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Comparative Analysis of Solar Tower and Parabolic Trough Systems for Solar Heat in a Steel Industry

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Abstract. Concentrated Solar Thermal (CST) systems emerge as a promising alternative to replace fossil fuels used in industrial thermal processes due to their high energy density and dispatchability. In this study, a comparative analysis of two CST systems, Solar Tower (ST) and Parabolic Trough Collector (PTC), has been made to replace natural gas used in the steam generation process in Türkiye's largest steel production plant, located in the Mediterranean Region of Türkiye. Both the ST and PTC systems were placed in a field area of approximately 0.4 km^2. The results have shown that, on a monthly basis, the PTC system could exceed the plant's thermal energy for two-thirds of the year, while the ST system could meet the plant's energy requirements for one-third of the year. This could reduce CO_2 by about 12.7 and 19.1 kilo-tones for ST and PTC at LCOH of about 68.9 and 36.9 EUR/MWh, respectively.

Keywords: Concentrated Solar Thermal (CST), Parabolic Trough Collector (PTC), Solar Heat for Industrial Processes (SHIP), Solar Tower

1. Introduction

Solar Heat for Industrial Processes (SHIP) has emerged as a possible alternative for reducing greenhouse gas emissions from energy-intensive industrial processes, particularly those that use high temperatures in the thermal treatment of metals and glass. Low-to-medium temperature operations (<400°C) account for 60-70% of industrial energy usage, making solar-thermal technologies ideal for meeting heat requirements, according to Jia et al. [5]. The heliostat integrated solar tower is a popular Concentrated Solar Thermal (CST) technology for SHIP applications, in which sun rays are focused onto a central receiver at the top of a tower, as stated by Jin et al. [4]. The optimization of the heliostat field is critical for commercializing solar power tower systems, since heliostat field expenditures, including land expenses, account for around half of the overall plant cost for SHIP systems, as indicated by Pidaparthi et al. [14]. Furthermore, the thermal receiver accounts for up to 30% of the overall plant cost, as reported by Leonardi et al. [8]. As a result, establishing cost-effective fields needs excellent design simulations.

On the other hand, according to Patnode [12], parabolic trough collectors (PTC) are line-focus systems which efficiently focus solar radiation onto a receiver tube filled with heat-transfer fluid, resulting in moderate and high temperatures suitable for thermal applications. This makes them adaptable to a variety of industrial processes that need direct high-temperature applications, providing an environmentally safe option for a wide range of thermal requirements. According to Kutscher et al. [7], PTC systems can reach temperatures of about 150 to 400°C, making them appropriate for a wide range of thermal applications. This temperature range is ideal for use in fields such as industrial manufacturing and desalination, which require direct high-temperature heat. For the high-temperature heat processes, PTC systems that use synthetic oils as the working fluid, operating temperature becomes a limiting factor, therefore, it is necessary to mention the importance of coupling PTC system with a conventional heating apparatus to achieve desired operational temperature while integrating this renewable thermal collector system.

In the context of Türkiye's commitment to achieving net-zero emissions by 2053, the country boasts substantial solar energy resources, making CST systems a pertinent consideration for industrial applications Demir [25]. Following the withdrawal from the Paris Agreement in 2016, Türkiye seeks sustainable solutions to reduce its carbon footprint. CST systems, such as PTC and ST, play a crucial role in converting sunlight into heat at medium and high temperatures, addressing various industrial needs, including process heat, steam generation, and chemical reactions, as stated by Nathan et al. [10]. This study delves into the feasibility of PTC and ST systems in industrial processes within the Turkish context, shedding light on their respective advantages and limitations. As Türkiye harnesses its abundant solar resources to transition towards a greener future, understanding the applicability of CST systems becomes essential in achieving its ambitious emission reduction goals.

One of the energy-intensive industries is the steel industry. In the integrated steel process, the Blast Furnace route is used for liquid crude iron production. Blast Furnace is a thermochemical process where iron ore is reduced by coke and coal (PCI) [9]. For thermochemical reactions, hot blast air is blown from the bottom of the blast furnace by using turbo blowers, as presented in Krapf and Stephens' and Wang et al.'s studies [6] [18]. As Spechtenhauser [15] mentioned in his study, blast furnace blower driven by a steam turbine are used where the pressure and the temperature of steam are 43 bar and 453°C respectively. To increase the speed of blast air, the steam pressure can be increased up to 98 bar while the temperature increases to approximately 520°C [15]. Integrated Iron and Steel facilities are plants that produce steel from ore, primarily through the blast furnace process, where liquid pig iron is initially produced. Metallurgical coke is used as the bed material for the production of liquid pig iron, enabling the reduction process of iron-containing sinters, pellets, and lumpy ores. Coke also serves as a reducing agent and a source of heat. Additionally, part of the heat requirement is met using PCI coal, reducing process costs noted by Díez et al. [2].

