23rd International Conference on Renewable Energies and Power Quality (ICREPQ'25)
Tenerife (Spain), 25th to 27th June 2025
ISBN-13: 978-84-09-66511-2

Modeling and Optimization of Parameters for Parabolic Trough Collectors in Solar Heat for Industrial Processes: A Case Study in Tashkent

A.E. Khaitmukhamedov, D.Y. Jalilov and O.A. Abdulkhaev

Physical-Technical Institute of Uzbekistan Academy of Sciences
2B Chingiz Aytmatov Street, 100084 Tashkent (Uzbekistan)

Abstract. This article provides a comprehensive analysis of using parabolic trough collectors (PTCs) for industrial heating in Tashkent's climate. It examines the energy, environmental, and economic benefits of this technology, considering various temperature modes and system configurations. Using the System Advisor Model (SAM) software, the study identifies optimal parameters for the solar multiple (SM) and thermal energy storage (TES) system to minimize the levelized cost of heat (LCOH). Optimal configurations achieve a 46% capacity factor (CF) with a SM of 2 and 12-hour storage, resulting in an LCOH of 3.6 ¢/kWh$_{th}$ for medium-temperature systems, and a CF at an LCOH of 4.2 ¢/kWh$_{th}$ for high-temperature systems with a SM of 2.5. The environmental analysis shows significant potential for reducing greenhouse gas emissions compared to conventional heating sources. The findings validate the economic viability and environmental efficiency of PTCs in Uzbekistan and can inform strategies for integrating solar technologies into the region's industrial sector, supporting decarbonization and sustainable development goals.

Key words. Parabolic trough collector, System Advisor Model, solar multiple, levelized cost of heat, thermal energy storage.

1. Introduction

The extensive use of fossil fuels in various industries significantly contributes to climate change. Transitioning to clean and renewable energy sources, such as solar thermal technologies, is essential for sustainable future development. Solar thermal technologies provide the possibility of obtaining heat without harmful emissions for numerous industrial processes that require low (below 150°C) or medium (150-400°C) temperatures. Global industries are adopting these renewable solutions to stabilize energy costs and achieve environmental and social goals.

In 2019, global energy consumption was 418 exajoules, with projections of a 14% increase by 2050. The industrial sector, consuming over 32% of global energy, primarily uses this energy for heating. Over 40% of CO_2 emissions in 2020 were linked to industrial heating predominantly powered by fossil fuels. The global shift towards efficient technologies like Concentrated Solar Power (CSP) is expected to play a significant role in reducing carbon emissions, with CSP's cost falling by 68% since 2010 and its market share potentially reaching 11.3% by 2050.

In 2022, the number of Solar Heat for Industrial Processes (SHIP) installations saw a record increase, with over 1.089 operational SHIPs providing 856 MW$_{th}$, primarily to the food and beverage industry [1]. Flat-plate, PTCs, and evacuated tube collectors are commonly used, with over 400,000 m² of solar collectors installed globally.

Uzbekistan aims to become a regional leader in solar energy, planning to build 19,000 megawatts of "green capacities" by 2030 and increasing renewable energy to 54% of its energy mix. Considering Uzbekistan's climatic features, characterized by high solar insolation (up to 3200 hours of sunshine per year) and average solar radiation of 1800-2000 kWh/m², PTCs are particularly promising for industrial heating. The country has a significant number of food industry, textile manufacturing, and chemical industry enterprises, where process heat in the range of 100-250°C is required - the temperature zone where PTCs demonstrate maximum efficiency. Currently, the Uzbek industrial sector's dependency on natural gas is about 85%, creating substantial potential for replacing fossil fuels with renewable energy sources (RES). Implementing PTCs would not only reduce the anthropogenic impact on the environment but also optimize production costs for industries through the use of free solar resources. This is especially relevant in the context of rising natural gas prices and state policies encouraging the use of RES including tax incentives and preferences for "green" investments.

