UNIVERSIDAD POLITÉCNICA SALESIANA ECUADOR
INGENIUS
Revista de Ciencia y Tecnología
https://doi.org/10.17163/ings.n27.2022.06
pISSN: 1390-650X / eISSN: 1390-860X

A review of the state-of-the-art of solar thermal collectors applied in the industry

Una revisión de los últimos avances de los colectores solares térmicos aplicados en la industria

Willian Carrión-Chamba[1], Wilson Murillo-Torres[1],
Andrés Montero-Izquierdo[2,*]

Received: 16-05-2021, Received after review: 28-06-2021, Accepted: 03-08-2021, Published: 01-01-2022

Abstract

The energy consumption associated with the industry sector represents 38% of the global energy demand, being an important aspect that marks the development of a country. In this sense, it is extremely important to diversify the different energy sources and incorporate the use of renewable energy sources, such as solar energy, not only with the idea of ensuring energy supply, but also as elements that enable the reduction of energy emissions generated by the use of fossil fuels. This work addresses the main solar collector technologies that may be incorporated into different types of industries, based on experiences and research in other countries. Based on this review, it has been seen that an important part of the industries worldwide requires temperatures up to 250 °C in their processes, which makes suitable the use of solar energy technology. Depending on each industry, flat plate, vacuum tube, Fresnel type or parabolic trough solar collectors may be used. Finally, the savings associated with some facilities are detailed and the challenges related to this sector are addressed.

Keywords: Solar energy, solar thermal collectors, industrial applications.

Resumen

El consumo energético asociado al sector de la industria representa el 38 % de la demanda de energía a nivel global, siendo un aspecto importante que marca el desarrollo de un país. En este sentido, es sumamente importante diversificar las distintas fuentes de energía e incorporar el uso de fuentes renovables de energía, como la solar, no solamente con la idea de asegurar el suministro energético, sino también considerando como elementos que permitan la reducción de las emisiones generadas por el uso de combustibles fósiles. El presente trabajo aborda las principales tecnologías de colectores solares que pueden ser incorporadas a distintos tipos de industrias, basado en experiencias e investigaciones en otros países. Sobre la base de esta revisión, se ha visto que una buena parte de las industrias a nivel mundial requieren temperaturas en sus procesos hasta los 250 °C, lo que hace idóneo el uso de esta tecnología. En función de cada industria, se podrán usar colectores solares de placa plana, de tubos de vacío, del tipo Fresnel o cilindro parabólicos. Por último, se detallan los ahorros asociados a algunas instalaciones y se abordan los desafíos relacionados con este sector.

Palabras clave: energía solar, colectores solares térmicos, aplicaciones industriales

[1]Facultad de Ciencias Químicas, Universidad de Cuenca, Ecuador.
[2,*]Grupo de Ingeniería de Reactores, Catálisis y Tecnologías del Medio Ambiente - IRCMA, Facultad de Ciencias Químicas, Universidad de Cuenca, Ecuador. Corresponding author ✉: andres.montero@ucuenca.edu.ec.

Suggested citation: Carrión-Chamba, W.; Murillo-Torres, W. and Montero-Izquierdo, A. "A review of the state-of-the-art of solar thermal collectors applied in the industry," *Ingenius, Revista de Ciencia y Tecnología*, N.° 27, pp. 59-73, 2022, DOI: https://doi.org/10.17163/ings.n27.2022.06.

1. Introduction

Energy is a key component for the well-being and economic development of a nation, and thus an economy based on industrialization is one of the reasons of the increasing trend in energy consumption [1]. The industry sector employs 38 % of the global energy demand, representing the economic activity with the highest consumption of this resource [2]. For manufacturing industries, the energy sources generally come from fossil fuels and natural gas. However, greenhouse gas emissions produced by combustion of hydrocarbons, have become an environmental problem that accelerates the effects of climate change [3]. The current challenge faced by the industry sector is incorporating efficient alternatives of sustainable energy to reduce the air pollution levels [4]. In this situation, a solution is the implementation of systems based on renewable energies and energy efficiency measures, considering that in the future fossil fuels will reach their extraction limit. Due to its abundance and free availability, solar energy is one of the renewable resources with the greatest potential to reduce the levels of CO_2 emissions to the atmosphere [5]. It is possible to take advantage of solar radiation in two ways: direct conversion in electricity through photovoltaic cells and thermal conversion using solar collectors [6].

The use of solar thermal energy in industry has been the subject of research activity from the 70s through programs of the International Energy Agency (IEA) such as the Solar Heating & Cooling Programme [7]. At the end of 2019 the installed solar thermal power was 700 MWt, considering at least eight hundred projects with a total capturing area of approximately one-million square meters installed worldwide [8]. Food, textile, paper, metal, plastic and chemical industries highlight among the main industries that use solar thermal energy in their manufacturing processes [9]. According to the type of industrial process, solar collectors may be classified in three categories based on their temperature range: low temperature (< 150 °C), medium temperature (150 - 400 °C) and high temperature (> 400 °C) [10]. However, in commercial and industrial companies there is a greater demand at temperatures below 250 °C [11]. This paper comprises a review of the latest advances on solar thermal collectors applied to industry through the presentation of technical, economic and environmental aspects, considering real facilities and dynamic simulations of the systems analyzed.

2. The use of solar thermal energy

The solar thermal energy consists of using energy from the sun to heat a heat carrying fluid and transfer this heat to another medium within a process or system. This type of renewable energy can substitute or reduce the use of fossil fuels and due to the existence of a competitive market it is considered as one of the most economic commercial alternatives for producing heat [12]. However, the intermittency of solar energy makes necessary to have available auxiliary thermal storage systems, which results in larger investment costs and, in turn, lower economic viability for the execution of new projects [13]. Thermal energy may be stored in the form of latent heat or sensible heat; however, in the latent heat mechanism with phase change materials (PCM) it is required a smaller storage volume since the energy density is larger than in heat sensible materials [7].

Solar thermal collectors are devices in charge of transforming solar energy into thermal energy through different operating principles that vary according to the type of collector used [14]. The main aspects to be taken into account in industrial applications for installing a solar thermal system are the target temperature, energy requirement, economic criteria, space availability and degree of maturity of the technology analyzed [15]. Based on temperature ranges and the use in industry, this work covers low and medium temperature collectors.

2.1. Low temperature collectors

2.1.1. Flat plate collector

The flat plate collector (FPC) transforms solar energy into thermal energy using a panel constituted by a glazed cover, which enables solar light to pass, hit and be absorbed by the selective surface of an absorbing plate. Figure 1 shows the cross section of an FPC where its components may be seen.