Many integrated iron and steel plants have coke batteries and coke production is carried out within their own site. The coke gas (COG) emitted from this process has approximately 4500 kcal/m^3 of thermal energy and an emission load of 0.67 kg $CO_{2,eq}$/m^3. In the blast furnace process, oxygen-enriched air (with a maximum O_2 ratio of 25%) is blown from turbo blowers at a temperature of 1200°C. Carbon in the coke is converted to carbon dioxide, and the resulting carbon dioxide reacts again with carbon to form carbon monoxide molecules. The resulting carbon monoxide facilitates the reduction of iron from its Fe_2O_3 (hematite) form to metallic iron (Fe^0). During this process, off-gas containing CO (22-25%), CO_2 (22-25%), H_2 (3-5%), and N_2 (48-52%) is emitted. This gas, known as BFG (blast furnace gas), has a thermal energy of 700-900 kcal/m^3 and an emission load of 0.87 kg CO_2eq/m^3. BFG, COG, and natural gas are utilized to generate steam for pressurizing blast air for the blast furnace process in turbo blowers, according to Gürsoy et al. [3]. This study aims to heat up 100,000 tonnes/year of water to have steam at 40 bar and 435^{o}C using PTC and ST systems. In this way, natural gas consumption and, therefore, carbon emissions are expected to be reduced significantly. Considering weather variability, such as cloudy days and cloud transitions on partly cloudy days, together with relatively low direct normal irradiance values, the necessity of coupling solar thermal systems with a conventional heating treatment should be underlined for achieving operating temperatures. This operating temperature can be achieved by ST systems during hours of sunshine; however, PTC systems require this treatment due to the temperature constraint of the conventional heat transfer fluids (HTF) used in these systems. CO_2 reduction value is calculated as approximately 70,000 tonnes/year if the process is completely driven by CST systems. Hence, as explained above, the integrated steel process is quite energy intensive, and it requires high temperature heat energy of 7.9 GWh on a monthly basis.

2. Methodology

2.1 Solar Tower (ST) Modelling and Layout Optimization

Solar Tower (ST) systems, also referred to as central receiver systems, are optically complex systems that employ thousands of heliostats, each independently tracking the sun's movement throughout the year, to concentrate sunlight onto a fixed receiver continuously. In this study, in order to cope with a number of important design parameters, a widely-used ST system optimization software, System Advisor Model (SAM) by NREL [23] and its built-in heliostat field generation tool, SolarPILOT is used. The industrial process heat module of SAM has been employed for ST performance modelling. The design of the systems consists of two main steps. The first step is the heliostat field generation and optimization within the given land boundaries in a predetermined installation area. The second is the system -including the receiver and the tower- optimization with the finalized heliostat field.

Figure 1 shows the heliostat field generation process as a flowchart. The heliostat field generation process begins by collecting the initial inputs, such as installation location and land boundaries. Then, weather data or solar irradiance models are input to create simulation points for design evaluation. Next, a comprehensive list of potential heliostat positions within specified land boundaries is generated. The performance of the field is simulated, considering each potential heliostat position across the simulation points, which can be computationally intensive. The heliostats are then sorted based on specified performance metrics, typically by power output. Subsequently, the power delivered by each heliostat is calculated under design point conditions. Based on the results, heliostats are removed from the layout, starting from the least performing while ensuring that the power produced at the reference condition remains above the designated threshold. This iterative process ensures optimal layout design for solar power plants, as depicted by Wagner and Wendelin [17].

