Solar Process Heat in Industrial Systems- A Global Review

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abstract

In developing countries, industries and manufacturing sectors consume a major portion of the total consumption of energy, where most of the energy is used for low, medium or high temperature heat generation to be used for process applications known as process heat. The necessity to commercialize clean, cheap and efficient renewable sources of energy in industrial applications emerges from increasing concerns about greenhouse gas emissions and global warming and decreasing fossil fuel use in commercial sectors. As an abundant source of energy, solar energy technologies have proven potential. Recent research shows currently only a few industries are employing solar energy in industrial processes to generate process heat while replacing fossil fuels. Solar thermal power generation is already very well-known and getting popular in recent years while other potential applications of the concentrated heat from solar radiation are little explored. This review paper presents a detailed overview of the current potential and future aspects of involving solar industrial process heating systems in industrial applications. In order to keep pace with this emerging and fast growing sector for renewable energy applications, it is necessary to get in depth knowledge about the overall potential of industrial processes in individual industrial sector where solar process heat is currently in use and identifying industrial processes are most compatible for solar system integration depending on temperature level and the type of solar collector in use. Furthermore, the promising sectors needs to be identified for the use of solar heat using industrial processes for the integration of solar heat, so that countries with immense solar energy potential can use those technologies in future to reduce fossil fuel consumption and develop sustainable industrial systems. This paper presents a comprehensive review of the potential industrial processes that can adopt solar process heating systems and thus driving towards sustainable production in industries.

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1. Introduction

Recent trends of energy production and consumption in manufacturing industries are notably unsustainable due to rapidly increasing greenhouse gas emissions. Developing countries throughout the world are trying to industrialize their own economy to create new opportunities for the young generation to address their own country as a developed one. For mitigating poverty through sustainable development, every developing country is following their own energy policy for employing environmentally friendly energy specifically in the industrial sectors [4, 7, 12, 13, 99].

As a renewable and abundant source, solar energy systems are future sustainable solutions for industrial consumers although, some places have inadequate solar energy resource where solar industrial process heating may not be feasible, but many other places receive abundant solar radiation and implementing such systems will drive the industries towards sustainable zero carbon production future. Industrial processes are mainly dependent on either electricity or fossil fuels to supply industrial process heat. As the non-renewable energy sources are going to be finished in future and considering all the drawbacks like GHG emissions, demand for renewable energy sources is imminent. The major drawback which hinders the scope for small and medium scale industries to integrate renewable energy systems in their production processes is the high capital cost while mostly the importance goes for ensuring continued supply of process heat from solar energy systems [7,12,13,100].

Industrialized and developed regions in Europe, Asia and North America are successfully using solar thermal systems in industrial processes. Solar thermal energy for electricity generation is also becoming popular in different parts of the world. Feasibility of commissioning and running such systems are heavily dependent on radiation intensity. If the regional and seasonal variation is not significant, then a supplementary energy storage system may not be necessary depending on the type of application. Where seasonal variation is quite dominant where reduced radiation available in winter for a few months, energy storage systems may improve the overall performance of the system.

This review paper discussed the fundamentals of solar thermal energy and solar collectors, and the temperature range for industrial applications where process heat is in use. According to solar industrial process heating (SHIP) plants database information, promising industrial sectors are identified and further explained with current literature and plant installation information. The most widely used industrial processes with solar thermal applications are thus identified and reviewed. This review aims to identify the existing potential of solar industrial process heating systems in industrial sectors, where to integrate solar industrial process heating systems, which collectors are suitable for specific processes depending on temperature requirements. The authors systematically analyzes existing solar industrial process heating plants throughout the world, thus identify 11 key industrial sectors, mostly developed 6 processes. In these identified and integrated industrial sectors and processes are categorized through suitable solar collector type and process heating temperature ranges. This paper also discusses the future potential of solar industrial process heating systems.

Section 1 gives an overview of the importance of solar process heat for industrial sectors, and the objectives of this review paper. **Section 2** discusses the present literature, trying to identify the potential sectors for solar industrial process heating systems. **Section 3 and Section 4** gave an insight into solar thermal energy and solar industrial process heat. **Section 5** illustrates the most widely used solar collector types for process heating systems. The process heat requirements by temperature range are discussed in **section 6**. Then **section 7** explains the criteria for selecting a suitable solar collector for an integrated solar process heating system. **Section 8** worked on temperature range of solar process heat applications, followed by **Section 9** where most common solar driven industrial process stages are discussed through current potential, plants in operation and existing literature. **Section 10** described a range of industries where solar process heat is in use, how they are employing solar process heat, where they are employing it and how it is performing. Finally **Section 11** and **Section 12** analyze and compare existing potential research and reviews throughout all industrial sectors to find gaps in the gap of research and also the gap of solar process heating system integration in industries.

2. Methodological Approach

There are very few research papers which try to identify potential industrial sectors for integration of solar heat in industrial processes and none of them analyze the potential industrial sectors in respect of existing SHIP plants globally to determine the potentials for others which are feasible and already in practise. This review paper is the first one to do such an analysis in SHIP.