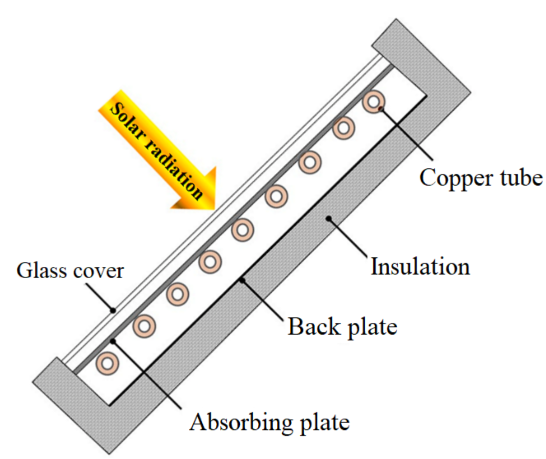

Figure 1. Parts of a flat plate collector [16]

After being intercepted by the plate, the thermal energy is transferred to the inside of the tubes through which the heat carrying fluid circulates, to finally go to a storage system, or be used directly [17]. The system heat loss is reduced using thermal insulation in the lower and lateral parts of the carcass; similarly, the glass cover minimizes the convection and radiation heat losses emitted from the absorbing plate [18]. A particular feature of the FPCs is that they take advantage of direct and diffuse solar radiation; however, since they are stationary, they receive less energy per unit area of the collector [17]. These devices operate in a low temperature interval (< 100 °C) and since they have a simple structure compared with other collectors, they have a low cost in the market [19].

2.1.2. Vacuum tube collector

The vacuum tube collector or evacuated tube collector (ETC) consists of a specific number of crystal tubes each of which is constituted by two concentric tubes. The inner tube is covered by a selective absorbing layer, while each concentric unit is separated by the vacuum sealing principle [18]. The objective of generating vacuum is to reduce the convection and conduction heat losses; in addition, it is a technical advantage that enables operating the device at temperatures higher than FPCs.

The operation temperature of an ETC may reach values up to 120 °C [20]. In addition, the high thermal efficiency and the relatively low cost of this collector are the main reasons of its high competitiveness in the market [21]. There are two main types of ETCs:

1. Heat-pipe ETC: This collector is based on the operating principle known as evaporation-condensation cycle. The process starts when the heat tube receives solar radiation which makes that the highly volatile fluid (for example, methanol or ethanol) contained in it changes from liquid to gaseous state, causing that the vapor goes to the upper part of the tube where the condenser is located [18]. After condensing the vapor releases latent heat to the main circuit and then the condensed liquid returns to the lower part of the tube to complete the circulation cycle [22]. Figure 2 shows the cross section of a heat-pipe vacuum tube collector.

2. Direct flow ETC. In this collector, the inside of the absorbing tube is vacuum insulated and has a U-shaped tube built-in which enables the inlet and outlet of the fluid (Figure 3). The inner tube is made up of metal and is covered with a coating of selective material to accelerate heat transfer to the fluid and reduce radiation losses. During the process, the cold fluid enters and absorbs heat from the U-shaped tubes heated by solar radiation to finally be discharged through the outlet of the pipes [17].

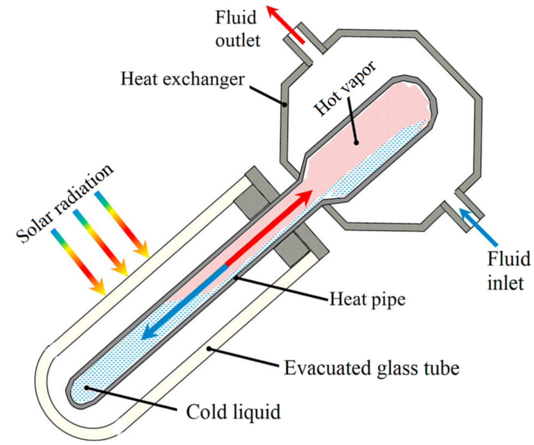

Figure 2. Cross-section of a heat-pipe tube collector [16]

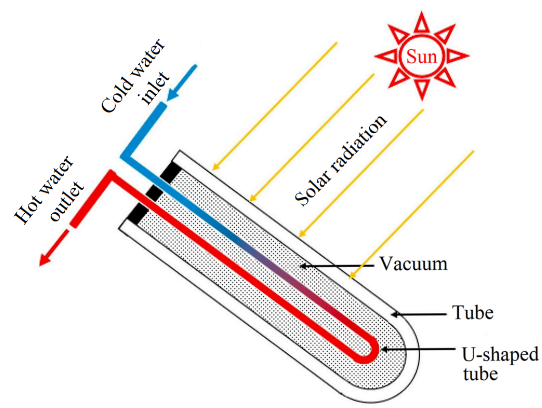

Figure 3. Cross-section of a direct flow vacuum tube collector [9]

2.1.3. Compound parabolic collector

The compound parabolic collector (CPC) consists of two parabolic surfaces covered by reflective material that share the same center. The absorbing tube is located in the center of these parabolas, which enables capturing the incident solar radiation that enters the opening area of the collector within the acceptance angle [19].

The construction design of these devices enables a better use of the diffuse solar radiation and reduces the action of performing continuous tracking adjustments [23]. There are various models which adapt to achieve a higher efficiency; a very practical example is to couple the CPC with vacuum tubes. In industrial applications, the CPCs reach temperatures < 150 °C [24]. Figure 4 shows a schematic representation of this collector where it is seen the two parabolic surfaces that concentrate solar radiation in the absorbing tube.

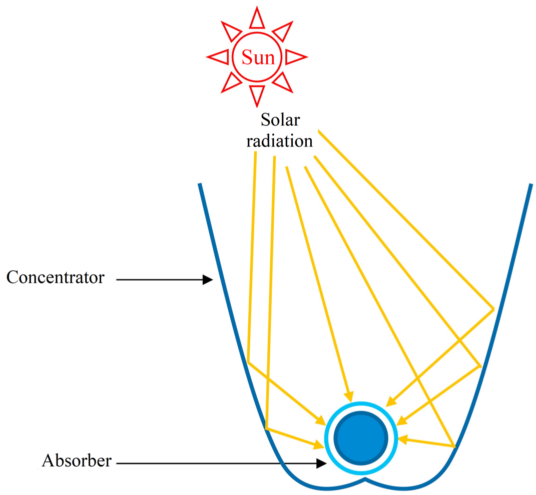

Figure 4. Compound parabolic collector [9]

2.2. Medium temperature collectors

2.2.1. Evacuated flat plate collector

The evacuated flat plate collector (EFPC) combines the design of the FPC and the vacuum principle of the ETC. Figure 5 shows that a collector of this type consists of: a structure constituted by an aluminum carcass and various elements such as a glass cover, an absorbing plate, a copper coil for heat exchange and a lower plate. The inner vacuum enables achieving a higher thermal efficiency since the conduction and convection losses are eliminated; in addition, this effect causes that the collector occupies less surface than the ETC. Medium temperatures between 120 and 180 °C may be reached with this technology, to fulfill requirements of industrial heat [25].

