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Review

Prospects and Challenges of Solar Thermal for Process Heating: A Comprehensive Review

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Abstract: To mitigate the consequences of climate change, there is an increasing need to minimize the usage of fossil fuels, especially in the industrial sector because the majority of the industrial sector primarily rely on fossil fuels to meet their needs for heat energy, and a practical strategy to reduce reliance on fossil fuels is to use energy from the sun. Due to their environmental advantages, energy security, and viability as a potential substitute for fossil fuels, solar thermal collectors are acknowledged as promising technology to harness solar thermal energy fir process heating applications. This review is a thorough compendium and evaluation of contemporary literature on solar thermal collectors and their applications in industry. Apart from applications, this review paper also assesses the challenges and limitations currently hindering the global acceptance of this technology in the industrial sector.

Keywords: solar thermal energy; solar thermal technologies; solar collectors; industrial process heating; solar energy integration

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1. Introduction

Globally, for any nation to expand, modernize, and experience economic growth in the industrial sphere, energy is both a key requirement and a necessity. Since industrialization, there has been a significant change in the energy system. As people become wealthier and demographics rise, there is an increase in the need for energy in many nations around the world. In the absence of any increase in energy efficiency, this excess demand will result in an annual growth in our worldwide consumption of energy [1]. Figure 1 [1] shows the consumption of different resources on a global scale in 2019. Just 15.7% of primary energy worldwide in 2019 originated from low-carbon (nuclear and renewable) sources. The objective of switching to a low-carbon power system is far from being achieved. Since the 1990s, our rate of progression has been less remarkable. By 1994, 13.5% of our energy came from low-carbon sources. Only 2 percentage points have been added to this in 25 years. Although it is moving correctly, it is doing so much too slowly, perhaps much slower than most people anticipate [1]. The industrial sector has a substantial influence on the world economy [2]. However, the problem remains how to fulfil the forthcoming thermal energy necessities for satisfying the energy insistence of the industrial sector because of the significant rise in worldwide energy demands. Particularly, the industrial sectors consume 32–35% of total global energy [3]. The average data for energy intake in the industrial sector depicts the usage to be around 35% of the global energy [4]. Global energy is under increasing pressure because of the accelerating economic and demographic growth. Due to excessive use, the principal energy sources such as fossil fuels are beginning to exhaust as demand for energy rises. Along with a risk of potential economic meltdown, the continuous

use of fossil fuels is also harming the environment, over the past decade global warming has increased drastically [5]. Fossil fuels predominate in the energy mix of the industries. Therefore, it is crucial to minimize fossil use and still meet the expanding energy demands of industry to promote intergenerational equality and lower greenhouse gas emissions [6]. Researchers S. Mekhilef, R. Saidur and A. Safari forecasted the industrial energy growth till 2030 and it is apparent in Figure 2 that this trend of increasing demand in the industrial sector will continue in the future [7]. As the effects of climate change start to be felt around the world, the need to adopt renewable energy technology is becoming increasingly crucial. The power generation industry has been the main target of efforts to deploy more renewable energy sources in place of conventional fossil fuel power plants. In the USA, the sector that produces electric power had a five-fold rise in renewable energy generation from 2009 to 2018 [8]. Other countries around the world are also adopting the renewable energy but only for power generation. Despite the inclining adoption of renewables in electrical power sector, most of the process thermal energy in industries is still produced through the burning of fossil fuels. The industrial sector in the America utilized 33% of the nation's net energy in 2020, and fossil fuel combustion accounted for 78.5% of that energy [9]. Additionally, it should be remembered that petroleum and natural gas products account for about 80% of all energy use [10]. Therefore, the adoption of renewable energy resources on a global scale for process heating and other industrial application is crucial.

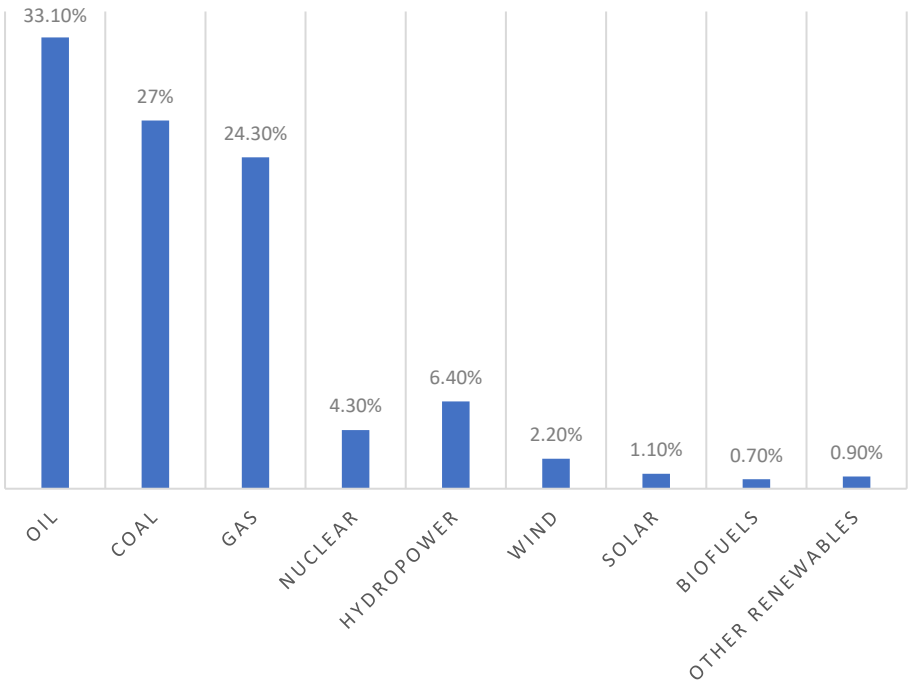

Figure 1. Global resource usage in 2019 [1].

Solar energy has the highest potential of all available renewables, it generates clean energy that is not harmful to the environment while it is being used. Several solar conversion devices can convert solar radiation into heat or electrical energy. Photovoltaic cell (PV) and solar thermal systems are two large categories of solar energy conversion technologies. Solar thermal systems turn solar radiation into heat, whereas solar PV systems directly convert solar energy into electricity. Systems for converting solar energy to heat typically have a substantially better conversion efficiency than systems for converting solar energy to electricity [11]. Fossil fuels are burned to provide process heat for industries, which results in GHG emissions and environmental degradation, solar energy systems represent a sustainable alternative for the future [12]. Installing such a system will move enterprises toward a future of zero carbon emissions because solar energy is widely available.

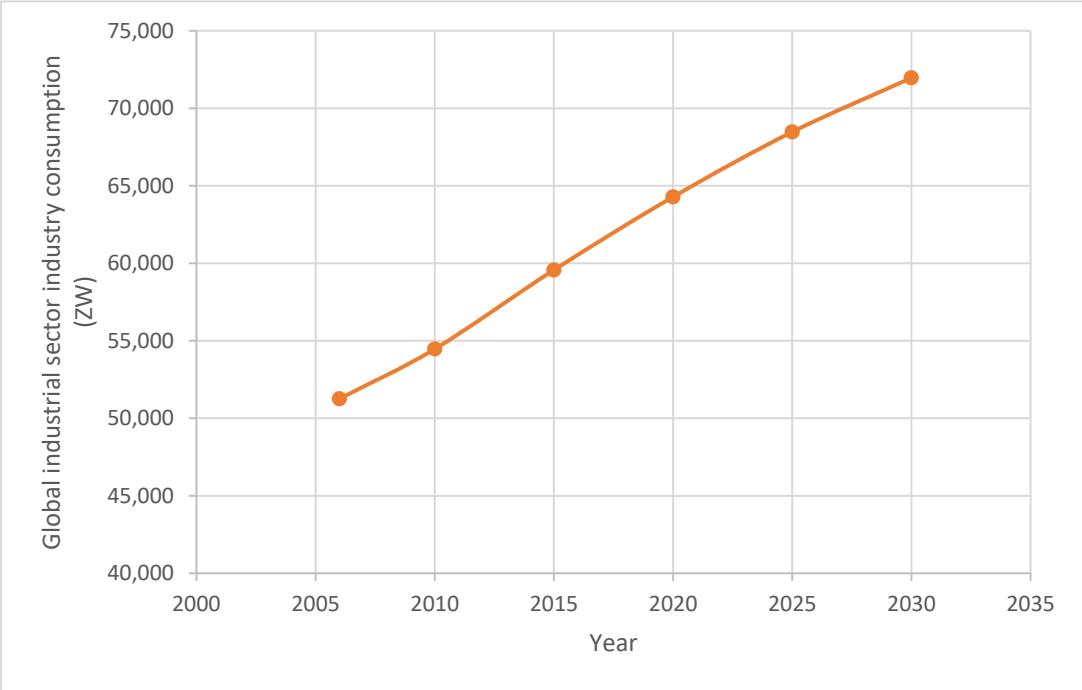

Figure 2. Global projections for industrial sector consumption [7].