The renewable energy potential in Uzbekistan totals 117,984 million toe, with solar energy representing a significant portion at 50,973 million toe in gross potential and 177 million toe in technical potential. Given its geographical position and favorable climatic conditions, Uzbekistan is well-suited for industrial-scale solar energy utilization, and there is practical interest in assessing the technical and resource potential of PTC [2].

The goal of this work is to demonstrate the potential of PTCs for producing heat in industrial processes under the climatic conditions of Tashkent, taking into account energy, environmental, and economic aspects. The study analyzes four cases of PTC for SHIP systems. These cases vary in terms of inlet and outlet temperatures, which are necessary for specific industrial processes, as well as the sizes of the solar field and TES volume, combined with the parameters of commercially available collectors. The assessment of all four cases, covering energy, environmental, and economic aspects, is conducted in the context of Tashkent's climatic conditions.

2. Methodology and Results

A. Methodology

In this study, SAM software of National Renewable Energy Laboratory (NREL) was used to model the impact of key design parameters such as SM and TES on cases of PTC systems for generating heat in industrial processes, as well as to determine the optimal variant. SM is a main parameter for determining the dimensions of the solar field. It is calculated as the proportion of thermal energy generated by the system at the design point to the thermal energy needed by the plant during standard operations [3]. The size of the solar field is influenced by the value of SM; a higher SM leads to a larger reflective surface area, allowing the system to produce increased amounts of thermal energy.

The studied effects are related to the annual energy production volume and optimal sizes that minimize LCOH. The simulation process allows for the analysis of the impact of system design parameters on the economic competitiveness of various PTC cases. SAM integrates hourly simulation with performance and financial models to evaluate energy output and its cost. Most of the input data in SAM can be used as parametric variables for analyzing the impact of changes in performance, cost, and financial indicators on model outcomes [4]. The model is developed in accordance with the flowchart presented in Figure 1.

Main calculations were conducted considering the climatic conditions of Tashkent, using coordinates with longitude 41.32878° and latitude 69.29253°, which correspond to the location of the Test Base of the Physical-Technical Institute of Uzbekistan Academy of Sciences. The economic feasibility of PTC largely depends on the levels of DNI (Direct Normal Irradiance) available at the chosen site. In this study, the DNI data was obtained from the NREL National Solar Radiation Database (NSRDB) for the year 2019. For this location, the total annual DNI is 1653.45 kWh/m², which is considered an acceptable annual threshold for implementing projects using PTCs. Typically, to ensure high economic efficiency of PTC systems, the cumulative annual value of DNI at the site should be in the range from 1600 to 2000 kWh/m²/year [5, 6]. Meanwhile, the weighted average value of the DNI for the chosen location is 507 W/m², which also serves as the design point DNI value for the systems under consideration. Based on meteorological data for the considered location, it is evident that the PTC systems will operate successfully during the summer months, satisfactorily in spring and autumn, and minimally and irregularly in winter.

In this study, different cases were analyzed, which are related to SHIP systems intended for generating low and medium temperature heat, i.e., cases differ in terms of the temperatures required for corresponding industrial processes. For all cases, the same types of PTC (FLABEG Ultimate Trough RP6 for oil-based heat transfer fluid), receivers (Schott PTR80), and heat transfer fluid (Therminol VP-1, with a working temperature range from 12°C to 400°C, a product of Eastman, widely used in PTC installations) were used [7-9]. Assumptions regarding the optical parameters of the parabolic mirror, glass envelope, and tracking were also standardized. In each case, an ideal vacuum is assumed between the glass envelope and the absorber.

For the analysis of the solar system project with PTC, the following assumptions were made for a period of 25 years. Economic indicators for Uzbekistan were taken from official sources of the Central Bank of Uzbekistan and the State Tax Committee. The inflation rate is 10.5%, and the annual interest rate is 13.5%. Value-added tax (VAT) is set at 12%, and corporate income tax at 15%.