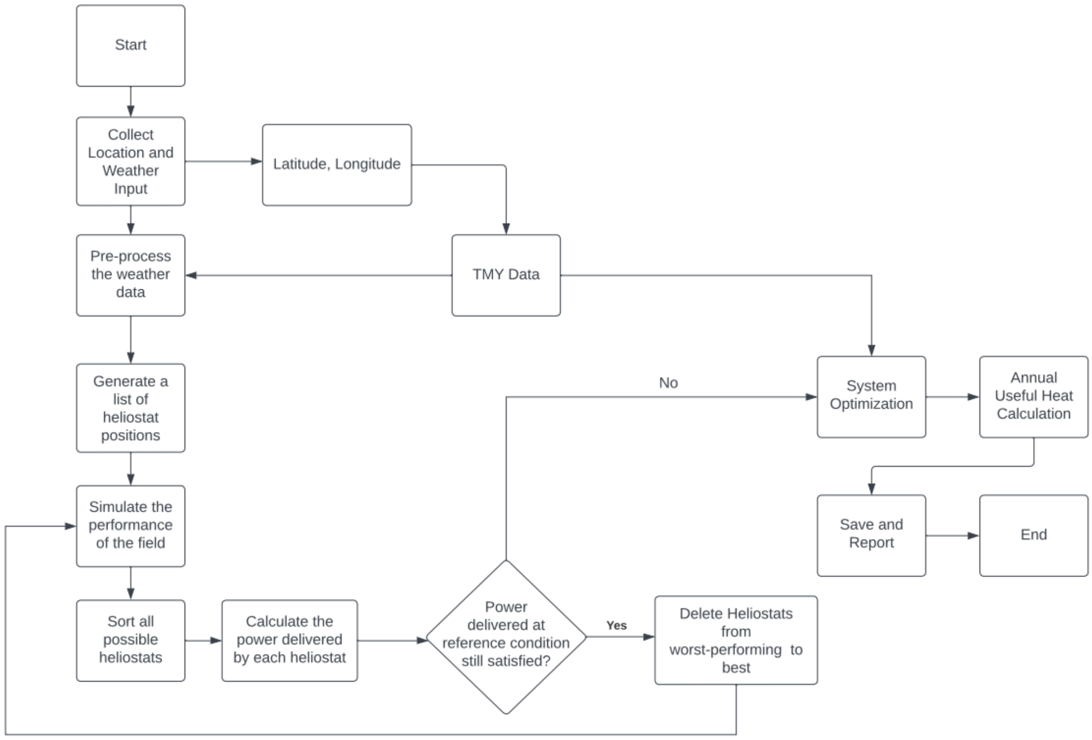

Figure 1. *Process flowchart generation of the heliostat field.*

After having the final design of the heliostat field achieved, a system optimization is performed. SolarPILOT uses the algorithm named COBYLA for system optimization regarding various design parameters, such as tower and receiver geometries alongside heliostat field geometry, for enhanced system performance and productivity while minimizing the total cost of the plant [17]. This algorithm copes with nonlinear objective function optimization and employs derivative-free optimization, making it suitable for complex scenarios where derivatives are unavailable. SolarPILOT calculates peak receiver flux to enforce constraints during optimization, ensuring solutions meet specified limits. The objective function to be minimized in SolarPILOT is given below:

$$Z(\bar{x}) = \frac{C_{tot}(\bar{x})}{E_{ann}(\bar{x})}\left(1 + \left(1 - \min\left[\frac{\dot{q}_{sf}(\bar{x})}{\dot{q}_{sf,des}(\bar{x})}, 1\right] P\right)\right) \tag{1}$$

In this context, $\bar{x}$ represents the set of optimization variables, C_{tot} denotes the total cost of the plant in EUR, E_{ann} stands for the anticipated yearly energy production from the solar field in MWh, $\dot{q}_{sf}$ signifies the thermal power output of the solar field under reference conditions in MW_t, $\dot{q}_{sf,des}$ represents the intended thermal power output from the solar field under reference conditions in MW_t, and P is a constant used to adjust the penalty for solar fields that generate less power than the desired output. One should note that if the penalty term is considered constant, the objective function becomes the unit cost of energy, in this case, minimization of the cost of produced heat [17].

2.2 Parabolic Trough Collector (PTC) Modelling and Layout Optimization

Regarding the study into optimizing the placement of PTC arrays and obtaining the resulting annual energy yield and collector efficiency, an in-house developed tool was employed that sensibly utilizes available land while factoring in potential in-array shading, maintenance paths and unavailable areas, leveraging detailed location and weather information, as well as manufacturer specifications for PTCs. The tool provides consistent spacing between arrays to minimize shading and ensure optimal land utilization by gradually searching within the given interval. This gradual search and concluding simulation flowchart are given in Figure 2.

During this search, the available solar resources are estimated using a clear-sky model based on an irradiance model developed by Hottel [20]. The sun's position and the angle of the incident rays with the collector aperture are obtained in accordance with the established procedures described by Duffie and Beckman [21]. Then, considering the available solar resources, the sun's position, and the collector aperture at a position at an indicated time, intra-array shading factors are calculated, which enables the calculation of the heat collected by the working fluid, taking optical losses due to incidence angle as described by Patnode [12] and heat loss through the receiver using the thermal efficiency fit given by Kutscher et al. [7] for the considered collector. Once the annual energy yield and the collector efficiency for the search increment are obtained, they are used as indicative parameters in a maximization-oriented loop. After the optimal spacing is obtained, hourly simulation for a year is carried out using TMY data obtained from a commercial weather software called Meteonorm [22].