This review paper's discussion will center on the worldwide advancement of solar collectors and solar thermal energy, as well as the required heat and temperature ranges for various industrial processes. To incorporate solar industrial process heating systems, the article identifies the most popular industrial processes with thermal applications. This research also includes choosing the best collector technology for applications based on the needed process temperatures. Section 2 of this research describes solar thermal energy, industrial heating requirements, and numerous investigations on solar based industrial process heating. Section 3 of this article is devoted to a thorough examination of several technologies of solar thermal energy extraction and their general features. Section 4 of this research emphasizes the use of solar thermal energy in process industries through various integration techniques. The last section gives an overall summary of this review paper and conclusions.

2. Heating for Industrial Processes and Solar Thermal Energy

The energy obtained via the conversion of sunlight into heat is called solar thermal energy. A solar collector is used to collect solar radiation for solar thermal conversion systems shown in Figure 3. These radiations may be employed for industrial purposes or saved for later use to directly heat water or air for heating purposed in the residential or commercial sector. Process heating systems in general comprise of a heating unit that generates and supplies heat as well as a circulation system for moving thermal energy to the final use [2]. The process heating is implemented via either direct or indirect mode [13]. In a direct scenario, heat is produced by the substance itself. Alternatively, in indirect systems, by means of one or many heat transfer mechanisms, heat is transferred from another source to the substance.

Research shows that more than half of the process heating happens under 250 °C, which lies exactly under the applicability of solar thermal collectors [14]. Utilizing thermal energy from the sun to heat industrial processes has several benefits. In addition to reducing GHG emissions, it lessens reliance on fossil fuels. However, integration of this heat into diverse processes of industries and choosing an effective solar thermal collector is challenging. An appropriate industrial method where thermal energy of sun can be used either regionally or globally has been identified through several studies. Additionally, a lot of academics have shown how to integrate solar heat into industrial processes using

the right solar thermal collector. In research [15], the issues associated with the rise of solar thermal technologies in the ASEAN countries are discussed. To reflect the region, the heat requirements for Malaysia's main industrial sectors are also analyzed. The research also offers an industry perspective on the technical expertise and awareness needed to successfully adopt solar thermal technology in industry. The effectiveness of the collector and the heat removal factor were considerably impacted by the concentration ratio, flow rate of the fluids, and surface area [16]. Research [17] concludes that installing evacuated solar collectors in industrial processes appears to be the most advantageous solution supporting the core of this review.

Large scale studies of solar thermal process heating have been carried out to show the practicality of this system. Ref. [18] carried an analysis of a 5MW solar collector-based plant for process heating. The researcher used parabolic trough collector (PTC) to achieve process heating for a plant in lake city Utah and concluded that using parabolic trough collector system could reduce annual emissions of CO2 by 3,582,422.47 kg as compared to a natural gas-based plant. Additionally, approximately $99,900 and $357,004 in yearly external cost reductions were achieved [18]. Another researchers [19] investigated the adoption of Solar IPH and complementary solar thermal energy technologies in China and listed the top 10 potential industrial sectors. They anticipated that China would reduce its CO2 emissions by 98.22 MT and a minimum 39.40 MT of coal commensurate by 2020. Researchers [20] did a comprehensive overview of different sectors in Switzerland. The traditional solar thermal systems have a significant potential to provide process heat for Swiss industry. Research lists the best industrial sectors for implementing solar thermal systems, the best techniques, and the places where such installations are most likely to occur. Because of their significant energy consumption for process heating and high proportion of low working temperatures, the food, fabric and apparel, paper, chemical, and medicinal sectors are found to be intriguing for the deployment of solar thermal systems. Together, these four industrial sectors in Swiss industry required 33PJ heat in 2016 for process heating, accounting for about 21% of total energy production in country. Another large scale study [21] developed the mathematical structure of solar IPH for Germany's most viable industrial sectors and came to the conclusion that by incorporating solar IPH into German enterprises, approximately a demand of 3.4% or 16 TWh of the heating load could be satisfied. A study on the integration of parabolic trough collectors to the industry for process heating reported a decrease in the levelized cost of the heat from $34.10/MWh$_{th}$ to $31.83/MWh$_{th}$ [22]. The same research also reported a decrease of 22.2% in GHG emissions [22]. Analyzing the results of given four large scale studies show that solar thermal technology holds an immense potential to assist industrial process heating on a global scale.

There also have been numerous studies regarding the feasibility and characteristic mapping of solar thermal technology. Researchers [23] evaluated the viability of solar-powered process heating applications and discovered that flat-plate collectors offer the lowest cost to generate heat by solar for operating temperatures below 60 °C, while ETC reflectors are more economically viable at temperatures above about 70 °C. For all of Madrid's examined inlet temperatures, industrial solar heating systems are practical. Applications for solar process heat in Würzburg with intake temperatures under 60 °C are economically viable. Researchers [12,24] compared the outcomes of systematic reviews of ten other nations to the Australian case study. The researchers evaluated various industries in the selected countries and suggested suitable SHIP plant. Another study by [25] demonstrates the dependability and effectiveness of three different collector systems that are appropriate for providing industrial process heat in various climatic locations. Two distinct types of collectors were discussed based on their application as a function of location. The flat plate collectors achieved 95 °C in European climate and concentrating collectors achieved supply temperatures b/w 160 °C to 250 °C. Process heating system with solar assistance was examined by a researcher [26]. Process heating was produced with the least amount of fossil fuel use possible by combining a PV and a solar thermal collector system. According to the findings. Performance mapping demonstrates that the SAPH system operates more

effectively at higher radiation levels and lower mass flow rates. These studies point out the viability of different types of solar thermal collectors under specific application temperature and flow requirements. These studies can assist the selection of appropriate technology for process heating in industrial sector.

PV systems based heating also present a great alternative to fossil fuel based process heating. However, Ref. [27] analyzed the costs of photovoltaic and solar thermal systems for process heating. It was concluded in the research that the solar thermal systems deliver cheaper and more cost-effective energy than PV installed systems.

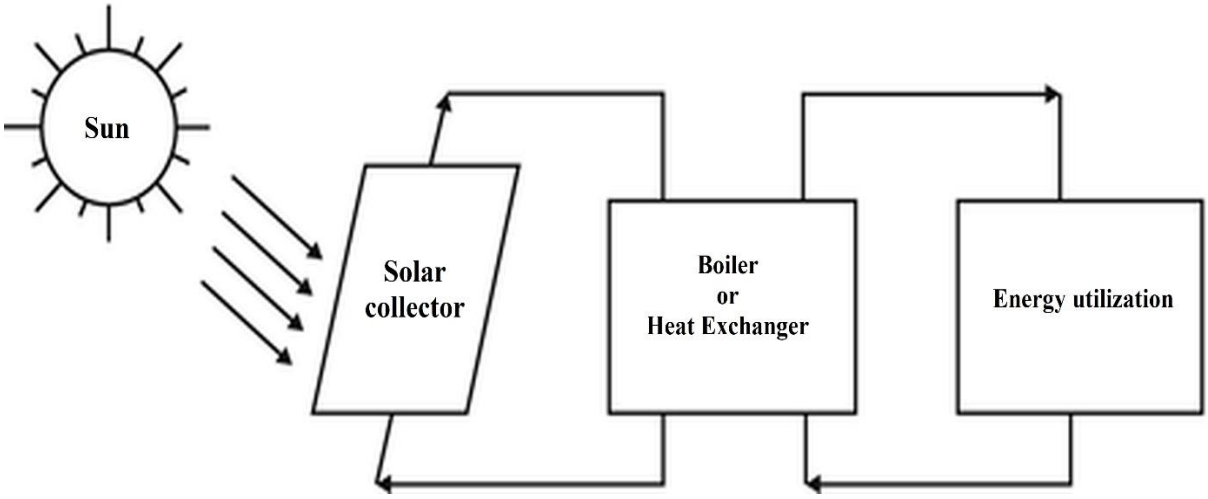

Figure 3. Systems to convert sunlight to heat.

3. Current Global Technologies of Solar Thermal Energy

With the advancement of contemporary science over the past ten years, many solar energy (SE) technologies have been launched at greatly varying costs. The enormous need for energy to be used for economic development, coupled with the rising cost of fossil fuels, is a pressing issue on a global scale [28]. The energy consumption is always rising, yet conventional sources have limited supplies [29]. Sunlight is arguably the most potent energy source that Earth receives, and it comes from the Sun. sunlight can be harvested as Solar thermal energy, electrical energy, or a combination of the two [30]. Photovoltaic cells are an efficient and environmentally friendly way to turn solar energy into electric energy. However, about 15–20% of solar radiation, depending on PV mechanization, is believed to be converted into electricity by solar photovoltaic cells, making them an extremely inefficient source of electrical energy [31,32]. Contrastingly, solar thermal collectors directly convert the solar energy into heat that is fed to the working fluid. Additionally, the integrated systems, such as solar concentrated photovoltaic thermal, also known as CPVT, and photovoltaic thermal (PVT) are developing technologies. Although compared to separate PV or STCs systems, an integrated collectors have far higher electrical and thermal outputs but still these systems are limited to research only. There is ongoing research being done on these integrated systems to assess their feasibility in real world conditions. Therefore, they are not viable for global adoption at this moment. There are many different solar thermal collectors on the market and Figure 4 lists a variety of different types. This portion of the study provides an overview of the solar thermal collector types and their development worldwide.