The target internal rate of return (IRR) for the project was set at 15%, which aligns with the recommended values for similar projects in this area. These data provide a comprehensive assessment of the economic efficiency and potential profitability of the project, allowing all key financial aspects to be considered during modeling and planning.

The final cost of the solar field using FLABEG Ultimate Trough RP6 technology was determined to be $204 per square meter, calculated according to the methodology presented in the study [10]. The costs of TES, which affect the LCOH, are also based on data from the study by Jürgen Dersch, et al [11], where the size of TES is assessed through the built-in thermal storage model in SAM. All these parameters are presented in Table 1.

Table I. Installation costs.

Parameter	Value
Site improvements	25 $/m²
Solar field	127 $/m²
HTF system	52 $/m²
Storage	40 $/kWh$_{th}$
Heat sink	120 $/kW$_{th}$
Balance of plant	90 $/kW$_{th}$

Thus, the used model calculates the levelized cost of clean heat transferred from the solar field to the heat sink. The model accounts for the electric power consumed by pumps transferring the liquid heat transfer fluid (HTF). Besides the operation of the pumps, the model also calculates the electric power needed to control the collectors, where each PTC assembly consisting of 10 modules with five absorbers each requires 125 watts of power. The calculation of the total power consumption by the collector field management system takes into account the number of PTC assemblies required for each case. Additionally, the model includes costs for maintaining the temperature of the HTF to prevent freezing, using heaters with 0.5 and 1 MW of power, which is critical for maintaining system efficiency at low temperatures. All these electricity costs are accounted for when calculating the annual operating costs of the system at a rate of $0.078/kWh. These costs are then summed with other fixed annual operating costs, constituting 1.5% of the capital costs in the financial model.

Fig. 1. Flowchart for modelling solar PTC systems using SAM software.

B. Results and Discussion

This section discusses the outcomes obtained using SAM, as described in the methodology section, applied to typical cases of SHIP. The modeling results demonstrate how changes in key parameters of SHIP system affect the annual amount of thermal energy produced, LCOH, and CF.

Figure 2 shows the changes in annual thermal energy output with a 10 MW_{th} heat sink capacity. The energy production depends on the SM, ranging from 1 to 3 with a step of 0.1, and the duration of operation of the TES system, which varies from 0 to 15 hours at 1-hour intervals. The data analysis indicates that the growth in annual energy production slows down as the SM and TES duration increase, underscoring the importance of finding an optimal ratio of these parameters. This allows for maximum operational efficiency of the system without the need for excessive capital investments in solar collectors or enhancing the TES system.

Figure 3 illustrates the impact of the TES system duration and SM size on the LCOH and the CF for a heat sink with a thermal capacity of 10 MW_{th}. The LCOH is represented by a color gradient, while CF is visualized as contours. The data analysis shows that both LCOH and CF increase with the rise in the SM and the duration of the TES operation, although the dependencies of these indicators differ and are somewhat opposite in nature. Specifically, the pattern of CF growth is similar to the curve depicting the annual energy production's dependency on the SM, as shown in Figure 2, indicating that an increase in CF leads to a corresponding rise in heat production by the respective installation.

Unlike CF, the dependency of LCOH on the SM size and TES capacity manifests differently. An excessively large solar field with small TES capacities leads to significant losses of thermal energy, as the heat sink is unable to utilize all the thermal energy from the solar field for many hours. A high SM allows the plant to operate under design conditions for most of the year but requires shedding excess solar energy for a significant part of the summer. Without energy storage, plants relying solely on solar energy are limited to annual CF around 25%.