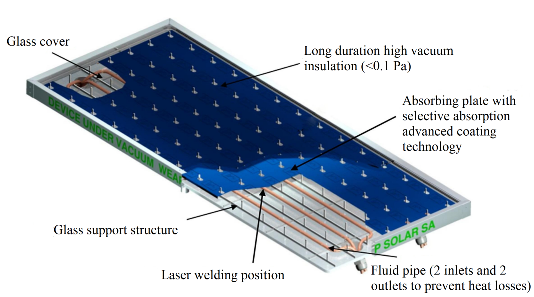

Figure 5. Structure of the evacuated flat plate collector [25]

2.2.2. Parabolic Cylinder collector

The parabolic cylinder collector or parabolic trough collector (PTC) has a parabolic-shaped sheet that reflects direct solar radiation and concentrates it in the receiving tube located along the focal line. In general, the metal absorbing tube is covered with a selective material (copper) which improves heat transfer to the inside of the tube through which the heat carrying fluid circulates. This absorbing pipeline is vacuum insulated with a glass tube to reduce the convection thermal losses, although optical losses are produced by the effect of reflection [19]. These collectors should be coupled to a tracking system to get aligned to the sun trajectory during the day (Figure 6).

The orientation of the collector may be configured in north-south direction with east-west tracking to capture more energy during summer; whereas, if the objective is maximizing the energy during winter the appropriate direction of the collector should be east-west with north-south tracking [26]. Solar concentration modules with a capturing area smaller than 250 m^2 and operating at a medium temperature below 300 °C are normally used in industrial processes with this type of collectors [27]].

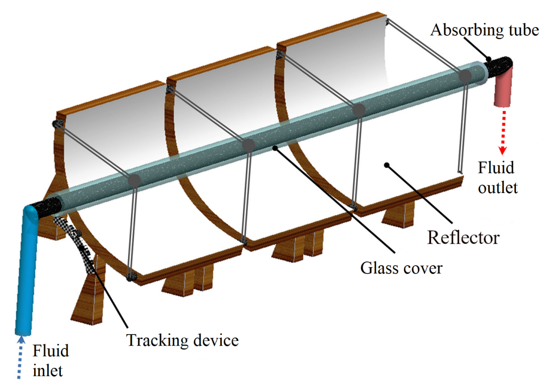

Figure 6. Scheme of a parabolic cylinder collector [16]

2.2.3. Linear Fresnel collector

The linear Fresnel collector (LFC) consists of two main parts: a stationary absorbing tube through which the heat carrying fluid circulates and a series of reflecting mirrors aligned horizontally that are coupled to a uniaxial tracking system [19]. The operating principle of the collector occurs when the solar radiation impacts on the reflecting mirrors (either curved or flat) and is directed to concentrate in the absorbing tube (Figure 7).

To maximize the concentration of solar energy, particular designs decide to install a CPC collector on the upper part of the receiver or focal point with the objective of redirecting solar radiation to the absorbing tube [28]. One of the advantages that make an LFC competitive with respect to a PTC is its simple construction, which implies a lower investment cost; however, optical and geometrical limitations such as shading and blocking between mirrors reduce the degree of efficiency of the collector [27]. In industrial processes, this type of collector may reach medium temperature intervals (60 ºC $<$ T $<$ 250 ºC) [29].

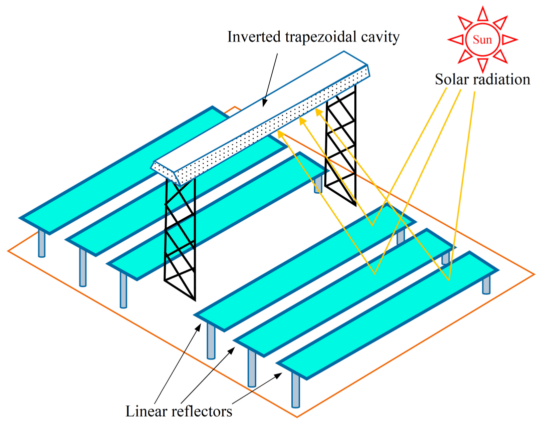

Figure 7. Scheme of a linear Fresnel collector [9]

The efficiency (η) equation may be employed to compare the performance between collectors.

$$\eta = a_0 - a_1 \frac{(T_m - T_{amb})}{G} - a_2 \frac{(T_m - T_{amb})^2}{G} \quad (1)$$

Figure 8 shows a comparison between efficiencies for various solar thermal collectors according to Equation (1), where: T_m corresponds to the mean temperature of the heat carrying fluid, T_{amb} is the ambient temperature, a_0 is the optical performance, a_1 is the first-order coefficient of losses, a_2 is the second-order coefficient of losses and G is the global irradiance. For this comparison, it is assumed a global irradiance of 1000 W/m^2 and an ambient temperature of 20 °C; it is observed through equation (1) that FPC collectors achieve a high efficiency for a low ΔT, whereas as this variable increases its efficiency is drastically reduced. The opposite occurs with the remaining collectors, for which the efficiency reduces as the value of ΔT increases not so drastically. It is even observed that the PTC collector maintains its efficiency almost constant as the temperature differential ΔT increases.

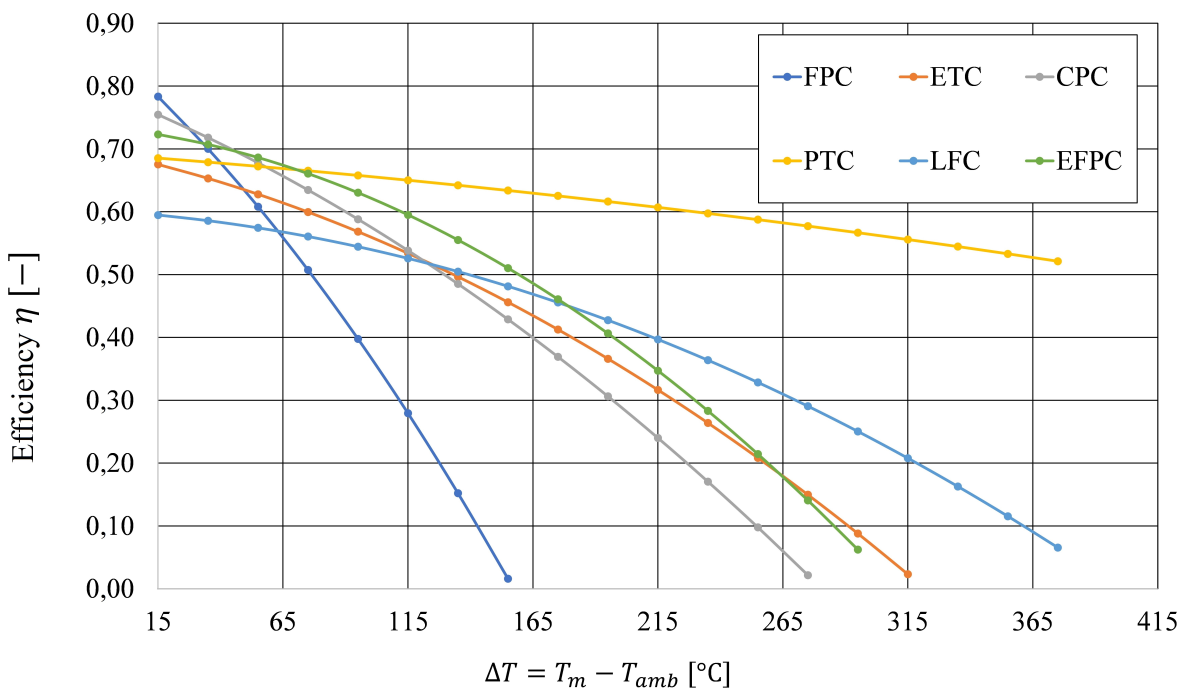

Figure 8. Comparison between solar collectors (Prepared by the authors)

3. Application of solar thermal energy in industry

Solar thermal energy has become a key component that will contribute to the decarbonization of the industry sector. The worldwide heat consumption in the industry sector is approximately 85 EJ, of which 30 % corresponds to the demand of low temperature heat [30]]. A review of case studies is presented hereafter, based on computer simulation, for industrial applications.