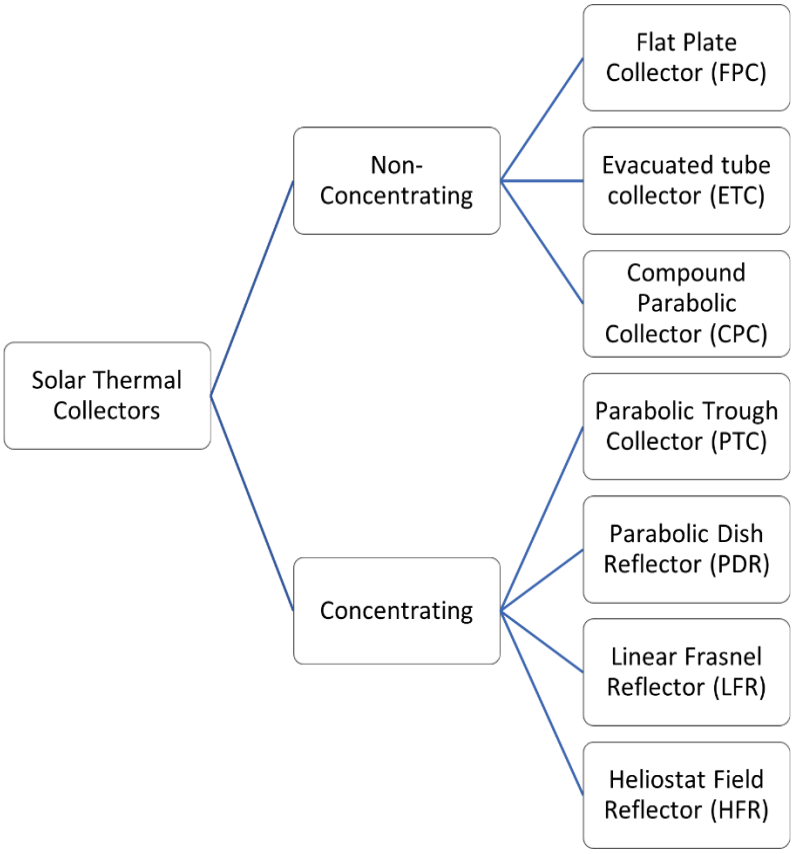

Figure 4. Solar thermal collectors [2,4,33].

3.1. Non Concentrating Solar Collectors

Direct (beam) solar radiation at different angles along with diffuse radiation that has been dispersed by the atmosphere can both be used by non-concentrating collectors. They can be mounted in a fixed orientation and do not have to track the position of the sun [34]. Non-concentrating solar thermal collectors are set up to ensure that most solar radiations may be collected. These collectors are placed at a specified tilt and slope that is determined by latitude [35]. In general, there are three different types of non-concentrating solar thermal collectors:

(a) Flat plate collectors (FPC)
(b) Evacuated tube collectors (ETC)
(c) Compound parabolic collectors (CPC)

3.1.1. Flat Plate Collectors (FPC)

A flat-plate collector (FPC) uses water as the working fluid to capture solar energy and convert it into low grade thermal energy. It is the core of solar thermal equipment with various potential applications in sub 100 °C temperatures range [36]. Flat plate collectors can capture both diffuse and direct solar radiations. They can be further divided into glass and no glass type flat plate collectors. Glass flat plate collector components include fins, insulation layer, tubes, absorber plates to which piping and fins are connected, and glazing protection. Incident sunlight passes through a clear cover and hits the darker absorber surface in these types of collectors. The absorber takes in a much higher proportion of the energy, which is subsequently transferred to the liquid that is circulated in the tubes. In contrast, there is no layer of glass or other radiating material in non-glass solar collectors [35].

A flat plate collector in Figure 5, is constituted of an absorber plate with a back plate and a transparent glass covering. When using air, a passageway is created between the

plate of absorber and the rear plate. Copper pipes attached on the absorber plate offer flow pathways whenever water is utilized as the working fluid. When collectors are used for long time period, dust accumulates on their glass covers and negatively impacts their performance. Ref. [37] outlined the impact of dust accumulation and varied cleaning techniques used in different zones of the globe. The lack of solar tracking and working temperatures above 70 °C causing convection heat loss, which lowers collector efficiency, are two major drawbacks of FPCs [38,39].

According to [40] flat-plate systems typically function and attain their greatest efficiency between 30 to 80 °C. However, certain new types of collectors that use vacuum insulation can enable these to operate at up to 100 °C. It has also been demonstrated that selective coatings may raise the stagnant temperature of the fluid in FPC to 200 °C [41]. Furthermore, Table 1 enlist the parameters of a typical FPC.

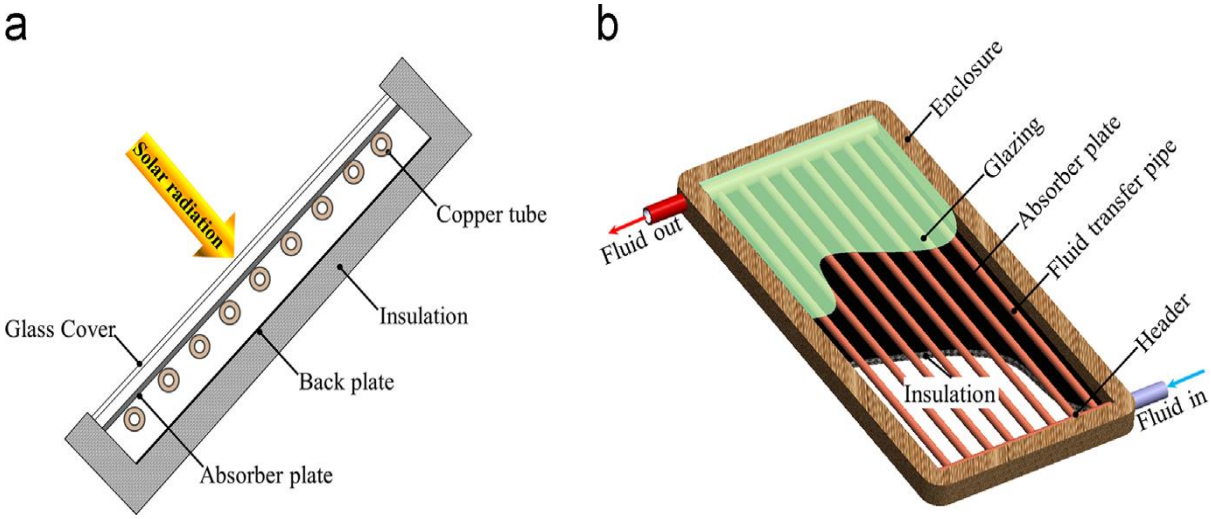

Figure 5. Flat plate collector construction (**a**) end view and (**b**) isometric view [35].

3.1.2. Evacuated Tube Collectors (ETC)

An evacuated tube collector comprises of a heat pipe retained inside a glass container, as can be seen in Figure 6. When comparing heat loss between solar collectors, the ETC collector outperforms the FPC by a wide margin [42]. The heat pipe employs a liquid to absorb solar insolation heat and carries that heat through cycles of evaporation and condensation to another working fluid. The liquid within the heat pipe changes phases when exposed to solar radiation and becomes vapor, which then under the force of buoyancy rises to upper portion of heat pipe. At the top, in the heat exchanger section of the heat pipe, vapors condense after transferring the energy to working fluid. The condensed liquid falls to the heat pipe's bottom due to gravitational influence and the pattern repeats accordingly [35]. Heat pipe collector performance was discovered to be more susceptible to environmental factors, including sun radiation and ambient temperature. One crucial design factor is the distance from the evaporator to the condenser [43]. To reduce convictive heat loss and stop the interior materials from deteriorating due to climate change, the glass enclosure is evacuated. To allow the inner liquid to undergo a phase shift at low temperatures, heat pipes are often also evacuated [44]. The sun's radiation's incidence angle shift has no discernible impact on its efficiency. When installing tubes, this ETC feature offers versatility in tube orientation ranging from 25° to 60° [35]. At elevated temperature, in industrial applications, ETCs are more effective than FPC in the temperature gradient of 50–200 °C. Because of the benefit of the vacuum formed between the tubes, this type of collector is popular and efficient in cold environments [45]. Ref. [46] carried out an experimental investigation to assess the performance of a heat pipe ETC and an FPC in a household water heating system. When using ETC instead of FPC, the results showed a 13% improvement in total system effectiveness. Table 1 enlist the properties of a typical evacuated tube collector.