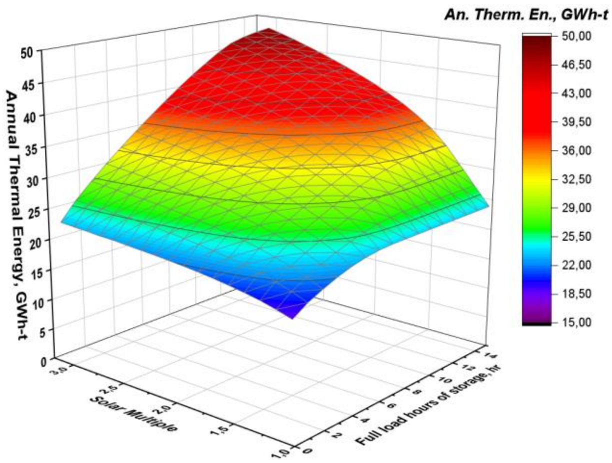

Fig. 2. Impact of the TES system duration and SM size on the annual thermal energy output with a 10 MW_{th} heat sink capacity.

On the other hand, with small values of SM and an excessively large TES system, another problem arises: the lack of sufficient additional thermal energy from the solar field to support the high consumption of the heat sink. As a result, a significant increase in net capital costs due to the large TES system is not offset by an increase in the production of useful thermal energy.

Representing LCOH as a color gradient and CF with contour lines enables the identification of TES capacities and SM sizes that achieve an optimal design with the lowest LCOH while maintaining a constant CF. For example, in low and medium temperature SHIP systems with a 10 MW_{th} heat sink capacity, the optimal values are TES capacity of 12 hours and SM of 2. These indicators

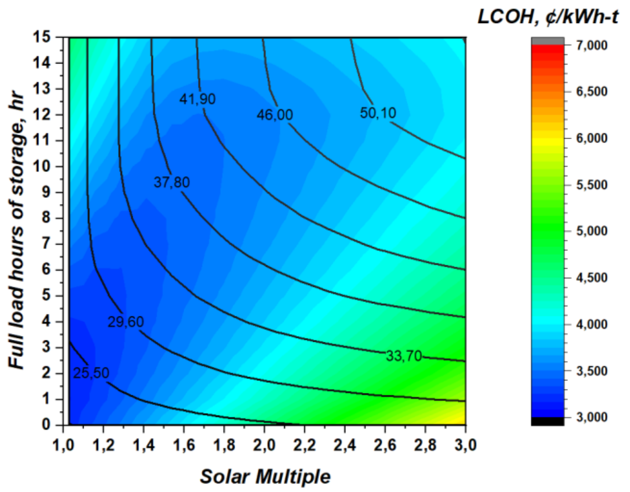

Fig. 3. The impact of the TES system duration and SM size on the LCOH and the CF for a heat sink with a thermal capacity of 10 MW_{th}. In the graphs, LCOH is represented as a color gradient, while CF is depicted using contours.

achieve CF of 46% and the lowest LCOH at 3.6 ¢/kWh_{th}. For high-temperature SHIP, the optimal values are TES capacity of 12 hours and SM of 2.5, achieving a CF of 46% and the lowest LCOH at 4.2 ¢/kWh_{th}.

C. Sensitivity Analysis

Based on the analysis of effects from parameters such as the inlet and outlet temperatures of HTF and the design value of DNI, tornado diagrams were constructed to evaluate their impact on the annual production of useful heat, LCOH, and CF. Variations in parameters were set at a 10% level.

Changes in parameters that had the greatest impact on the annual production of useful heat were associated with the design value of DNI, followed by the outlet and inlet temperatures of HTF for all considered cases. With a baseline annual production of around 40 GWh_{th}, a 10% increase in the design value of DNI led to a reduction in annual heat production due to the decreased solar field area required to achieve the corresponding SM at a 10 MW_{th} heat sink capacity. Conversely, a 10% decrease in DNI leads to an increase in annual production.

The study showed that changes in the outlet temperature of the HTF have the most significant impact on LCOH, which is critical for assessing the economic viability of the plants. At a benchmark cost of about 3.58 ¢/kWh_{th}, a 10% increase in the outlet temperature of the HTF led to a decrease in LCOH for all cases. A decrease in temperature by 10% increased LCOH. The impact of the inlet temperature of HTF on LCOH varied depending on the case, where an increase in this temperature increased LCOH in cases 1 and 4, and decreased it in cases 2 and 3. In the context of CF, the impact of the design value of DNI and HTF temperatures was similar to their impact on the annual production of useful heat, which makes sense since CF is proportional to the amount of heat produced.