A research study to evaluate the viability of integrating an FPC as a heat generation system for preheating raw material in two fish flour producing companies was conducted in South Africa. The study demonstrated that the installation profitability is justified in factory A, because it is required a relatively constant heat monthly demand and due to the high cost of fuel oil which make this system a competitive solar technology. However, installing an FPC system in factory B is not feasible due to the low cost of carbon and because the seasonal demand profile is variable [31]. A study to evaluate the performance of incorporating a heat storage system with phase change materials together with FPC collectors in the tropical zone of Merida-Mexico revealed that lauric acid, due to its thermophysical characteristics, is the most appropriate PCM to obtain a higher thermal gain throughout the year. In addition, the financial analysis indicated that the maximum value of 17.2 % in the internal rate of return is achieved if the heat storage system is coupled with an arrangement of five FPC collectors for the water heating process in a clothing factory [32].

On the other hand, Anastasovski [33] analyzed the performance of eighteen solutions for integrating solar heat in an ethanol producing industry considering ETC and PTC technologies, considering solar radiation in typical days during the seasons of the year. The findings show that the most attractive solution is the design with ETCs coupled to a heat storage system with high pressure water during the winter solstice, since it enables replacing 35 % of the heat required and recover the investment in approximately 4.5 years.

In other study, Maillot, Castaing-Lasvignottes and Marc [34] simulated four different cases to assess the direct and indirect integration of coupling ETC collectors in the vapor generation system of a yogurt producing industry. According to the technical evaluation, the highest saving of fuel is 24 %, which is achieved when the collectors with a capturing area of 555 m^2 are directly integrated in the tank of the boiler.

Table 1 shows technical aspects for industrial applications, existing and at a simulation level, based on thermal systems with FPC and ETC technologies.

Table 1. Technical, economic and environmental aspects of the application and simulation of solar collectors with FPC and ETC technologies for industrial processes in different countries of the world

Location	**Industry**	**Temperature industrial process (°C)**	**Capturing area collector (m^2)**	**Solar fraction (%)**	**Savings**	**Source**
South Africa	Production of fish flour preheating	70	384-FPC	81	32 061 liters of fuel oil	[31]
Macedonia	Production of ethanol water heating preparation of saline solutions and molasses	95	n/a-ETC	n/a	approx. 57 % of fuel oil	[33]
Reunion Island	Yogurt-vapor generation from the direct integration of the solar collector in the tank of the boler	160-170	555-ETC	n/a	24 % of fuel	[34]
Marocco	Milk-water heating drying and cleaning of fruits, colling and pasteurization	60-90	400-ETC	41	77,23 tCO_2e/year	[35]
Ethiopia	Clothes-water heating dyeing	50-90	472-ETC	56,3	252,2 tCO_2e/year	[36]

In the case of CPC collectors, Milczarek *et al.* [37] experimented with the drying of tomato and plum marcs with a solar drum dryer, for which they used 26 external CPC with a capturing area of 98.3 m^2 that enabled heating the drum surface to a minimum temperature of 92°C. The final result demonstrated the effectiveness of solar thermal energy to achieve stability in the storage of these fruits and vegetables. In Argentina, the CPCs have shown to be an economic and environmentally viable alternative at temperatures that oscillate between 100 y 150 °C since the leveled energy cost is between 2.5 and 16.9 euros per kWh/m^2. Similarly, the ranges associated to the reduction of greenhouse gas emissions by substituting electricity and natural gas by this solar system are between 179 and 348 $kgCO_2/m^2$·year and between 113 and 220 $kgCO_2/m^2$·year, respectively.

Table 2 shows cases about applications and simulations with PTC and LFC capturing technologies.

Table 2. Technical, economic and environmental aspects of the application and simulation of solar collectors with PTC and LFC technologies for industrial processes in different countries of the world

Location	**Industry**	**Temperature industrial process (°C)**	**Capturing area collector (m^2)**	**Solar fraction (%)**	**Savings**	**Source**
Italy (Molina di Fiemme)	Pasta-water heating-drying of pasta	135	840-PTC	23	4,7 tCO_2/week	[11]
Cyprus (Limasol)	Drinks-vapor generation-cleaning, pasteurization and sterilization	188	288-PTC	n/a	40 €/t of vapor	[38]
Switzerland (Saignelégier)	LMilk-water heating-cleaning	117	627-PTC	12	69 tCO_2/yerar	[39]
Portugal (Santarém)	Production of agglomerated of expanded cork preheating of bolier feeding water	170	1328-PTC	36,9	76,5 tep and 201,8 tCO_2e/GJ	[40]
Morocco (Rabat)	Asphalt-bitumen heating	160	n/a-PTC	40	0,75-1,5 tCO_2/year/kW	[41]
Indonesia	Niquel mining vapor generation for sulfur heating	135-145	n/a-LFC	n/a	45 000 USD/year	[42]
Italy (Sicily)	Wheat pasta overhead water pasta drying	120-140	6602-LFC	40	n/a	[43]

The study by means of dynamic modeling of a solar field with PTCs, for water heating in the process of drying Italian pasta in an Italian factory, evidenced that the design of this system has the capability of guaranteeing 23 % of the weekly thermal energy demand used in this process [11]. In the work by Ghazouani, Bouya and Benaissa [15], the design and operating parameters of a small PTC were analyzed with the purpose of maximizing the thermal and economic efficiency and the energy performance under the meteorologic conditions of the city of Rabat; with the improvement of the technical features of the collector they were able to supply more than 12.84 MWh/year at a competitive smaller cost of 0.022 USD/kWh with each device.

In the case of milk industry, Biencinto *et al.* [44] proposed an innovative thermal storage system supplied by a field of PTCs to contribute to the heat demand at three different temperature levels in the pasteurization process. According to the simulation results, the use of thermal storage based on pentaglycerine (PCM) covering a range of three hours may fulfill 20-27 % and 40-52 % of the annual energy demand in the cities of Graz-Austria and Almería-Spain, respectively.

In their study conducted for the implementation of solar thermal energy in the milk industry in India, Sharma *et al.* [45] determined that through the installation of PTCs it is possible to reach a solar fraction between 16 and 33 % according to the location of each factory. However, the low cost of fossil fuels and the inability of solar systems to fulfill the total heat demand in manufacturing processes, make these investments unsecure.