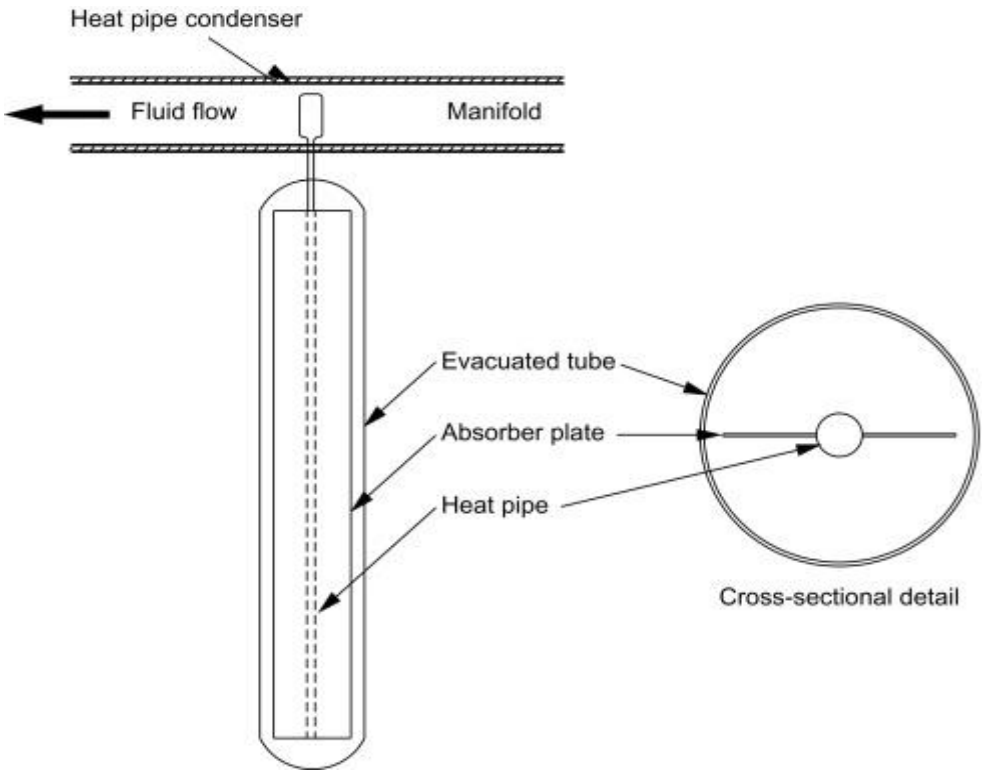

Figure 6. Evacuated tube collector [47].

3.1.3. Compound Parabolic Collectors (CPC)

CPCs have the capacity to completely reflect all incoming radiation onto the internal absorber within a range. Opting a trough with two parabola portions confronting each other can lessen the need to move the concentrator to compensate for the shifting sun position, as shown in Figure 7 [48]. Compound parabolic concentrators (CPC) may accept incoming radiation from a broad range of angles. Radiation reaching the aperture of acceptance angle gets delivered to absorber surface by using internal reflectors [49]. The walls of CPC are often protected by glass to prevent dust and other outside elements from negatively affecting their performance [35]. CPC have been constructed in two fundamental types: symmetric and asymmetric. These types typically include the two primary varieties of absorbers: fin-type models having pipe absorbers and tubular absorbers [50]. The formation of an air gap between the reflector and lens in CPC greatly enhances optical efficiency. The optical losses caused by internal reflection are decreased by this air gap [51]. Stationary CPC with a low concentration ratio of up to two, are utilized as non-imaging concentrators. CPCs are also frequently covered in glass to guard them from dust and other objects that could harm their performance. With periodic tilt changes, the CPC may be operated in without a tracking mode and produces concentration ratios around 3–7 [52]. Table 1 enlist the parameters of a typical CPC.

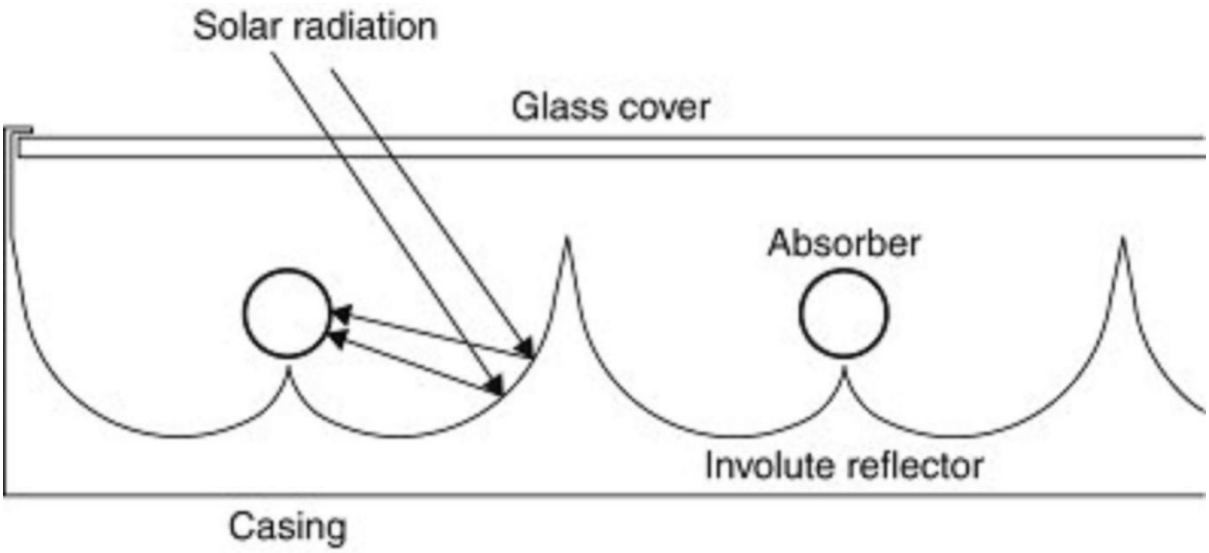

Figure 7. Compound parabolic collectors [53].

3.2. Concentrating Collectors

The incident radiations can be concentrated on a relatively small collection region by adding an optical system that connects the incident radiations and thermal absorber surface. As a result of this setup, the temperature would be higher than with non-concentrating solar collectors [54]. Because the sun moves throughout the day, situating an optical system in concentrating collectors is crucial. Concentrators and receivers constitute concentrating collectors. Commercially, a variety of concentrator and receiver designs are available. The rooftop and facades of buildings may be combined with fixed solar concentrators, which can minimize the area of collectors and get greater temperature heat resources, particularly in the wintertime for different applications [55]. Focusing solar collectors, with the exception of power plants, are not employed to a suitable level in this industry despite having a total utilization capability for process industries heating systems [56]. In general, there are four types of concentrator collectors:

(a) Parabolic trough collector (PTC)
(b) Parabolic dish reflector (PDR)
(c) Linear Fresnel reflector (LFR)
(d) Heliostat field reflector (HFR)

3.2.1. Parabolic Trough Collectors (PTC)

A parabola-shaped solar thermal collector known as a parabolic trough has a polished metal mirror lining. Direct solar energy is focused onto an absorber tube in PTC systems using the reflective lining of a linear parabolic reflector, which passes along the concentrator's focal line. The pipe contains the working fluid that then absorbs and transmits heat to the process [57]. PTC are fabricated by coiling a reflective material into a shape of parabolic as shown in Figure 8. The PTC system can induce heat at temperatures ranging between 50 °C and 400 °C. The tracking system of solar collectors is a particularly delicate component because, in addition to tracking the sun accurately, it also protects the collector from potentially dangerous environmental circumstances like gusty winds, overheating, etc. The tracking of sun along single axis is typically sufficient for a PTC system. PTC is tracked along north-south direction when oriented in east-west direct or vice versa. The choice of orientation generally fluctuates depending upon the application and seasonal changes [58]. Ref. [59] presented a summary of the current parabolic trough collectors and the prototypes being created for them. According to the study, since the operating fluid can reach a temperature up to 400 °C, such collectors can be used in steam power cycles to produce electricity. Ref. [60] claimed that solar power generation utilizing parabolic

trough collectors is a most consistent and reliable technology based on a thorough analysis of the subject. They did, however, underline the need to reduce the price. Table 1 lists the parameters of a typical PTC.

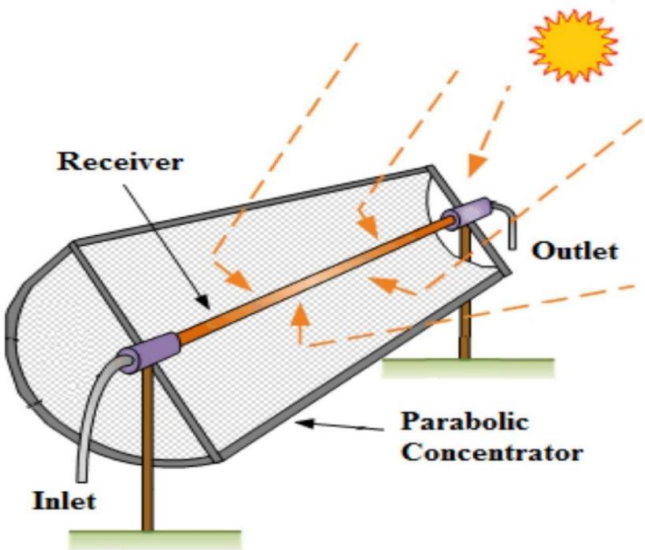

Figure 8. Parabolic trough collector [61].