D. Validation of Results

In this section, we compare the cost metrics of optimized SHIP with a 10 MW_{th} heat sink, modelled for the location in Tashkent, with existing SHIP projects around the world. Figure 4, adapted from source [12], presents the LCOH (¢/kWh_{th}) for various energy sources and applications from existing projects based on data from Eurostat; Trinomics Report for the European Commission; IEA-SHC: IEA-SHC task 52, Classification and Benchmarking; Solar Heat Worldwide 2018; Energy Visualisation Portal (europa.eu). This figure also includes LCOH values for the all modeled SHIP cases. As shown in Figure 4, the LCOH for the modeled systems is lower than the threshold values of LCOH for European countries. A comparison is also made between the modeled SHIP in Tashkent and existing SHIP projects based on various technologies worldwide.

3. Conclusion

This work presents a comprehensive analysis of the potential for using PTCs to generate thermal energy in SHIP under Tashkent climatic conditions. The study covers the energy, economic, and environmental aspects of applying this technology, allowing for well-founded conclusions about its prospects for the region.

Based on the modeling conducted using SAM, cases of using PTCs to generate heat across various temperature ranges were analyzed. The analysis showed that the optimal system parameters depend on the required temperature mode and can significantly impact the project economic indicators.

The main findings of the study can be summarized as follows:

1) *Energy Efficiency*. Optimizing the size of the solar field and the TES system allows for a significant increase in the CF. For low and medium temperature installations, optimal parameters are a SM of 2 and a TES capacity of 12 hours, which provides a CF of 46% at a minimum LCOH of 3.6 ¢/kWh_{th}. For high-temperature installations, optimal parameters are a SM of 2.5 and a TES capacity of 12 hours, providing the same CF at LCOH of 4.2 ¢/kWh_{th}.
2) *Economic Feasibility*. The economic analysis conducted showed that the minimum cost of generating thermal energy for low and medium temperature installations is about 3.4 ¢/kWh_{th} at a SM of 1.5 and a TES duration of 8 hours. For high-temperature installations, the minimum cost is 3.8 ¢/kWh_{th} under the same parameters. These values are significantly low, confirming the economic competitiveness of the considered technology in Uzbekistan conditions.
3) *Comparative Analysis*. Comparing the obtained results with existing SHIP projects worldwide shows that the proposed installation cases demonstrate high competitiveness on key indicators such as specific production of useful heat, total solar field area, and LCOH. The specific investment costs for the considered cases range from \$446.9 to \$483.7 per m², which is an acceptable level for modern solar thermal technologies.