May Tzuc *et al.* [46] performed an optimization model with PTCs to be integrated in the milk industry considering four different types of climates in Mexico. The research states that these collectors may fulfill a demand ranging between 40 and 80 % of the heat used in pasteurization. Similarly, the annual saving in emissions for the four climatic regions with the application of this technology oscillates between 39.5 and 95.3 tCO_2.

Cortés *et al.* [47] indicated that the integration of PTCs in the food industry in Chile results technically and economically feasible, because this technology would be competitive with fossil fuels if in most of the regions of the country the installation cost of the solar field is under 250 USD/m^2.

Ktistis, Agathokleous and Kalogirou [38] demonstrated that PTCs coupled with a concrete storage system is a viable alternative to be used in the drinks industry in Cyprus, since the vapor production cost for cleaning, pasteurization and sterilization processes of the factory with this solar system is 10 €/t, as opposed to 50 €/t which is the cost of vapor generation when a conventional boiler is employed with fuel price of 700 euros per ton.

Regarding LFCs, Laadel *et al.* [48] argued that this solar collector coupled to a heat system is technically suitable for integration in Moroccan industries, since they may reach solar fraction values up to 40 % without including thermal storage. Buscemi *et al.* [43] examined the possibility of generating heat from a solar field with LFCs for pasta drying in an Italian factory. The simulation result of this solar system with concrete storage generates a solar fraction of 40 % and an investment recovery time of eight years.

There are research works about the application of solar heat which are exploring other sectors and operations, such as for example the asphalt industry for heating bitumen [41]; in management processes of industrial and residual waters [49] and in vapor generation for the pharmaceutical industry using LFCs [50].

In this context, the contribution of new research works about adjusting the design of solar collectors has enabled searching for alternatives to improve performance and reduce the leveled cost of heat for these thermal systems. For example, the innovative design of an FPC with only one collector tube with spiral shape compared with a conventional FPC with the same area and tubes of the same diameter and length, achieves an improvement of 21.45 % in thermal efficiency when operating with a mass flow of 0.026 kg/s and 1011 W/m^2; in addition, the pressure drop of the fluid is reduced with the spiral design of the tube and it is possible to save 30 % of the total of manufacturing materials [51].

An experiment conducted in Las Vegas-USA about the design of a support structure for a PTC using wood, demonstrated that the collector may have an appropriate performance for thirty years with a continuous monitoring and maintenance of the wood. The economic analysis determined that the estimated installation cost of this design was 56.14 USD/m^2, which significantly reduces the leveled cost of heat for generation of vapor in the industrial process [52].

4. Suppliers of solar thermal collectors

According to the Solar Payback program, 251 MW$_t$ related to solar thermal systems were installed during 2019, intended to industry worldwide, a value significantly larger than the 39 MW$_t$ installed in 2018 [53]. This program counts around 76 worldwide suppliers of solar capturing technologies, most of which produce their own systems. Table 3 presents the suppliers that had installed more than ten projects by the end of 2019, under the modality of «turnkey»

Table 3. Suppliers of «turnkey» solar collectors [53]

Collector	Supplier/Country	Projects	Area (m^2)
FPC	Modulo Solar/Mexico	89	15 616
	Inter Solar Systems/India	22	10 400
ETC	Sunrain Solar Energy /China	72	52 970
	Linuo Paradigma/China	47	90 470
	Ritter Energie-und Umwelttechnik/Germany	29	5165
	Sunda Solar Energy/ China	16	9432
	Himin/China	15	29 627
PTC	Inventive Power/Mexico	66	10 570
	Vicot Solar Technology/China	24	22 560
	Soliterm/Germany	20	37 069
Paraboloid dish	Megawatt Solutions/India	32	16 545
Heat supply contract	Millennium Energy Industries (MEI)/Jordan	22	3611
	Solid Energy Systems/Austria	15	11 779
n/a	Casolar/Mexico	14	n/a

5. Costs of the technologies

In order to integrate a solar heat system in an industry, it is necessary to consider the operating temperature of the solar collector, its cost, the operating and maintenance requirements, as well as other factors related with the use of soil, the time variability of production and the price of fuels [54]. It is also necessary to know that the cost of collectors generally represents between 50 and 70 % of the solar thermal system investment [55]. Table 4 details the areal cost of the different solar capturing technologies, however, it should be taken into account that the information provided about the economic values of the devices is based on referential amounts from simulations and scientific studies.

6. Saving in greenhouse gases emissions

In 2018, direct emissions of CO_2 coming from the industry sector reached a value of 8.5 $GtCO_2$, which represents 24 % of global emissions. The Sustainable Development Scenario proposed by IEA mentions that to reach zero net emissions in 2070, industry emissions must be reduced 1.2 % annually to reach 7.4 $GtCO_2$ in 2030 [56]. The different solar capturing technologies are an alternative to contribute to achieve this environmental goal. A study conducted in China determined that the ten industrial sectors that integrate solar capturing technologies in their productive processes may reduce approximately 98.22 million tCO_2 in 2020 [55].

Table 4. Costs of the different solar capturing technologies

Collector	Country	Cost (USD/m^2)	Source
FPC	Mexico	287 *	[57]
	Chile	330-687	[54]
	Zimbabwe	220-347	[58]
ETC	Mexico	472 *	[57]
	Chile	460-817	[54]
	Zimbabwe	157-433	[58]
CPC	Spain	268-387 *	[59]
	Italy	131 *	[11]
PTC	Mexico	402 *	[57]
	Spain	393-666 *	[59]
	Chile	379-1263	[54]
	Italy	262 *	[11]
LFC	Spain	309-506 *	[59]
	Italy	199 *	[11]

*Monetary units adjusted from euros to USD, considering an exchange rate of 1.19 USD per euro, according to the average price of the currency in the period July 2020-July 2021 [60].

On the other hand, McMillan *et al.* [61] demonstrated that in USA the PTCs combined with a sensible heat storage system using water or synthetic oil, are the technology that may be employed to fulfill the heat demand in industrial processes in most of the country; and its installation might represent an annual saving of 137 million of metric tons of CO_2.

Another research evidenced that the installation of solar thermal systems in various processes of the cotton textile industry in India might reduce between 2.46 and 7.67 million tCO_2 annually [62]. In Europe, Kylili *et al.* [63] analyzed the emissions reducing potential associated with the installation of low temperature solar thermal systems for heating water in industries. In their study, they evaluated the pollution degree based on the phases of the life cycle of the system, and concluded that it is possible to save between 35 and 75 GJ of energy, and between 2 and 5 tCO_2/kWt depending on the geographic zone.

7. Research challenges and opportunities

According to the literature reviewed, there is a progressive trend in the use of solar thermal energy in various industrial processes, but the real installed capacity is still small. Hereafter, some topics that may be addressed are presented, in order to promote the extensive use of solar thermal energy in industry.

- Development of new thermal collectors and storage technologies: research on new materials that improve the thermal generation efficiency and reduce the weight of collectors. In storage systems it is essential to search for alternatives with higher thermodynamic efficiency to reduce the impact of solar intermittency [64].
- Adaptability to industrial processes: the industry sector requires an innovative integration between solar collectors and process technologies that are adapted to different sectors and location of industries [64].
- Investment in R+D: The current crisis related to COVID-19 will reduce the R+D investment in the private sector, and thus the Governments of the most important economies will be in charge of promoting policies and economic support that motivate the R+D in this area [65].