3.2.2. Parabolic Dish Reflectors (PDR)

The PDR system comprises of a dish shaped design with a paraboloid geometry where a heat receiver at the dish's focal point receives concentrated sunlight that enters the collector aperture, as shown in Figure 9 [62]. The PDR has a two-axis tracking mechanism that directs solar energy toward the receiver. The PDR resembles an antenna for a satellite dish. After absorption of solar radiations, the receiver distributes the heat energy through a heat exchanger to a flowing fluid [49]. The PDR can achieve temperatures over 1500 °C due to its constant sun-facing orientation [35]. Comparatively speaking, with respect to the CPC, parabolic dish collectors are more efficient since they can track the sun on an axis. Due to tracking mechanism, high reflector construction costs, and wind stress, parabolic collectors have spatial structure [63]. PDR powered Stirling and Brayton engines are among the options under investigation right now [64,65]. Excellent optical efficiency, reduced start-up losses, and flexibility are all benefits of parabolic dish engines that can be quickly expanded up to fulfil the power requirements in distant areas where central power is very expensive. Table 1 enlist the parameters of a typical PDR.

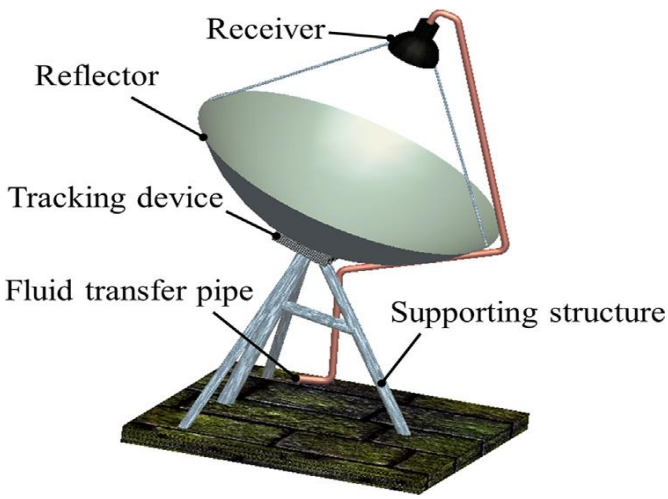

Figure 9. Parabolic dish reflector (PDR) [35].

3.2.3. Linear Fresnel Reflectors (LFR)

LFR design comprise of linear reflective strips that concentrates the solar radiation to a receiver mounted on a tower [66]. Working fluid inside the pipes gets heated and transmitted to further process [67]. The LFR system is almost like a broken PTC system where the parabolic reflectors are broken into pieces and laid on a linear surface focusing on a common receiver, shown in Figure 10 [68]. Compared to PTC, these are less efficient and attain lower temperatures [35]. LFR typically cost less than PTC because they are affixed to the ground using a flat or elastically rounded reflectors, which also lowers the installation expense. Moreover, due to the reflector's single receiver, there are no options for the reflector's orientation or placement [69]. LFR are reliable and economical for temperature requirements of up to 300 °C [70]. However, LFR system's requirement of large spacing between each reflector to prevent shadowing effect is a significant downside of this technology. It is possible to reduce this by increasing the height of the absorber tower but doing so will drive up the cost of said system. Technology of this kind works well in desert regions where land scarcity is not a problem [69]. Because of the higher cosine losses caused by the employment of a stationary receiver and single axis tracking in a horizontal plane, linear Fresnel collectors perform less efficiently optically and thermally than parabolic troughs [71], but the lower cost offsets this disadvantage [72]. Another advantage of being a single axis tracking system is the simplicity of the mechanism as compared to others like heliostat which employs a two axis tracking system [73]. Table 1 enlist the parameters of a typical LFR.

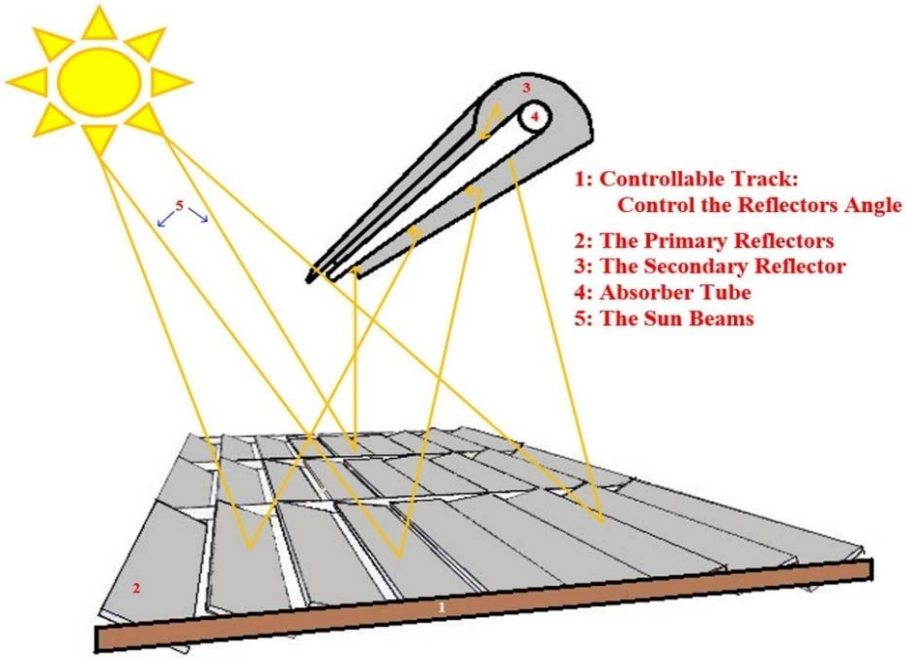

Figure 10. Linear Fresnel reflector [68].

3.2.4. Heliostat Field Reflector

In HFR, several flat reflectors are organized in a way that all the mirrors reflect the incoming solar radiations to a common point to achieve high thermal radiant energy as shown in Figure 11 [74]. With this setup, significant heat can be generated to heat and pressurize boiling water or steam to a very high temperature. The working fluid can use the heat energy it absorbs to produce heat or use it to generate thermal power in industry [35]. HFR systems have the concentration ratio between 300 and 1500, and the central receiver is also extremely effective at high temperatures due to having a common absorber [75]. These can be controlled to achieve extremely high temperatures up to 2000 °C [70]. Since the system doesn't require any field piping configurations and can readily concentrate all

of the solar energy received at the central receiver, it is significantly efficient and reliable for large loads in comparison to other concentrated solar power systems [76]. A researcher [77] suggested a method called "YNES" to create the optimized field layout. In this optimized system, water, liquid sodium, or molten salts can be used as the heat transfer medium inside the steam generator, while synthetic oil combined with rock fragments can be used as the thermal storage medium [78]. To soak thermal energy and convert water into steam, a steam generator is situated in the central tower of the heliostat field, where an optimized field architecture can effectively reflect solar light [79].

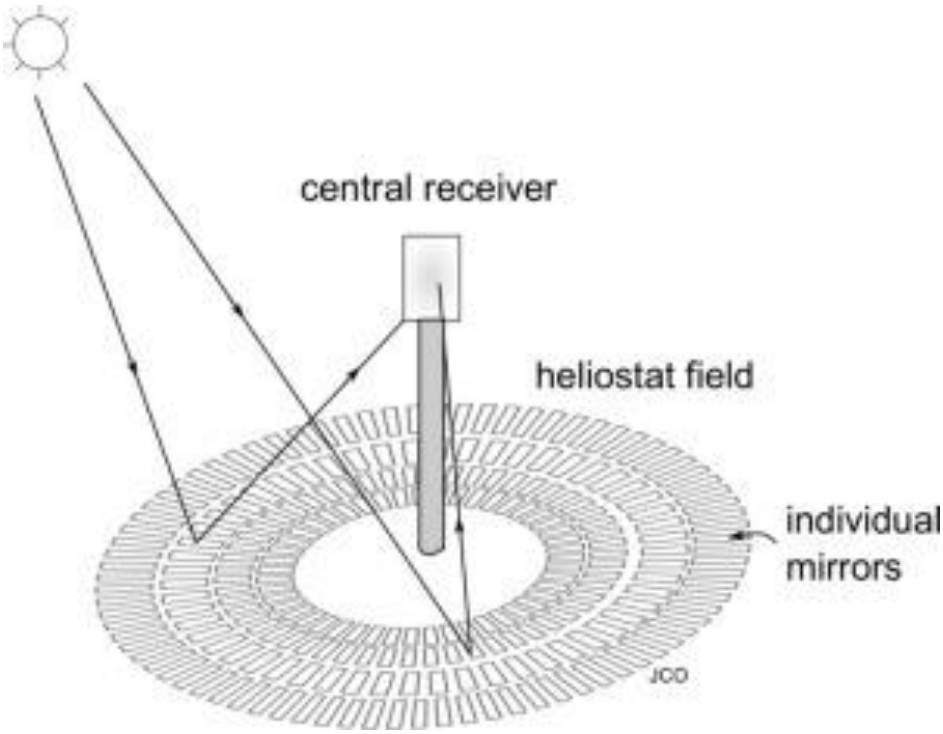

Figure 11. Heliostat field reflector (HFR) [80].