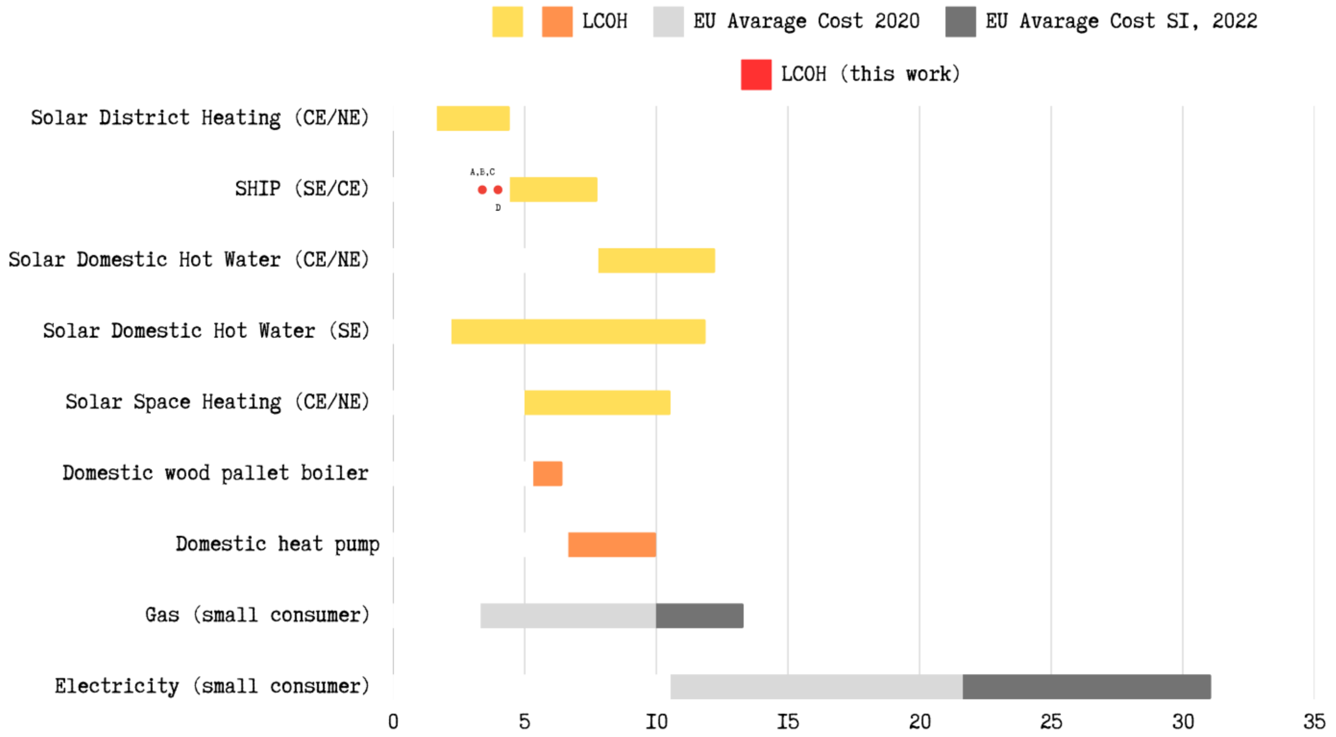

Fig. 4. LCOH (¢/kWh$_{th}$) for various energy sources (adapted from [12]). CE – Central Europe; NE – Northern Europe; SE – Southern Europe; EU – European Union. Red dots indicate the LCOH values for the optimal system cases considered in this work (A,B,C for medium-temperature systems, D – for high-temperature systems).

4) *System Sensitivity*. Sensitivity analysis showed that the main factors affecting the performance and economic efficiency of the system are the design value of DNI and the temperature parameters of the HTF. This underscores the importance of accurately accounting for local climatic conditions when designing solar thermal installations.

Based on the conducted research, the following practical recommendations can be formulated for the development of CSP technologies in Uzbekistan:

When designing PTC systems, it is advisable to target optimal values of the SM in the range of 1.5-2.5 and a TES capacity of 8-12 hours, which ensures a minimum LCOH within 3.4-4.2 ¢/kWh$_{th}$ while maintaining high CF values of at least 40%. When implementing projects, it is advisable to consider the specifics of local climatic conditions, especially the level of DNI, which significantly affects the system's performance. Finally, to enhance the economic efficiency of deploying PTCs in the industrial sector, it is necessary to provide mechanisms for government support, including tax incentives and preferences for "green" investments, which will help achieve goals for decarbonizing the economy and increasing the share of RES to 54% by 2030.

Further research may be directed at exploring the possibility of integrating solar thermal installations with other RES, as well as developing new materials and technologies to increase system efficiency. Particular interest presents in investigating the potential use of nanofluids as HTF to enhance heat transfer and reduce energy losses.

Thus, the conducted research confirms the prospects for the development of CSP technologies in Uzbekistan and creates a scientific basis for the implementation of practical projects in this area. The results obtained can be used in the development of state policy in the field of renewable energy and in forming a strategy for decarbonizing the country's industrial sector.