8. Conclusions

Until 2019, the solar thermal energy incorporated in industrial processes represented an installed power of 700 MW_t, being a continuously growing alternative within this economic sector.

In the industrial sector, solar thermal collectors are mainly used for water heating and vapor generation. Food industries are the ones that have mostly integrated these technologies, since most of their processes require low temperature heat. However, various studies have evaluated that solar thermal energy may be implemented in mining, textile and pharmaceutical industries, among others.

In order to integrate solar thermal technologies in industry, it should be mainly considered the thermal energy demand of the process, the production profile, the available space, the geographic location, and the type and cost of the collector.

It has been seen that the main obstacles that prevent the expansion of solar thermal technologies in the industrial market are the low cost of fossil fuels, economic thermal storage systems still being researched and nonexistent or inefficient energy policy.

References

[1] B. Koçak, A. I. Fernandez, and H. Paksoy, "Review on sensible thermal energy storage for industrial solar applications and sustainability aspects," *Solar Energy*, vol. 209, pp. 135–169, 2020. [Online]. Available: https://doi.org/10.1016/j.solener.2020.08.081

[2] IEA. (2020) World energy balances: Overview. [Online]. Available: https://bit.ly/3jEw90a

[3] S. H. Farjana, N. Huda, M. A. P. Mahmud, and R. Saidur, "Solar industrial process heating systems in operation - current ship plants and future prospects in Australia," *Renewable and Sustainable Energy Reviews*, vol. 91, pp. 409–419, 2018. [Online]. Available: https://doi.org/10.1016/j.rser.2018.03.105

[4] V. Pranesh, R. Velraj, S. Christopher, and V. Kumaresan, "A 50 year review of basic and applied research in compound parabolic concentrating solar thermal collector for domestic and industrial applications," *Solar Energy*, vol. 187, pp. 293–340, 2019. [Online]. Available: https://doi.org/10.1016/j.solener.2019.04.056

[5] S. H. Farjana, N. Huda, M. P. Mahmud, and R. Saidur, "Solar process heat in industrial systems - a global review," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2270–2286, 2018. [Online]. Available: https://doi.org/10.1016/j.rser.2017.08.065

[6] S. K. Verma, N. K. Gupta, and D. Rakshit, "A comprehensive analysis on advances in application of solar collectors considering design, process and working fluid parameters for solar to thermal conversion," *Solar Energy*, vol. 208, pp. 1114–1150, 2020. [Online]. Available: https://doi.org/10.1016/j.solener.2020.08.042

[7] C. A. Schoeneberger, C. A. McMillan, P. Kurup, S. Akar, R. Margolis, and E. Masanet, "Solar for industrial process heat: A review of technologies, analysis approaches, and potential applications in the united states," *Energy*, vol. 206, p. 118083, 2020. [Online]. Available: https://doi.org/10.1016/j.energy.2020.118083

[8] W. Weiss and M. Spörk-Dür, *Solar Heat Worldwide*. IEA Solar Heating & Cooling Programme, Austria, 2020. [Online]. Available: https://bit.ly/2WT0yPM

[9] K. Ravi Kumar, N. V. V. Krishna Chaitanya, and N. Sendhil Kumar, "Solar thermal energy technologies and its applications for process heating and power generation - a review," *Journal of Cleaner Production*, vol. 282, p. 125296, 2021. [Online]. Available: https://doi.org/10.1016/j.jclepro.2020.125296

[10] IEA. (2017) Renewable energy for industry. [Online]. Available: https://bit.ly/3BGLYty

[11] M. Bolognese, D. Viesi, R. Bartali, and L. Crema, "Modeling study for low-carbon industrial processes integrating solar thermal technologies. a case study in the italian alps: The felicetti pasta factory," *Solar Energy*, vol. 208, pp. 548–558, 2020. [Online]. Available: https://doi.org/10.1016/j.solener.2020.07.091

[12] A. Shahsavari and M. Akbari, "Potential of solar energy in developing countries for reducing energy-related emissions," *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 275–291, 2018. [Online]. Available: https://doi.org/10.1016/j.rser.2018.03.065

[13] A. Gautam and R. Saini, "A review on sensible heat based packed bed solar thermal energy storage system for low temperature applications," *Solar Energy*, vol. 207, pp. 937–956, 2020. [Online]. Available: https://doi.org/10.1016/j.solener.2020.07.027

[14] L. Evangelisti, R. De Lieto Vollaro, and F. Asdrubali, "Latest advances on solar thermal collectors: A comprehensive review," *Renewable and Sustainable Energy Reviews*, vol. 114, p. 109318, 2019. [Online]. Available: https://doi.org/10.1016/j.rser.2019.109318

[15] M. Ghazouani, M. Bouya, and M. Benaissa, "Thermo-economic and exergy analysis and optimization of small ptc col-

lectors for solar heat integration in industrial processes," *Renewable Energy*, vol. 152, pp. 984–998, 2020. [Online]. Available: https://doi.org/10.1016/j.renene.2020.01.109

[16] S. Suman, M. K. Khan, and M. Pathak, "Performance enhancement of solar collectors - a review," *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 192–210, 2015. [Online]. Available: https://doi.org/10.1016/j.rser.2015.04.087

[17] M. Imtiaz Hussain, C. Ménézo, and J.-T. Kim, "Advances in solar thermal harvesting technology based on surface solar absorption collectors: A review," *Solar Energy Materials and Solar Cells*, vol. 187, pp. 123–139, 2018. [Online]. Available: https://doi.org/10.1016/j.solmat.2018.07.027

[18] M. P. Islam and T. Morimoto, "Advances in low to medium temperature non-concentrating solar thermal technology," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2066–2093, 2018. [Online]. Available: https://doi.org/10.1016/j.rser.2017.08.030

[19] G. Barone, A. Buonomano, C. Forzano, and A. Palombo, "Chapter 6 - solar thermal collectors," in *Solar Hydrogen Production*, F. Calise, M. D. D'Accadia, M. Santarelli, A. Lanzini, and D. Ferrero, Eds. Academic Press, 2019, pp. 151–178. [Online]. Available: https://doi.org/10.1016/B978-0-12-814853-2.00006-0

[20] A. Veera Kumar, T. Arjunan, D. Seenivasan, R. Venkatramanan, and S. Vijayan, "Thermal performance of an evacuated tube solar collector with inserted baffles for air heating applications," *Solar Energy*, vol. 215, pp. 131–143, 2021. [Online]. Available: https://doi.org/10.1016/j.solener.2020.12.037

[21] M. Aramesh and B. Shabani, "On the integration of phase change materials with evacuated tube solar thermal collectors," *Renewable and Sustainable Energy Reviews*, vol. 132, p. 110135, 2020. [Online]. Available: https://doi.org/10.1016/j.rser.2020.110135