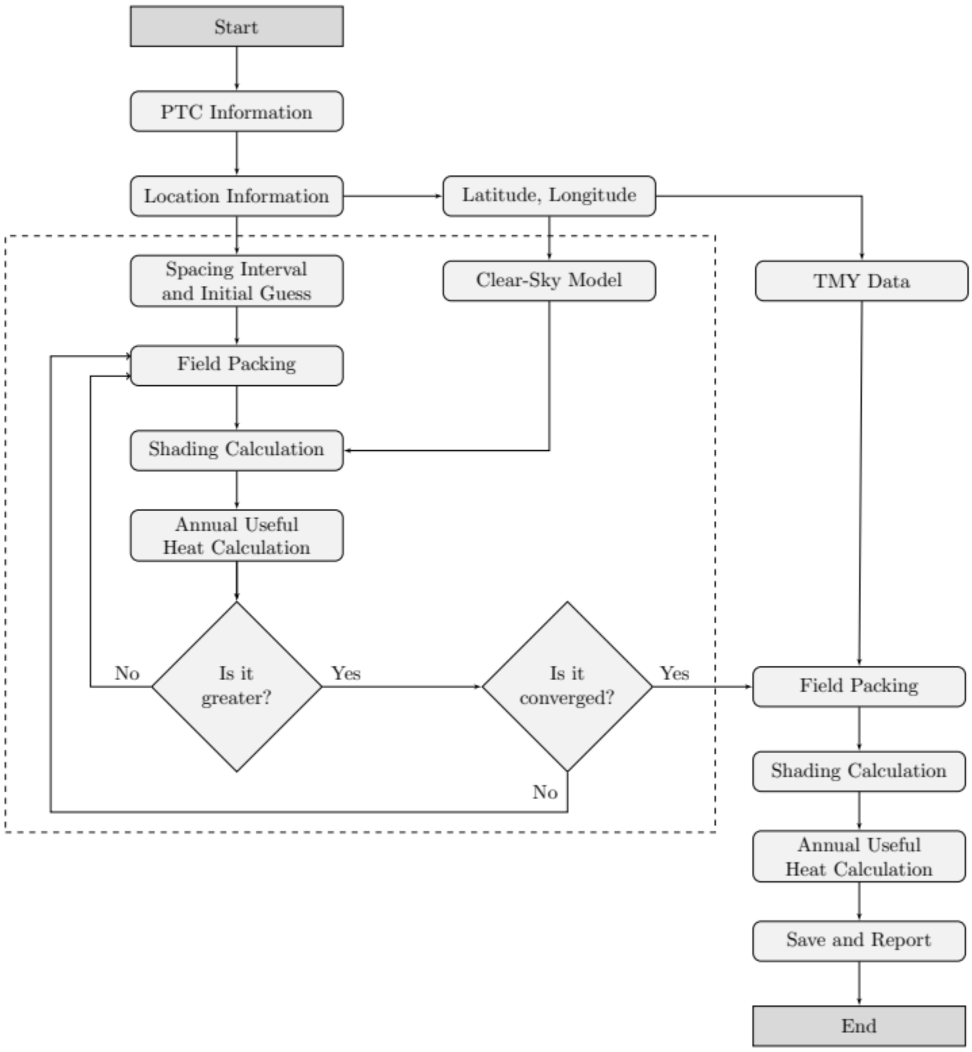

Figure 2. *Process flowchart for generation and optimization of the PTC field.*

2.3 Case Study and Integration of the CST Systems into the Process

In this study, a methodology has been developed for a case study of the integration of two CST systems, which are ST and PTC, into a steel industry located in Türkiye. For a given prescribed installation field which has a concave polygonal shape, an ST and a PTC system is optimally selected to satisfy the thermal demands of the steel production company, which is constant thermal energy of 7.9 GWh/month throughout the year due to 7/24 operation of the factory. This energy is used to produce 100,000 tonnes/year of steam at 40 bar and 435°C in the steel factory. The installation region is located in Mediterranean Region of Türkiye (36°44'41.71"N, 36°13'23.46"E). The location of the case study is shown in the map of Europe which is colored in accordance with long-term averaged DNI data provided by SolarGIS [24] in Figure 3.

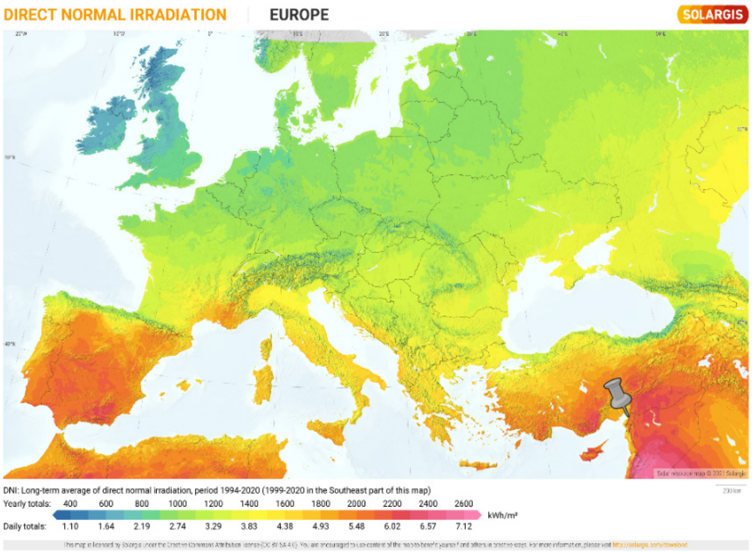

Figure 3. *Direct Normal Irradiation (DNI) Heat Map for Europe [24]. The pin shows the installation location selected for this study.*

According to Asif et al. [26], there are three important climatic conditions which affect the thermal performance of the CST system are solar irradiation, dry bulb temperature and the wind speed for the installation field. In CST systems, Direct Normal Irradiation (DNI) is the irradiation data of interest, which can be regarded as the energy input to the CST system. Wind speed and the dry bulb temperature, on the other hand, strongly affect the thermal losses due to convective heat transfer. Hence, they should be taken into consideration in the thermal performance calculations. The thermal performance calculations utilize a special type of climatic data frame called Typical Meteorological Year (TMY) Data, which is statistically obtained and presented as a resource with the user manual by Wilcox et al. [19], synthetic data used to represent the climatic conditions of the region. Even though the thermal performance simulations have been done on an hourly basis, for convenience, the meteorological input data are given on a monthly averaged basis in Figure 4 and Figure 5.