Acknowledgement

The authors are grateful to NREL for providing access to SAM software. This work was conducted under the budget theme "Development of fundamental principles for the efficient utilization of solar thermal applications with nanofluids and heat storages based on phase change materials" of the Physical-Technical Institute of Uzbekistan Academy of Sciences. The authors also would like to thank the Grant PRIM 01-22 funded by the MUNIS project, which is jointly implemented by the World Bank and the Ministry of Higher Education, Science, and Innovations of the Republic of Uzbekistan.

References

[1] World Map of Solar Thermal Plants | Solar Heat for Industrial Processes (SHIP) Plants Database n.d. http://ship-plants.info/solar-thermal-plants-map?collector_type=5 (accessed July 30, 2024).

[2] A.E. Khaitmukhamedov, "Development Dynamics of Concentrating Solar Power Technologies", Applied Solar Energy (2022). Vol. 58, Issue 2, pp. 318-321. Technologies. Appl. Sol. Energy 58, 318–321 (2022). https://doi.org/10.3103/S0003701X22020074

[3] Steinfeld, A., Wirz, M., and Roesle, M. (2016). Design point for predicting year-round performance of solar parabolic trough concentrator systems. J. Sol. Energy

Eng. May 2014, 136(2): 021019. https://doi.org/10.1115/1.4025709
[4] Jain, A., Chalapathi Rao, P. N. B. V., Choudhury, P., Mehta, R., & Mittal, S. K. (2013). Optimization studies for hybrid and storage designs for parabolic solar trough systems with the system advisor model. *Environmental Progress & Sustainable Energy*, 32(4), 1247–1254. https://doi.org/10.1002/ep.11719.
[5] Mukeshimana, M. C., Zhao, Z.-Y., & Nshimiyimana, J. P. (2021). Techno-economic analysis and viability assessment of concentrating solar power under climatic conditions of Rwanda. International Journal of Energy and Water Resources, 1-17. https://doi.org/10.1007/s42108-021-00161-1.
[6] Parrado, C., Girard, A., Simon, F., & Fuentealba, E. (2016). 2050 LCOE (Levelized Cost of Energy) projection for a hybrid PV (photovoltaic)-CSP (concentrated solar power) plant in the Atacama Desert, Chile. Energy, 94, 422–430. https://doi.org/10.1016/j.energy.2015.11.015.
[7] Lovegrove, K., & Stein, W. (2012). Concentrating solar power technology principles—developments and applications book (1st ed.). Woodhead Publishing Limited
[8] Manikandan GK, Iniyan S, Goic R. Enhancing the optical and thermal efficiency of a parabolic trough collector – A review. Appl Energy 2019;235:1524–40. https://doi.org/10.1016/J.APENERGY.2018.11.048.
[9] Nawsud ZA, Altouni A, Akhijahani HS, Kargarsharifabad H. A comprehensive review on the use of nano-fluids and nano-PCM in parabolic trough solar collectors (PTC). Sustainable Energy Technologies Assessments 2022;51:101889. https://doi.org/10.1016/J.SETA.2021.101889.
[10] Aly, A., Bernardos, A., Fernandez-Peruchena, C. M., Jensen, S. S., & Pedersen, A. B. (2019). Is Concentrated Solar Power (CSP) a feasible option for Sub-Saharan Africa?: Investigating the techno-economic feasibility of CSP in Tanzania. Renewable Energy, 135, 1224–1240. https://doi.org/10.1016/j.renene.2018.09.065.
[11] Jürgen Dersch, Simon Dieckmann, Klaus Hennecke, Robert Pitz-Paal, Michael Taylor, Pablo Ralon, “LCOE reduction potential of parabolic trough and solar tower technology in G20 countries until 2030”, AIP Conference Proceedings (2020). 2303, 120002. https://doi.org/10.1063/5.0028883.
[12] Energising Europe with Solar Heat | A Solar Thermal Roadmap for Europe. Available at: https://solarthermalworld.org/wp-content/uploads/2022/06/Solar-Thermal-Roadmap-2030.pdf (accessed July 30, 2024).