Table 1. Solar collector parameters [4,81].

Collector Types		Operating Temperature (°C)	Absorber
Non-Concentrating	FPC	30–80	Flat
	ETC	50–200	Flat
	CPC	60–240	Tubular
Concentrating	PTC	60–300	Tubular
	PDR	100–1500	Point
	LFR	60–250	Tubular
	HFR	150–2000	Point

3.3. Heat Exchanger

For many industrial processes, heat exchangers are essential components because they mechanically transmit heat energy between fluids [82]. The mechanism of heat exchange, the type of fluids involved, the compaction of surface, design features, flow configurations, and heat exchange mode can all be used to classify heat exchangers [83]. Heat exchangers are utilized in process heating to transfer the heat of solar collectors to a storage device or heating fluid without mixing the working and heating fluids [84]. The following are some fundamental varieties of heat exchangers used in process industries:

3.3.1. Plate Heat Exchangers

A particular kind of heat exchanger transfers heat among two fluids by using metal plates. Since the fluids are dispersed across the plates, this offers a significant benefit over a traditional heat exchanger in that a significantly wider surface area is exposed to the fluids [85]. In commercial applications for hot water, plate HXs are now widespread. Combination boilers now produce more domestic hot water (DHW) due to their fusion of excellent heat transfer efficiency and compact physical size.

3.3.2. Shell and Tube Heat Exchangers

The tube and shell heat exchanger comprises of a shell that is filled inside with a number of tubes. To transfer heat between the two fluids, one flows through inside the tubes and the other runs over them (via shell). The group of pipes is known as a tube bundle and can include several kinds of tubes, such as plain, finned, etc. The design of a tube and shell HXs is straightforward, and its construction and upkeep are reasonably inexpensive. They also have a particularly high rate of heat transfer, however taking up more room than a plate type heat exchanger with a comparable thermal exchange capacity [86].

3.3.3. Double Pipe Heat Exchangers

These are the simplest type of heat exchanger. They use two or maybe more concentric cylindrical tubes or pipes of different diameter to transfer heat between two fluids. The internal pipe serves as a conductive barrier, allowing one fluid to pass through and another to pass around it via the outer pipe to form an annulus [87].

4. Integration of Industrial Process Heat with Solar Thermal Energy

There are a number of possible fields of use for solar thermal energy at high and medium temperatures (80–240 °C), in addition to low temperature uses [88]. Solar energy can be used as a direct provider of heat for industrial processes or as a power source for electrical energy. This paper only centers on the thermal systems of solar energy. Figure 12 depicts a model of a solar collector system combined with an auxiliary source to provide process heat for a conventional industry with multiple process requirements. However, incorporating and optimizing solar energy for industrial applications presents several challenges, which are covered in more detail later in this section. Different solar thermal collector types, as explained in the previous section, are frequently used to convert solar radiation into heat for different industrial processes [89]. Depending on the operating temperature requirements for heat applications, these industrial processes can be classified into two categories, as demonstrated in Figure 12 [49].

The intermittency of solar energy prevents solar thermal energy from reliably meeting industrial heat requirements. Solar thermal energy storage systems (STES) can be used to resolve this inconsistency. This section also discusses several techniques and materials for storage, as well as the performance characteristics and restrictions. Additionally, the cost of energy for industrial process heat relies on the process's temperature, the amount of process heat required, the area covered, and solar radiation intensity.

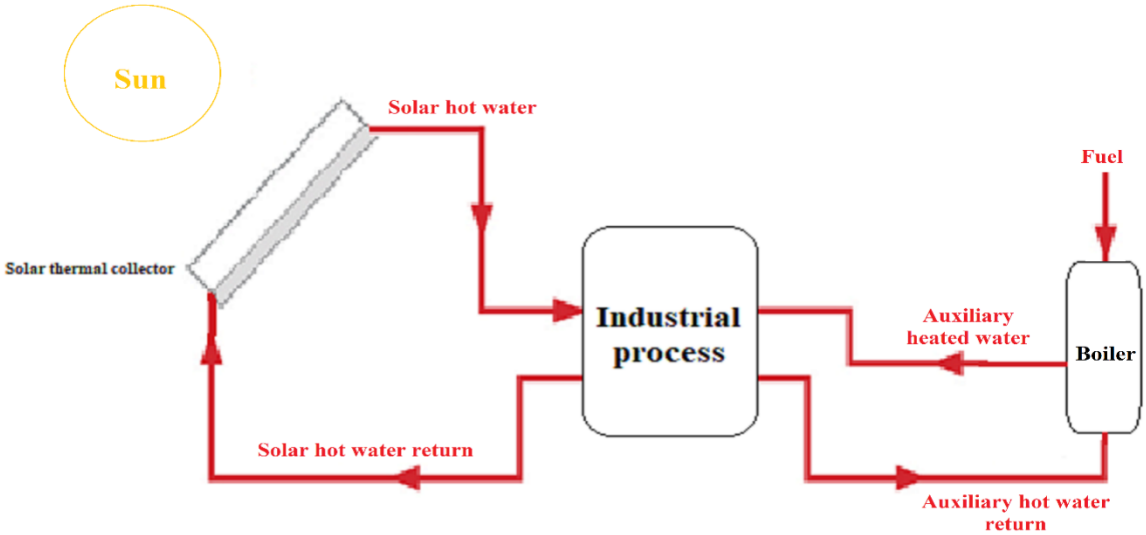

Figure 12. Integration of solar thermal energy to industrial processes.

4.1. Potential Industries for Solar Thermal Integration

Process heating is the most common process found in most of the industries. This section discusses some of the prime candidates to integrate the solar energy for process heating.

4.1.1. Food Industry

The most significant industrial sector for solar fusion with low-temperature operations (below 150 °C) is the food industry, which includes the food production, beverages, and farming of food. Indeed, 47% of all process heat projects implemented worldwide are dedicated to the industries of beverages and food [90]. Most industrial operations require low- to moderate heat [91] and Table 2 enlists heating requirements for some of the most common processes found in the food industry.

Table 2. Food industry processes [92,93].

Process	Temp. (°C)	Process	Temp. (°C)
Drying	40–200	washing	30–80
Blanching	60–110	cooling	80–100
Pasteurization	60–140	Scalding	45–90
Space Heating	30–70	Evaporating	40–130
Thickening	110–130	cooking	70–120
cleaning	60–90	Sterilization	100–140
smoking	20–85	Pre-Heating	20–40

4.1.2. Automobile Industry

The automotive sector is under a lot of pressure to produce more ecologically friendly goods. The entire manufacturing chain needs to be more sustainable, not just the cars alone [94]. Electricity and petroleum products, such as natural gas used in automobiles, are two of the main sources of overall energy use [95]. The construction of automobiles involves a variety of techniques that use a lot of energy, such as heat or electricity. Electricity, hydrocarbons like natural gas, and other fossil fuels are the primary energy sources used during the manufacturing of automobiles [82]. One manufacturing procedure that significantly increases a vehicle's carbon output is paint curing since the temperatures can reach up to 200 °C [94]. Fresnel collector systems are typically used at elevated temperature requirements. Table 3 enlists heating requirements of some common automobile industry processes.

Table 3. Automobile industry process [95,96].

Process	Temp. (°C)
Cleaning	90
Zinc Phosphating	80
Drying	90
Drying of molds	100
Tempering	200
Paint conditioning	40
Paint curing	200
Paint Drying	100

4.1.3. Paper Industry

The majority of paper industry processes operate at low to medium temperatures. Process heating accounts for a sizable amount of the energy needs for the paper industry, which is frequently satisfied by fossil fuels. Additionally, emissions of GHG as a consequence of burning fossil fuels during the production of paper have a substantial impact on global warming [97,98]. Most of the process heat is used in operations, such as bleach and wash with heated water, pulping, curing, and boiler water heating, depending on the particular specifications [82]. Table 4 enlists heating requirements of some common paper industry process.

Table 4. Paper industry process [99,100].

Process	Temp. (°C)
Pulp preparation	120–170
De-Inking	60–90
Bleaching	120–150
Paper drying	90–200

4.1.4. Textile Industry

The textile industry, like most other industrial sectors, depends on a steady supply of water, mostly for the dying process. Process requirements are medium to higher temperatures around 80 °C, which consumes a significant quantity of heat energy [24]. The installed heat capacity in this industry is 26 MW_{th}, or 5% of the total installed capacity for solar heat incorporation in the world [82] which isn't nearly enough. Common processes in a textile industry requiring heat are listed in Table 5. There is also literature reporting using solar concentrators to supply process heat in textile sector [100–103].