Figure 4 shows that the minimum and the maximum direct normal irradiations are observed to be 121 and 261 W/m^2 in January and June, respectively. Whereas Figure 5 shows the dry bulb temperature (°C) and wind speed data used in the simulations for ST and PTC. The input data given above is as expected such that monthly averaged dry bulb temperature in the prescribed region is about 28°C in summer and about 10°C in winter. The wind speed, on the other hand, exceeds 2 m/s in July and August and decreases below 1 m/s in October.

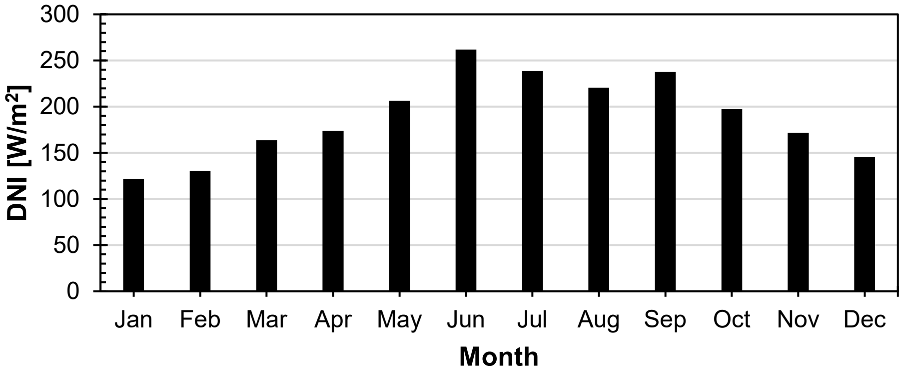

Figure 4. *Monthly averaged Direct Normal Irradiation (DNI) data used in the simulations.*

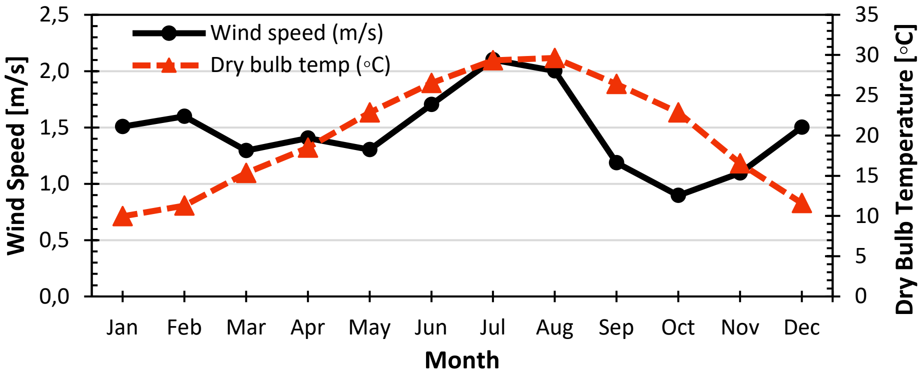

Figure 5. *Monthly averaged Dry Bulb Temperature and Wind Speed data used in the simulations.*

Even though two different methodologies for ST and PTC layout generation have been followed in this study, the concave polygonal installation field is the main constraint for layouts. A parametric search has been conducted for ST as there are more input parameters in this CST technology. The parametric search and the thermal performance calculations are done using SAM [23]. According to this parametric search, for the given installation field given by the steel production company, an ST system whose thermal power is 60 MW_t is found to be installed in the region. The important parameters used in the thermal performance calculations are given in Table 1 and Table 2 for ST and PTC, respectively. According to Blanco et al. [1], the heliostat field is obtained with the constraint that the minimum tower to heliostat distance is 0.75 times the tower height in order to eliminate the heliostats with significantly low total optical efficiencies due to reduced cosine efficiencies in that configuration.

Table 1. *Parameters used in thermal performance simulations for the solar tower system.*

Parameter	Value / Name
Heat Transfer Fluid (HTF)	Molten Binary Solar Salt (60% $NaNO_3$ – 40% KNO_3 by weight)
Number of Heliostats	2570
Tower Height	110 m
Square Heliostat Dimension	8 m
Receiver Height	14.8 m
Receiver Diameter	7.74 m
HTF Receiver Temperature Range	290 – 565 °C
Heliostat Mirror Reflectance	0.97
Receiver Coating Absorbance	0.94

According to Prieto et al. [13], concentrating solar power/thermal (CSP/CST) facilities in the commercial sector utilize solar salt, a thermal energy medium composed of 60-40 weight percent $NaNO_3$-KNO_3, owing to its established track record of effective performance. The target temperatures for HTF in the receiver inlet and outlet are selected in accordance with freezing and degradation temperatures of the binary salt given by Papade and Patil [11].

