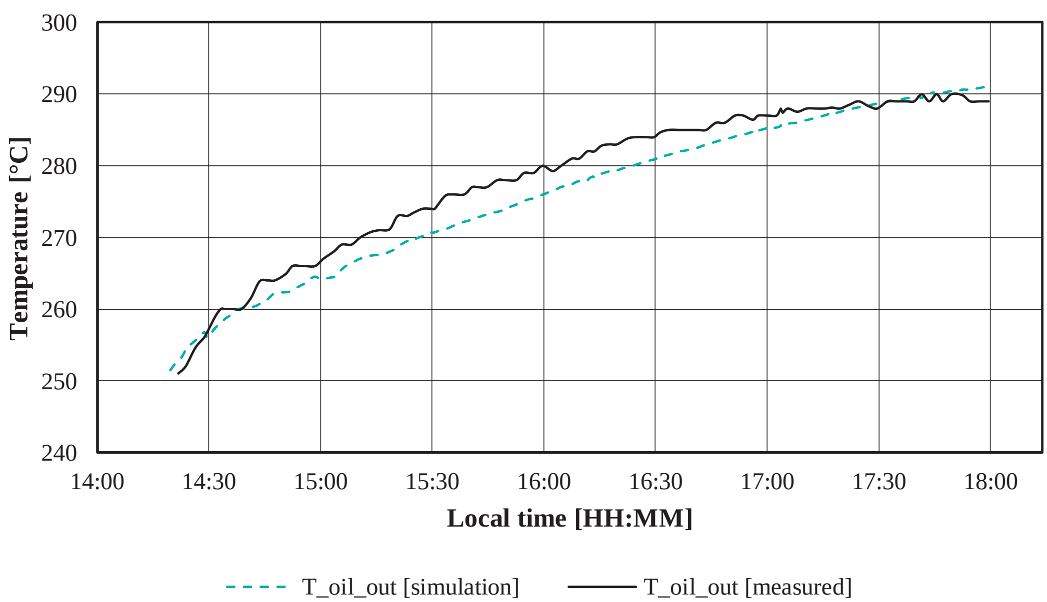

FIGURE 4. Comparison of measured vs simulated oil temperatures at the storage outlet

PERFORMANCE ASSESSMENT AND SENSITIVITY STUDY FOR THE PARABOLIC TROUGH COLLECTOR

After the validation of the dynamic model, a sensitivity study was carried out where several effects on the energy yield were investigated. The effects are hypothetical and were investigated to obtain a better understanding of the system. The simulations were carried out for a typical day with very good DNI conditions, as shown in Fig. 5. It should be noted that for the presented day the DNI data is not available after about 3:50 pm due to shading of the weather station. For all presented simulation results, the reference system is the KEAN plant in PTC-only steam production mode.

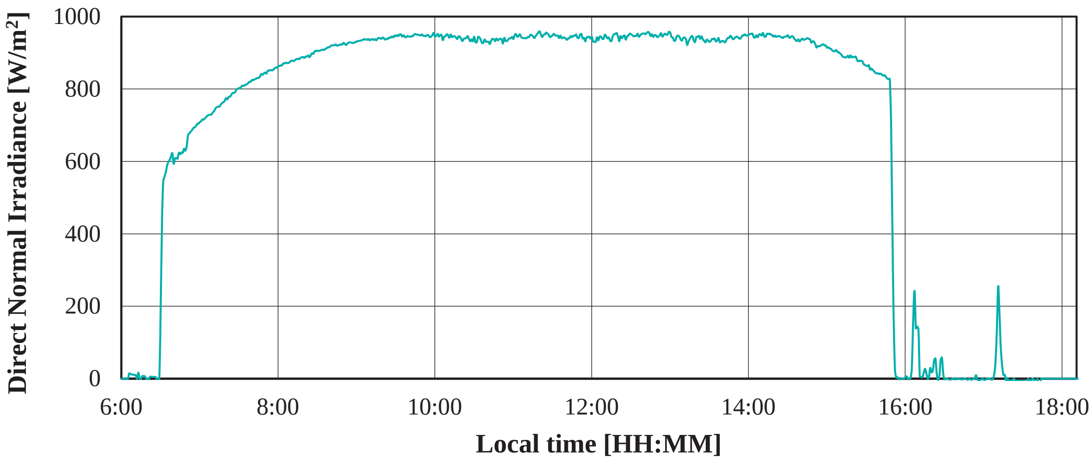

FIGURE 5. Direct Normal Irradiance for the reference day

Effect of Tracking Inaccuracy

The tracking accuracy is of high importance with respect to the efficiency of the PTC plant. Protarget AG developed a calibration method to achieve a high tracking accuracy of 99.5 %. The importance of accurate tracking can best be expressed in terms of expected energy yield losses compared to optimal tracking. The effect of inaccurate tracking on the thermal oil temperature T_{oil} and energy yield is shown in Table 1. The data reveals a loss in temperature of about 0.6 K for every 1 % tracking error compared to a reference tracking accuracy of 99.5 %. For the plant at KEAN in Limassol, a tracking error of ±1 % leads to a reduction in energy yield of about 10.5 kWh. The yield loss corresponds linearly to the tracking error.

TABLE 1. Effect of tracking error on oil temperature at collector outlet

Tracking error [%]	Change in T_{oil} (rms) at collector outlet [K]	Change in energy yield [kWh]	Percentage change in energy yield [%]
±1.5	−0.9	−15.8	−1.6
±2.5	−1.6	−26.3	−2.7
±3.5	−2.2	−36.9	−3.7

Effect of Inaccurate Axis Alignment of Individual Collector Rows

The effect of inaccurate axis alignment, i.e. when the two collector rows are not parallel to one another, was also explored. Simulations were conducted in which one collector row is correctly aligned at −23.7° from north, while the other has an angular axis deviation. It was found that the gain or loss in energy yield is negligible even if one collector row has a deviation of ±4°.

Comparison of the Energy Yield for Various Solar Field Alignments

As mentioned before, the industry sector can be very restricted on available land. This could mean that the collector is likely to be installed with an axis alignment that is somewhere between north-south and east-west. The effects on the energy yield are presented in Table 2. The simulation was carried out for three cases: North-south axis alignment (reference case), ±45° from north-south as well as ±90° (east-west axis alignment). The result is that the change in energy yield for a field aligned 45° towards east or west compared to the reference orientation accounts for −14.5 kWh, which corresponds to a decrease by 1.5 %. Furthermore, the decrease in energy yield of the PTC plant with an east-west collector axis orientation is 65.0 kWh, which is equivalent to a 6.7 % lower output.

TABLE 2. Effect of PTC field alignment on energy yield

Alignment compared to north-south collector axis orientation [°]	Change in energy yield [kWh]	Percentage change in energy yield compared to north-south collector axis orientation [%]
±45	−14.5	−1.5
±90	−65.0	−6.7

CONCLUSION

PTC plants for industrial process steam generation are increasingly important nowadays and in the future. The developed dynamic model is found to be suitable for evaluating the effect of single parameters on the overall performance of the plant. These parameters can be evaluated during the planning phase in order to predict the energy yield more accurately. Furthermore, the simulation tool’s high accuracy allows a detailed analysis of thermal losses for the desired operation parameters. The sensitivity study shows the effects of the presented parameter variations. The results show that the reduction in energy yield in PTC plants with a collector axis alignment within ±45° deviation from the north-south orientation is not significant. The change in energy yield is equivalent to only about −1.5 %, meaning that PTC plants of the presented type can be effectively deployed in the industry sector even with restricted availability of land.

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