[22] A. Shafieian, M. Khiadani, and A. Nosrati, "A review of latest developments, progress, and applications of heat pipe solar collectors," *Renewable and Sustainable Energy Reviews*, vol. 95, pp. 273–304, 2018. [Online]. Available: https://doi.org/10.1016/j.rser.2018.07.014

[23] S. A. Waghmare and N. P. Gulhane, "Design configurations and possibilities of reflector shape for solar compound parabolic collector by ray tracing simulation," *Optik*, vol. 176, pp. 315–323, 2019. [Online]. Available: https://doi.org/10.1016/j.ijleo.2018.09.082

[24] C. Jiang, L. Yu, S. Yang, K. Li, J. Wang, P. D. Lund, and Y. Zhang, "A review of the compound parabolic concentrator (cpc) with a tubular absorber," *Energies*, vol. 13, no. 3, p. 695, 2020. [Online]. Available: https://doi.org/10.3390/en13030695

[25] D. Gao, G. Gao, J. Cao, S. Zhong, X. Ren, Y. N. Dabwan, M. Hu, D. Jiao, T. H. Kwan, and G. Pei, "Experimental and numerical analysis of an efficiently optimized evacuated flat plate solar collector under medium temperature," *Applied Energy*, vol. 269, p. 115129, 2020. [Online]. Available: https://doi.org/10.1016/j.apenergy.2020.115129

[26] L. Kumar, M. Hasanuzzaman, and N. Rahim, "Global advancement of solar thermal energy technologies for industrial process heat and its future prospects: A review," *Energy Conversion and Management*, vol. 195, pp. 885–908, 2019. [Online]. Available: https://doi.org/10.1016/j.enconman.2019.05.081

[27] E. Zarza-Moya, "7 - concentrating solar thermal power," in *A Comprehensive Guide to Solar Energy Systems*, T. M. Letcher and V. M. Fthenakis, Eds. Academic Press, 2018, pp. 127–148. [Online]. Available: https://doi.org/10.1016/B978-0-12-811479-7.00007-5

[28] O. A. López-Núñez, J. A. Alfaro-Ayala, O. Jaramillo, J. Ramírez-Minguela, J. C. Castro, C. E. Damian-Ascencio, and S. Cano-Andrade, "A numerical analysis of the energy and entropy generation rate in a linear fresnel reflector using computational fluid dynamics," *Renewable Energy*, vol. 146, pp. 1083–1100, 2020. [Online]. Available: https://doi.org/10.1016/j.renene.2019.06.144

[29] D. Sakthivadivel, K. Balaji, D. Dsilva Winfred Rufuss, S. Iniyan, and L. Suganthi, "Chapter 1 - solar energy technologies: principles and applications," in *Renewable-Energy-Driven Future*, J. Ren, Ed. Academic Press, 2021, pp. 3–42. [Online]. Available: https://doi.org/10.1016/B978-0-12-820539-6.00001-7

[30] Solar Payback, *Calor Solar para la Industria*. Solar Payback. [Online]. Available: https://bit.ly/3jJE10l

[31] D. Oosthuizen, N. J. Goosen, and S. Hess, "Solar thermal process heat in fishmeal production: Prospects for two south african fishmeal factories," *Journal of Cleaner Production*, vol. 253, p. 119818, 2020. [Online]. Available: https://doi.org/10.1016/j.jclepro.2019.119818

[32] A. Cetina-Quiñones, J. Xamán, A. Bassam, M. Escalante Soberanis, and I. Perez-Quintana, "Thermo-economic analysis of a flat solar collector with a phase changing material under tropical climate conditions: Residential and industrial case," *Applied Thermal Engineering*, vol. 182, p. 116082, 2021. [Online]. Available: https://doi.org/10.1016/j.applthermaleng.2020.116082

[33] A. Anastasovski, "Improvement of energy efficiency in ethanol production supported with solar thermal energy – a case study," *Journal of Cleaner Production*, vol. 278, p. 123476, 2021. [Online]. Available: https://doi.org/10.1016/j.jclepro.2020.123476

[34] C. Maillot, J. Castaing-Lasvignottes, and O. Marc, "Modelling and dynamic simulation of solar heat integration into a manufacturing process in reunion island," *Procedia Manufacturing*, vol. 35, pp. 118–123, 2019, the 2nd International Conference on Sustainable Materials Processing and Manufacturing, SMPM 2019, 8-10 March 2019, Sun City, South Africa. [Online]. Available: https://doi.org/10.1016/j.promfg.2019.05.013

[35] A. Allouhi, Y. Agrouaz, M. Benzakour Amine, S. Rehman, M. Buker, T. Kousksou, A. Jamil, and A. Benbassou, "Design optimization of a multi-temperature solar thermal heating system for an industrial process," *Applied Energy*, vol. 206, pp. 382–392, 2017. [Online]. Available: https://doi.org/10.1016/j.apenergy.2017.08.196

[36] F. B. Tilahun, R. Bhandari, and M. Mamo, "Design optimization and control approach for a solar-augmented industrial heating," *Energy*, vol. 179, pp. 186–198, 2019. [Online]. Available: https://doi.org/10.1016/j.energy.2019.04.142

[37] R. R. Milczarek, J. J. Ferry, F. S. Alleyne, C. W. Olsen, D. A. Olson, and R. Winston, "Solar thermal drum drying performance of prune and tomato pomaces," *Food and Bioproducts Processing*, vol. 106, pp. 53–64, 2017. [Online]. Available: https://doi.org/10.1016/j.fbp.2017.08.009

[38] P. K. Ktistis, R. A. Agathokleous, and S. A. Kalogirou, "Experimental performance of a parabolic trough collector system for an industrial process heat application," *Energy*, vol. 215, p. 119288, 2021. [Online]. Available: https://doi.org/10.1016/j.energy.2020.119288

[39] M. H. Rittmann-Frank, J. Möllenkamp, M. Caflisch, and A. Häberle, "Evaluation of solar process heat systems in switzerland," *AIP Conference Proceedings*, vol. 2033, no. 1, p. 150005, 2018. [Online]. Available: https://doi.org/10.1063/1.5067158

[40] A. Castro, J. a. P. Cardoso, L. F. Mendes, P. Azevedo, and J. a. F. Mendes, "Pre-heating boiler feedwater for expanded cork agglomerate production using a parabolic trough system," *AIP Conference Proceedings*, vol. 2033, no. 1, p. 150002, 2018. [Online]. Available: https://doi.org/10.1063/1.5067155

[41] M. Ghazouani, M. Bouya, M. Benaissa, K. Anoune, and M. Ghazi, "Thermal energy management optimization of solar thermal energy system based on small parabolic trough collectors for bitumen maintaining on heat process," *Solar Energy*, vol. 211, pp. 1403–1421, 2020. [Online]. Available: https://doi.org/10.1016/j.solener.2020.10.074

[42] Suyanto, R. Hantoro, A. Suharto, R. Saleh, and T. D. Reynaldi, "A review of linear fresnel reflector technology for heating sulphur liquid in nickel processing industry," *AIP Conference Proceedings*, vol. 2088, no. 1, p. 020034, 2019. [Online]. Available: https://doi.org/10.1063/1.509528