In the PTC simulations, the average operational temperature is taken to be 350 °C for Sky-Trough collectors. The number of collectors in the used simulations is 1398 in 38 one-axis tracking rows. The collector type is SkyTrough^{TM} manufactured by the company named Sky-Fuel. SkyTrough is a utility-scale thermal energy generating system that overcomes the cost hurdles of classic solar concentrators by substituting a high-reflectance polymeric film for the traditional heavy, glass-based mirror. The collectors employ a lightweight aluminum space frame design for the optical substructure and torsional stiffness, precise parabolic ribs to define the optical surface, and ReflecTech® polymeric mirror sheets.

Table 2. *Parameters used in thermal performance simulations for the parabolic trough collectors.*

Parameter	Value / Name
Heat Transfer Fluid (HTF)	Syltherm 800
Collector Type	SkyFuel - SkyTrough^{TM}
Module Length	13.9 m
Collector Aperture Width	6.0 m
Aperture Area	83.4 m^2
Mirror Material	ReflecTech® PLUS
Temperature Range	200 – 500 °C
Optical Efficiency	0.77

The layouts for ST and PTC are given in Figure 6 and Figure 7 for the given installation field, whose land area is approximately 0.4 km^2. For the two CST systems given comparatively, no storage system is employed. The solar to total land ratios are 0.29 for PTC and 0.41 for ST, which shows that the stacking layout is more flexible in the solar tower system.

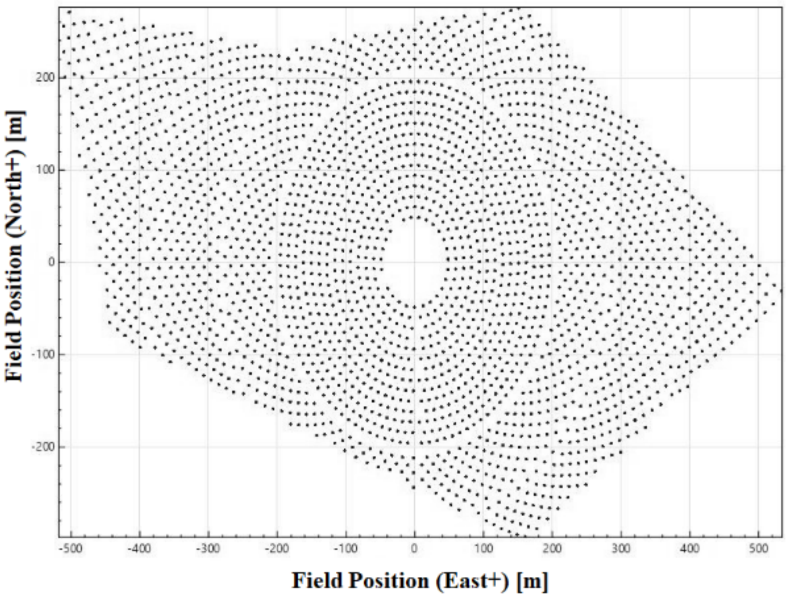

Figure 6. *Heliostat field layout for the solar tower system.*

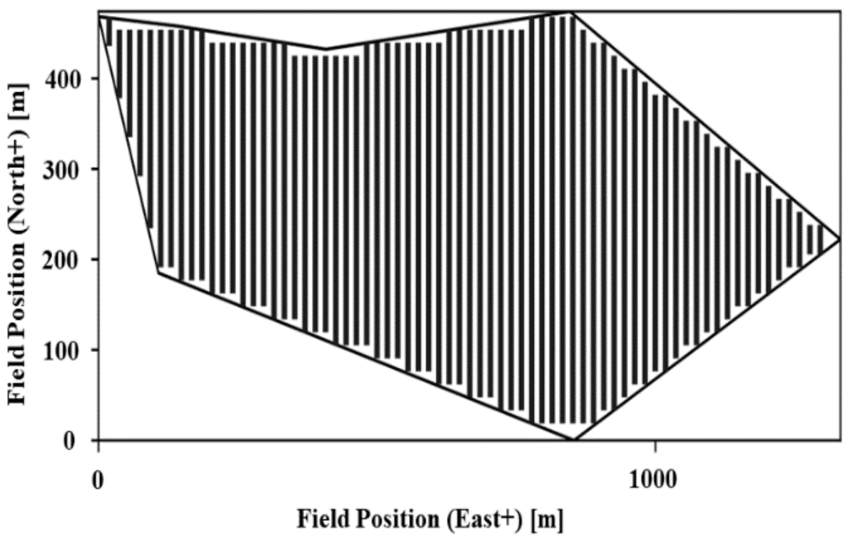

Figure 7. *Collector layout of the parabolic trough collectors.*

2.4 Economic Analysis

The economics of the ST and PTC systems are analyzed and compared by calculating levelized cost of heat (LCOH). The LCOH value gives an insight into the specific cost of the produced heat over the lifetime of the system and calculated as follows:

$$LCOH = \frac{C_{tot} + \sum_{i=1}^{n} \frac{M_i}{(1+r)^i}}{\sum_{i=1}^{n} \frac{E_{ann,i}}{(1+r)^i}} \tag{2}$$

where C_{tot} is the capital cost, M_i is the annual operating and maintenance cost at year i, $E_{ann,i}$ is the annual generated energy in year i, r is the discount rate which is estimated as a combination of degradation and interest rate, and n is the lifetime of the system. These parameters are obtained from NREL's suggested values [23] and summarized in Table 3.

Table 3. *Parameters used in the economic analysis.*

Parameter	Unit	Solar Tower	Parabolic Trough
Collector Capital Cost	EUR/kW	-	509
Tower Capital Cost	EUR/m^2	55.2	-
Receiver Capital Cost	EUR/m^2	204.8	-
Heliostat Capital Cost	EUR/m^2	130	-
Fixed Operating Cost	EUR/kW	-	7.27
Variable Operating Cost	EUR/kWh	0.004	0.001
Discount Rate	%	7	7
Lifetime	year	30	30

3. Results and Discussion

The simulation results provide noteworthy insights into the thermal energy generation by means of Concentrated Solar Thermal (CST) systems at the steel production facility. Specifically, the Parabolic Trough Collector (PTC) system shows a superior performance, producing 112 GWh of annual thermal energy, surpassing the Solar Tower (ST) system, which records a yield of 76 GWh/year. This difference in the monthly results becomes more significant during the summer months, as shown in Figure 8, owing to higher wind speeds during this period.

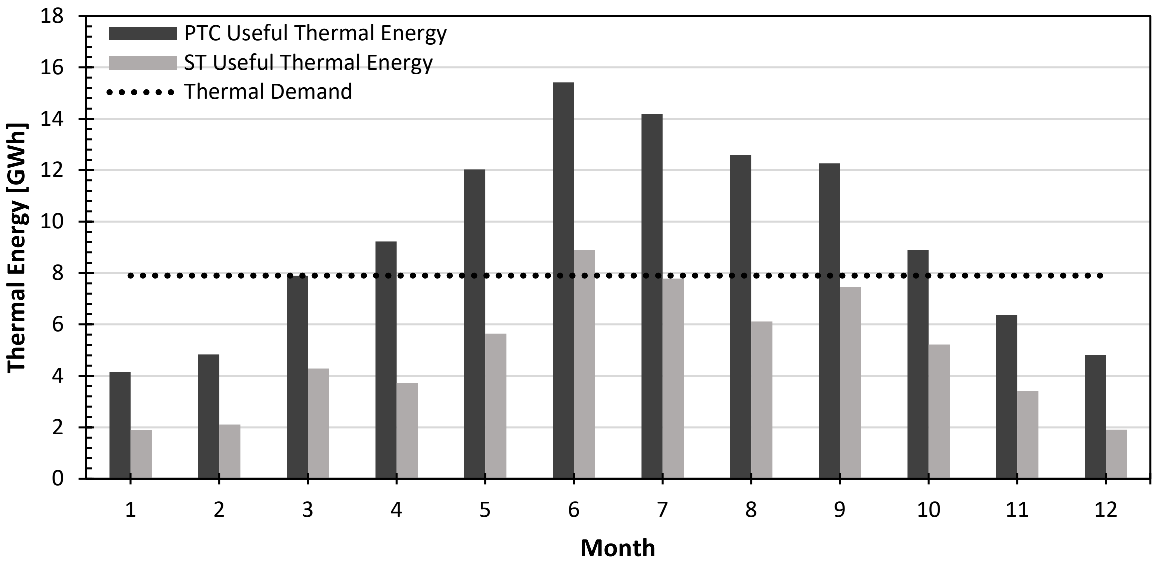

Figure 8. *Monthly useful thermal energy results for CST Systems and thermal energy demand of the process.*

The observed difference in performance is associated with the Solar Tower (ST) systems being prone to receiver convective losses due to their larger ambient air exposure areas in the receivers, especially in the external cylinder receiver, which has been employed in this study. In contrast, the PTC system benefits from a vacuumed layer on top of its tubular receiver, acting as a barrier against convective losses. This phenomenon becomes particularly significant during the summer months, which increases the performance gap between the two systems. The simulations have shown that the maximum monthly thermal energy output comes in June when the PTC system generates 15.4 GWh and the ST system produces 9.6 GWh. In contrast, the lowest monthly energy production occurs in January, when the PTC and ST systems generate 4.15 GWh and 3.37 GWh, respectively, due to low irradiation values and ambient temperatures in January. Annually, both the PTC and ST systems prove their effectiveness in meeting the thermal energy demand of the steel production process. Remarkably, the PTC system covers 118% of the total demand, surpassing the ST system, which meets 80% of the requirement, all within the constraints of the same land area.