Table 5. Process in a textile factory [104,105].

Process	Temp. (°C)
De sizing	60–90
Mercerization	60–70
Dyeing	70–90
Bleaching	90–95
Scouring	60–110
Finishing	40–110

4.1.5. Pharmaceutical

The production of medicinal products and the synthesis of the finished product place a significant energy demand on the pharmaceutical sector. The energy needs of the pharmaceutical sector are high. According to a study [106] HVAC account for around 65% of the energy requirement. The research, development, and production of mass medicinal goods are the three primary production phases in the pharmaceutical sector. The temperature varies between 160 °C and 180 °C depending on the procedure and the product [107]. Due to higher temperature requirements Fresnel collectors are employed [107]. A common steam system in the range of 180 °C is utilized to meet the heat as well as cooling requirements. Table 6 enlists the requirements of common processes in the pharmaceutical industry [107,108]. The pharmaceutical industry is thought to be the most promising area for economies in North America and Europe. Today, only the pharmaceutical companies in Greece and Egypt use solar process heat to generate process steam [109].

Table 6. Pharmaceutical industry process demands [107,108].

Process	Heating	Cooling
Sterilization	✓	
Chemical synthesis	✓	✓
Extraction	✓	✓
Coating	✓	✓
Granulation	✓	✓
Fermentation	✓	✓

4.1.6. Chemical Products

In several chemical manufacturing processes, heat is needed at low temperatures, and solar energy is employed as a complement to primary preheating procedures using other sources of energy. Chemical products generally require low temperature heat in the range of around 130 °C [24]. Therefore, flat plate collectors are more than enough for these generally lower temperature applications. In the case of chemicals requiring higher temperature heat integration, other types of collector technology can also be adopted. Table 7 enlists some of the most common processes found in chemical products industry along with their operating temperature ranges.

Table 7. Chemical industry process [24,110].

Process	Temp. (°C)
Biochemical Reactions	20–60
Distillation	100–200
Filtration	70–90
Pre-heating to boiler	30–80
Ancillary processes	120–180

4.1.7. Agriculture Industry

Multiple climate pollutants contribute to global climate change, with CO_2, methane, and Nitrogen oxides being the three main contributors to global warming [111]. Despite the fact that all these gases are connected to agriculture, methane and Nitrogen oxides account for the majority of direct agricultural emissions [112]. One of the key strategies to support low-carbon agricultural output is the utilization of solar energy in agriculture. Academics are currently undertaking a number of studies on the drawbacks and benefits of using solar greenhouses, solar air heaters, and greenhouse cover materials [113–115].

Agriculture items are frequently dried using solar air heaters and some of the most common processes are enlisted below in Table 8. Basically, most agricultural products are dried at low temperatures in the range of approximately 50–80 °C, and FPC type solar air heater can readily accomplish this.

Table 8. Agriculture process requirements [116].

Process	Temp. (°C)
Drying	80
Cleaning	60
Water Heating	90

4.1.8. Mining Industry

In distant mines where fuel prices are significantly higher than in cities, the SHIP applications would be especially useful [117]. Solar thermal systems allow for the low-temperature heating of gases or liquids. Simple non-concentrating types of solar technologies can be used to produce fluid temperatures up to 150 °C, whereas concentrated solar technologies can produce temperatures up to 400 °C [118]. With the highest percentage of (78%), the mining sector is a dominant sector utilizing solar thermal energy. Globally, mining sector accounts for two of the three largest SHIP plants in Chile and Oman [82]. Moreover, 14 mining facilities are currently in operation, eight of which integrate solar heat at process level and four of which do so at the supply level [119]. Since the sector is so large, there are still many opportunities of solar heating to be incorporated for lowering the carbon footprint in the mining sector. Table 9 enlists some of the common heat intensive mining processes. Several studies have been done to assess the environmental impact of mining industry around the globe [120–123]. All the research concludes that SIPH represents a favorable and economical choice for the mining industry.

Table 9. Mining industry process [24,124].

Process	Temp. (°C)
Cleaning	60
Electroextraction	50
Other processes	80

4.2. Solar Energy Systems

Industries employ a variety of solar energy systems for a wide range of processes, and for these numerous uses, a variety of collectors can be utilized. As a result, the focus of this segment of the research will be on various systems of solar thermal energy.

4.2.1. Solar Energy-Based Water Heating

The main component of this system is a solar collector array, which converts solar energy into thermal energy by absorbing it. Air, water, or any other liquid can be used as a heat transfer medium to absorb heat as it passes through the collector. Both active circulation and passive modes of heat transfer are feasible. The following systems are utilized for solar water heating

(a) Thermosiphon
(b) Integrated collector storage
(c) Direct circulation of water
(d) Indirect water heating
(e) Air systems

Integrated collector storage and thermosyphon are passive systems, so they do not require a pump for circulation, whereas the rest of the systems are active, so they do require

a pump for the circulation of heating fluid. In these systems, the non-concentrating type of solar collectors is preferred due to lower temperature requirements (below 100 °C) [49].

4.2.2. Solar-Based District Heating/Cooling

This system is mostly identical to solar water heating. In this system load is heating or cooling or both combined. Compared to using solar heating alone, combining it with solar cooling significantly increases the collector's effectiveness [125]. To ensure the uninterrupted supply of required energy to the load, the system is coupled with fans or pumps depending upon the heating fluid. District cooling can be achieved by thermodynamic cycles, e.g., absorption and adsorption, and by solar mechanical processes.

4.2.3. Solar-Based Desalination

The process of desalinating water with solar energy is known as solar desalination. The most prominent solar desalination method uses phase-change or thermal processes to desalinate seawater using solar thermal energy. Desalination can be accomplished in one of two ways: directly or indirectly. Direct systems use solar collector where the desalination process is completed in the collector, whereas in the case of indirect systems, one sub-system is used for the collection of thermal energy from the sun and the other is used for desalination.

4.2.4. Solar-Based Refrigeration System

Food and medication preservation as well as comfort cooling are both possible uses for solar refrigeration. This method typically uses cycles of adsorption and absorption to achieve significantly lower temperatures. The refrigerant in this cycle evaporates and absorbs energy throughout the cooling phase. In this system m the collector's tubes contain the refrigerant mixture, and the generator and absorber are typically separate vessels that can be joined. In this system, only active circulation is used to transfer heat.

4.2.5. Carbon Dioxide Capture and Storage

Increasing CO_2 emissions is the most serious environmental concern of this decade and industrial sector is the most dominant emitter. The three main solutions for reducing these emissions are CCS systems, extensive use of renewable sources, and improved energy conversion efficiency [126,127]. CO_2 adsorption tech is one of the CCS technologies that is receiving the most attention, because of its low energy usage and affordability [128]. Another potential adsorption method for CO_2 capture is the pressure-temperature swing adsorption (PTSA). PTSA offers a significant prospective for integration with solar energy because it is capable of utilizing low-grade thermal energy [129].

4.2.6. Solar Based Process Heating

Thermal energy is needed for industrial operations in a variety of temperature uses in the 80–240 °C range. The textile, manufacturing, and pharmaceutical industries, all of which use SHIP, are the ones that use the most energy. Most of these industries' procedures involve sterilization, drying, dyeing, cleanup, and other similar activities. In general, choosing a solar collector criterion for an industry is crucial to sustain the necessary temperature requirements. Another important factor to be contemplated is the amount of space needed to install these systems because they can also be placed on roof tops if the ground space isn't available. Naturally occurring flow of heating fluid due to gravity is a rooftop placement's main benefit, but the shading among neighboring arrays of collectors is to be prevented. Additionally, it is crucial to use a heat storage tank for industries that operate around-the-clock or on a day-and-night schedule to ensure that processes run smoothly and consistently even when solar radiation levels are low.

4.3. Industrial Heat Demand

The primary sources of energy for today's industrial heat requirements are fossil fuels and electricity, with relatively minor amounts of renewable resources being used in some industries. Decarbonization would therefore necessitate a significant change in the way industrial heat is produced [130]. Over two-thirds of all industrial energy consumed globally is used for process heat in industry temps below 400 °C. More specifically, a research shows that at temperatures under 100 °C, 30% of the total industrial heat demand is needed, and about 57% at temperatures below 400 °C [131]. A general classification and study of industrial processes is impractical due to the considerable variations in their conditions. This section of the study contains a discussion on the operating temperatures for various processes and appropriate collector types for each operation.