[43] A. Buscemi, D. Panno, G. Ciulla, M. Beccali, and V. Lo Brano, "Concrete thermal energy storage for linear fresnel collectors: Exploiting the south mediterranean's solar potential for agri-food processes," *Energy Conversion and Management*, vol. 166, pp. 719–734, 2018. [Online]. Available: https://doi.org/10.1016/j.enconman.2018.04.075

[44] M. Biencinto, R. Bayón, L. González, R. Christodoulaki, and E. Rojas, "Integration of a parabolic-trough solar field with solid-solid latent storage in an industrial process with different temperature levels," *Applied Thermal Engineering*, vol. 184, p. 116263, 2021. [Online]. Available: https://doi.org/10.1016/j.applthermaleng.2020.116263

[45] A. K. Sharma, C. Sharma, S. C. Mullick, and T. C. Kandpal, "Financial viability of solar industrial process heating and cost of carbon mitigation: A case of dairy industry in india," *Sustainable Energy Technologies and Assessments*, vol. 27, pp. 1–8, 2018. [Online]. Available: https://doi.org/10.1016/j.seta.2018.03.007

[46] O. May Tzuc, A. Bassam, L. J. Ricalde, O. Jaramillo, M. F.-B. nuelos, and M. Escalante Soberanis, "Environmental-economic optimization for implementation of parabolic collectors in the industrial process heat generation: Case study of mexico," *Journal of Cleaner Production*, vol. 242, p. 118538, 2020. [Online]. Available: https://doi.org/10.1016/j.jclepro.2019.118538

[47] F. Cortés, M. Ibarra, F. Moser, I. Muñoz, A. Crespo, and C. Murray, "Techno-economical evaluation of parabolic trough collectors systems

for steam processes in the chilean industry," *AIP Conference Proceedings*, vol. 2033, no. 1, p. 150003, 2018. [Online]. Available: https://doi.org/10.1063/1.5067156

[48] N. E. Laadel, H. Agalit, A. Mouaky, and E. G. Bennouna, "Potential of solar heat integration in medium temperature industrial processes in morocco," *AIP Conference Proceedings*, vol. 2126, no. 1, p. 150005, 2019. [Online]. Available: https://doi.org/10.1063/1.5117661

[49] C. Brunner, B. Muster-Slawitsch, A. Grubbauer, J. Koschikowski, I. Oller, C. Sattler, K. Hennecke, D. Krüger, M. Duke, and C. Ozansoy, *Solar Energy in Industrial Water and Wastewater management.* IEA Solar Heating & Cooling Programme, 2018. [Online]. Available: https://bit.ly/3BNw9kH

[50] A. Frein, M. Motta, M. Berger, and C. Zahler, "Solar dsg plant for pharmaceutical industry in jordan: Modelling, monitoring and optimization," *Solar Energy*, vol. 173, pp. 362–376, 2018. [Online]. Available: https://doi.org/10.1016/j.solener.2018.07.072

[51] S. K. Verma, K. Sharma, N. K. Gupta, P. Soni, and N. Upadhyay, "Performance comparison of innovative spiral shaped solar collector design with conventional flat plate solar collector," *Energy*, vol. 194, p. 116853, 2020. [Online]. Available: https://doi.org/10.1016/j.energy.2019.116853

[52] N. R. Peralta and P. Gleckman, "The engineering design of a high-performance parabolic trough collector using lumber for the support structure," *Solar Energy*, vol. 191, pp. 382–399, 2019. [Online]. Available: https://doi.org/10.1016/j.solener.2019.08.038

[53] Solar Payback. (2019) Mapa mundial de proveedores ship. [Online]. Available: https://bit.ly/3zRXZvJ

[54] G. Quiñones, C. Felbol, C. Valenzuela, J. M. Cardemil, and R. A. Escobar, "Analyzing the potential for solar thermal energy utilization in the chilean copper mining industry," *Solar Energy*, vol. 197, pp. 292–310, 2020. [Online]. Available: https://doi.org/10.1016/j.solener.2020.01.009

[55] T. jia, J. Huang, R. Li, P. He, and Y. Dai, "Status and prospect of solar heat for industrial processes in china," *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 475–489, 2018. [Online]. Available: https://doi.org/10.1016/j.rser.2018.03.077

[56] IEA. (2020) Tracking industry 2020. International Energy Agency, Paris. [Online]. Available: https://bit.ly/3neCjpU

[57] H. Ortega, *Energía solar térmica para procesos industriales en México. Estudio base de mercado.* Comisión Nacional para el Uso Eficiente de la Energía (CONUEE), Asociación Nacional de Energía Solar (ANES), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 2018. [Online]. Available: https://bit.ly/3l0qa5o

[58] T. Hove, "A thermo-economic model for aiding solar collector choice and optimal sizing for a solar water heating system," in *Africa-EU Renewable Energy Research and Innovation Symposium 2018 (RERIS 2018)*, M. Mpholo, D. Steuerwald, and T. Kukeera, Eds. Cham: Springer International Publishing, 2018, pp. 1–19. [Online]. Available: https://doi.org/10.1007/978-3-319-93438-9_1

[59] I. Lillo-Bravo, E. Pérez-Aparicio, N. Sancho-Caparrini, and M. A. Silva-Pérez, "Benefits of medium temperature solar concentration technologies as thermal energy source of industrial processes in spain," *Energies*, vol. 11, no. 11, p. 2950, 2018. [Online]. Available: https://doi.org/10.3390/en11112950

[60] BCE. (2021) Consulta por monedas extranjeras. Banco Central del Ecuador. [Online]. Available: https://bit.ly/3h9OS2a

[61] C. McMillan, C. Schoeneberger, J. Zhang, P. Kurup, E. Masanet, R. Margolis, S. Meyers, M. Bannister, E. Rosenlieb, and W. Xi, *Opportunities for Solar Industrial Process Heat in the United States.* National Renewable Energy Laboratory. NREL/TP-6A20-77760, 2021. [Online]. Available: https://bit.ly/3zYSsDG

[62] A. K. Sharma, C. Sharma, S. C. Mullick, and T. C. Kandpal, "Ghg mitigation potential of solar industrial process heating in producing cotton based textiles in india," *Journal of Cleaner Production*, vol. 145, pp. 74–84, 2017. [Online]. Available: https://doi.org/10.1016/j.jclepro.2016.12.161

[63] A. Kylili, P. A. Fokaides, A. Ioannides, and S. Kalogirou, "Environmental assessment of solar thermal systems for the industrial sector," *Journal of Cleaner Production*, vol. 176, pp. 99–109, 2018. [Online]. Available: https://doi.org/10.1016/j.jclepro.2017.12.150

[64] C. Brunner, B. Muster-Slawitsch, S. Meitz, and E. Frank, *Solar Heat Integrations in Industrial Processes.* IEA Solar Heating and Cooling Technology Collaboration Programme, 2020. [Online]. Available: https://bit.ly/3BNG8qb

[65] IEA, *Energy Technology Perspectives 2020.* International Energy Agency, 2020. [Online]. Available: https://bit.ly/3tqcep8