In Figure 9, the monthly system efficiencies for ST and PTC systems are given. The total system efficiencies are obtained by taking the ratio of total useful thermal energy output to total energy input, which is DNI in this case. The PTC system in the prescribed region shows a greater performance in total system efficiency of 0.54 on average, while the ST shows a total monthly average system efficiency of 0.28.

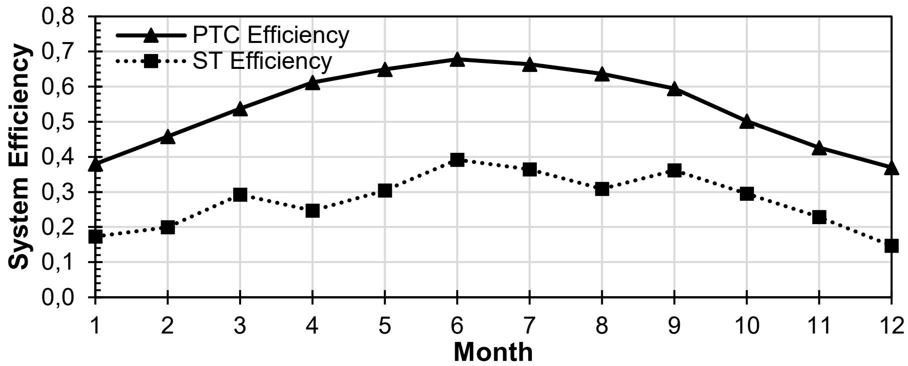

Figure 9. *Monthly system efficiencies for the parabolic trough collectors and solar tower system.*

Economically, the viability of these solar thermal systems is assessed through the Levelized Cost of Heat (LCOH). According to calculations based on NREL's suggested values, the LCOH for the PTC and ST systems stands at 36.9 and 68.9 EUR/MWh, respectively. Of significance is the close alignment of the PTC system's LCOH with the cost of natural gas at the analyzed steel production plant, which was recorded at 39.8 EUR/MWh as the average value in 2023. This emphasizes the PTC system's competitive character in terms of economic viability compared to conventional energy sources.

4. Conclusions

This paper presents a comparative methodology for meeting the thermal energy requirement of industrial processes using two concentrated solar thermal (CST) systems, namely, solar tower (ST) and parabolic trough collectors (PTC), considering a case study. The case study desires 100,000 tonnes/year of steam production at 40 bar and 435°C on an available land area of 0.4 km^2. After the layout and geometry of both CST systems are optimized, the results revealed that the PTC system could fulfil the steel production plant's energy demands for steam generation, which is about 7.9 GWh throughout the year, for two-thirds of the year, while the ST system could supply them for approximately one-third of the year. This could reduce the emission CO_2 in the steel production process by about 12.7 and 19.1 kilo-tonnes for ST and PTC, respectively.

In terms of energy, even though the PTC system could not satisfy the thermal energy demand in winter, the total annual useful thermal energy generated by PTC, which is 112.7 GWh is 18% higher than the total thermal energy demand which is 94.8 GWh; hence, a thermal energy storage system which can be operating in months without winter can be integrated into the PTC system. However, since the PTC system is restricted by its HTF operating temperature range, unlike ST, it cannot directly replace the currently in-use process for generating steam at 40 bar and 435°C for forementioned steel production process. However, PTC emerges as a very promising decarbonized alternative for applications such as pre-heating in steel production process of interest. On the other hand, on a monthly basis, the total annual useful thermal energy generated by ST, which is 58.4 GWh, is 62% of the total thermal energy demand of the process. Due to its wider and elevated temperature range, it can replace the whole process almost entirely in June, July and September, and it can decarbonize the steel production process by more than 65% in May and September.

Given that the process heat is considered an intermediate good and the company provides the land area for installation, ST and PTC installations are viable options for mitigating the use of natural gas in the industry, except for the high capital costs. The LCOH is estimated to be 36.9 and 68.9 EUR/MWh compared to the factory's 39.8 EUR/MWh natural gas tariff. Thus, the LCOH of PTC is comparable with the cost of natural gas. Overall, this study not only analyzes the feasibility of CST systems for a case study but also serves as a foundation for incorporating CST systems into steel industry facilities that can be applied in different global regions.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author, Onur Taylan. The data are not publicly available due to the data privacy concerns of the industrial company used as a case study in this paper.

Author Contributions

Deniz Değirmenci: Data curation, formal analysis, methodology, software, validation, visualization, writing-original draft. **Levent Güner**: Data curation, formal analysis, methodology, validation, visualization, writing-original draft. **Onur Taylan**: Conceptualization, methodology, project administration, supervision, writing-review&editing. **Didem Nedret İnceoğlu**: Project administration, resources, writing-original draft. **Selver Sakallı**: Resources, writing-review&editing. **Erdal Ünal**: Writing-review&editing.

Competing Interests

The authors declare that they have no competing interests.

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