4.4. Solar Thermal Energy Storage

The issue of solar intermittency necessitates the creation of a method for retaining solar energy to be used later when solar radiation is not prevalent [132]. A technological resolution to the disparity between demand and supply for heating and cooling is thermal energy storage. A diagram is shown in Figure 13 [133] for a storage system of solar thermal energy which pairs a solar thermal energy storage system with a FPC. In industrial settings, systems for generating process heat need a lot of heat. As a result, STES becomes very complicated and may include different heat units, different hydraulic configurations, and other equipment for greater yield [134]. This section, however, exclusively discusses the STES system that will be used to meet the process heat requirement, energy storing material or thermo-fluid, performance metrics, and limitations. Thermal storage system is divided into three categories depending on the storage medium [79]

4.4.1. Sensible Heat Storage

The most straightforward mechanism of storing heat energy is sensible heat storage, which involves heating and cooling the working substance to store the heat energy. This system has the most updated technology and a wise band of material availability [135–137]. Water is used as storing medium, due to its availability and cheapness. Water is the most prevalent and widely used heat storage medium, and it has industrial and domestic uses. The SHS technology uses the heat capacity and temperature change during discharging and charging. The specific heat, fluctuations of temperature, and the volume of storage material all affect how much heat is retained [138]. The only major disadvantage of this system is the bulkier size compared to other technologies due to having an extremely low heat capacity. Table 10 enlists the properties of some viable materials.

4.4.2. Latent Heat Storage

Systems for storing energy in phase-change materials are acknowledged as latent heat storages [139]. When the phase of the storage material changes, thermal energy is both stored and discharged [140]. In the case of LHS, the volume is decreased as the energy storage density rises. The LHS is dependent on the heat that is absorbed or released during a storage material's phase transition [141]. The usage of LHS systems with PCMs is an efficient method of storing heat energy and benefits from isothermal storage and high energy density [38]. Depending on their physical transition for heat absorption and desorbing characteristics, LHS materials are extensively categorized. PCMs are divided into many classes according to the type of material they are made from [142]. Table 10 enlists the properties of some viable materials.

4.4.3. Chemical Heat Storage

When certain chemical bonds are broken or formed during endothermal or exothermic reactions, some substances can absorb or release a significant quantity of thermal energy [143]. These qualities led to the development of the chemical heat storage systems. Numerous storage materials are accessible as a result of the wide spectrum of storage methods, which include adsorption process and reversible chemical reactions [144]. Three essential characteristics should be taken into account when building a chemical storage system: chemically high enthalpy change, high chemical reversibility, and straightforward reaction conditions [145]. Comparatively, THS seems to be a viable option for usage as a system to store energy [146]. THS systems can produce heat by chemical and sorption processes, and to create effective and affordable systems, the reversible reactions must be implemented according to the resource utilization of user [147,148]. Table 10 enlists the properties of some viable materials.

Table 10. Properties of certain favorable materials [149–151].

STES	Material	Density (kg/m^3)	Specific Heat	Latent Heat	Chemical Enthalpy
Sensible	Concrete	2240	1.13		-
	Soil	1300	0.46	-	-
	Brick	1600	0.84	-	-
	Rock	2240	0.9	-	-
Latent	Paraffin Wax	1802	-	1704	-
Thermochemical	Silica gel	600	1.13	-	1380
	Zeolite	650	1.07	-	1107
	$CaCl.H_2O$	2100	3.06	-	433

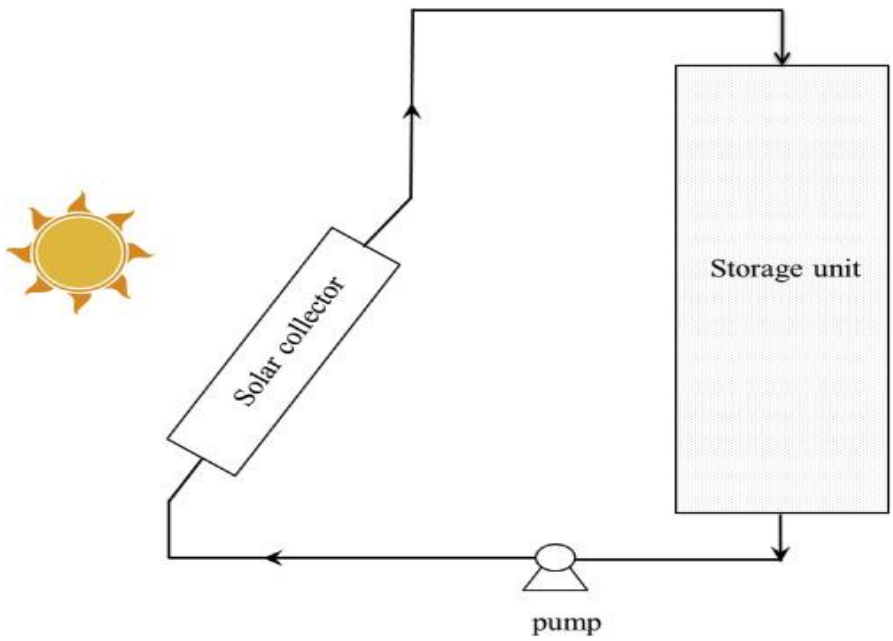

Figure 13. Solar thermal energy storage [133].

4.4.4. Performance Parameters of STES System

The performance and design assessment of solar thermal energy storage are considered to be the key factors in maximizing efficiency of the system. The focus of this section is on a range of variables to be optimized for performance improvement [152].

(a) Power: It can be characterized as the rate of discharging and charging measured in kW for the STES system.
(b) Size and capacity: The capacity of solar thermal storage containers is closely correlated with its container size. The capacity and size show a direct relationship.
(c) Operating temperature: Systems for storing thermal energy typically operate between 40 and 600 °C [153].
(d) Period of storage: Short-term storage that operates at extremely high temperatures. Sensible heat storage materials, such as molten salts and liquid metals, are appropriate alternatives. However, it takes a significant volume of storage material and significant capacity to operate for an extended period at low temperatures under 80 °C.
(e) Efficiency: The division of total energy dispatched to the user by the amount of energy dispensed to recharge the thermal energy storage system.

4.4.5. Challenges and Limitations of STES System

Due to several limitations, STES technology is not as suited as the use of fossil fuel. Future STES system improvements are sought, and to do so, several current restrictions must be considered. Some of the major restrictions are addressed in this section.

(a) PCM leakage: Utilizing phase-change materials is an efficient way to store solar thermal energy. Leakage can occasionally begin and PCM liquid will begin to flow once PCM melts [154].
(b) Heat loss: Larger temperature differences between the STES system and surrounding temperature lead to higher heat losses. Additional heat loss is also caused by inadequate insulation.
(c) Pressure: Water has a high vapor pressure, which necessitates the use of thick containers, which raises the cost and creates a leaking issue.
(d) Super cooling: Due to the substantial change in temperature between the charging and discharging states, super cooling is not advantageous. Most thermal storage materials of the PCM type exhibit it.
(e) Corrosion: The vessel is severely corroded by inorganic materials used in thermal energy storage systems.
(f) Safety: Materials used in these storage systems have a significant risk and are usually inflammable. The organic oils especially tend to be exceedingly difficult to work with in terms of safety.

5. Summary and Conclusions

5.1. Summary

The temperature requirements of the industrial process essentially determine the choice of solar thermal technology. The most significant factor affecting collector field sizing is the process temperature. The range of delivered temperatures can therefore be used to distinguish between different solar thermal collectors. FPC, CPC, and ETC can meet the requirements for temperature ranges of 30–80 °C, 60–240 °C, and 50–200 °C, respectively. Additionally, PTC, LFR, PDR, and HFR can meet temperature requirements of 60–300 °C, 60–250 °C, 100–500 °C, and 150–2000 °C. Solar collectors that are now on the market occasionally fall short of requirements due to increased manufacturing temperatures. To achieve the requisite higher temperatures in this situation, cascading or stacking many collectors is one of the possible methods.

In addition to the aforementioned, there are other general aspects that should be taken into consideration while selecting the appropriate technology. These parameters include

the land scarcity, the fluctuation and flexibility in temperature load, schedule, the possibility for temperature changes in the storage, and integration.

5.2. Conclusions

These are the conclusions reached because of this research:

1. According to research, the industrial sector uses between 32% and 35% of the world's total energy, and fossils are substantially burned in boilers and furnaces to create process heat for industries, which results in GHG emissions. Approximately 37% of all emissions worldwide are produced by the industrial sector. Installing a system for heating processes that utilizes solar thermal collectors as primary technology to harness the energy of the sun will provide a long-term answer for enterprises moving toward a future with zero carbon production, since solar energy is widely available.
2. To show readers the scope of solar thermal collectors' applicability, typical applications are given. These include heating and cooling of space, either residential or commercial, as well as refrigeration, water desalination, CCS technology, and implementation of solar thermal energy in industrial processes. From the literature, we also saw that systems that combine air and water as working fluids are more effective than individual systems.
3. Solar thermal energy has the capacity to meet the industrial demand for process heating, but given the intermittent nature of sunlight, there may be an unreliable outcome. Therefore, solar thermal energy storage systems are used to sustain the system load.
4. This study will assist decision-makers in creating a framework that will serve as a blueprint for managing the incorporation of solar thermal energy in global industrial development.

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