Lauterbach et al. studied and reviewed the potential in the field of solar industrial process heat integrated with suitable industrial processes. The annual specific energy gain is determined using TRNSYS simulation depending on temperature level, location and solar collector type [44]. In another work, **Lauterbach et al.** methodically analyzed an installed solar process heating system based on simulation and compared it with a validated model [42]. **Weiss et al.** reviewed the solar industrial process heating potential among countries for medium temperature collectors and sought a solution for SHIP integration problem [94]. **Schnitzer et al.** applied a newly developed investigation tool to investigate industrial energy systems and heat integration feasibilities through an Austrian dairy industry case study [77]. **IEA SHC task 33 and SolarPaces Task IV: Solar Heat for Industrial Processes** identifies and discusses potential industrial sectors for SHIP integration [36]. **Mekhilef et al.** reviewed solar energy utilization by industrial applications thus identified potential industries [53]. **Norton** illustrated the industrial applications of solar heat such as solar water heating system, solar drying system, solar furnaces, green houses, heating and ventilation systems, solar cooking, solar desalination and solar refrigeration [63, 64]. **Vajen et al.** outlined solar heat integration potential at supply level and process level in Europe, Germany and worldwide [91]. **Taibi et al.** reviewed and discussed renewable energy potential in industrial sectors such as biomass and low temperature solar process heat [89]. **Schmitt** performed several comprehensive studies to show the utilized process installations in food and beverage industries. He also developed a classification mechanism for SHIP integration [76]. **Modi et al.** reviewed solar driven heat and power generation systems [54]. **Pietruschka et al.** reported on the fundamental design, process system layout, operating conditions and industrial processes of three large scale solar process heat installations [69]. **Calderoni et al.** studied the feasibility analysis of integration of solar process heating systems in industrial processes in Tunisia followed by an economic analysis [9]. **Montes et al.** presented the parabolic trough solar collector based process heating system and their design results [56]. **Frein et al.** studies and presents the design procedure and analysis basics required for integrating a solar thermal plant into an industrial system [27]. **Schramm et al.** presents a new concept of solar process heat integration system based on solar tanks through solar tank volume simulation results [78]. **Larcher et al.** experimentally investigated the parabolic trough solar collector based integrated solar process heating system [41]. **Kalogirou** presented simulated results of the parabolic trough collector based solar process heating system performance located on Cyprus [38]. **Esen** experimentally investigated and presented the thermal performance of vacuum tube collector based solar cooker under varied refrigerant conditions [21]. **Silva et al.** developed an optimization method for parabolic trough solar collector based solar industrial process heating systems. In another research work **Silva et al.** also conducted uncertainly and sensitivity analysis for parabolic trough collector based steam generation plant [83-85]. **Coccia et al.** designed and experimentally tested a prototype model of a parabolic trough solar collector for process heating application [11]. **Naik et al.** reviewed all kinds of medium temperature application areas of concentrated solar thermal technologies in India [62].

This review work analyzes existing solar industrial process heating systems throughout industries over the world. These industries and their respective process systems are analyzed and explained based on their solar collector type, installed thermal capacity and expected temperature range. Existing research and review are also studied by industrial category. Thereby the more common industrial process stages integrated with solar systems are identified and presented in this paper. These industrial process stages are elaborated with their industrial category, country data, solar collector and temperature range specifications. In a later part, potential industrial sectors are identified and discussed to find the integration problems of solar industrial process heating systems and future research scope.

In this review, all industrial sectors are analyzed based on their respective process operations where solar heat is already in use, and also classified based on process operation and temperature range. The dominant industrial sector where solar process heating system is widely in use is food and beverage industries, comprising water heating, washing, pasteurization, cooking, drying etc. Then another sector that is textile industries where cleaning, drying, washing, fixing and pressing are the major operations utilizing solar process heat. The temperature ranges required for these process operations are also identified and reviewed to locate the potential sectors which are currently consuming a significant amount of fossil fuels to run the process operations but where the low range temperature can be easily achieved by using solar process heat. Also, this review paper will be of great help for different countries where solar heat is found in abundance but is not in utilization for industrial operations. Industrial authorities can easily get an overview from this paper where to utilize solar process heat and what can be achieved from this. Future research scopes in the field of solar industrial process heat and its impact on greenhouse gas emissions and sustainable development through the lifecycle assessment are also outlined in the last section of the paper.

3. Solar Thermal Energy

In simple words, while we get the energy from heat conversion gained from solar irradiation, is termed as solar thermal energy. Like other renewable energy systems, solar thermal energy can replace the fossil fuels in industrial systems. The energy conversion systems employ a variety of solar thermal collectors along with concentrators which accumulate and deliver solar radiation for process heat generation to be used in commercial or industrial plants. The type of solar collector, working fluid, installation parameters, heat exchanger specifications need to be considered for the specific process operation. However, the most important factor is solar energy could not be available to supply process heat in the system for 24 hours. Supplementary process heating systems should be equipped using phase change materials (PCM) or molten salts [86-88,97-102].

4. Solar Industrial Process Heating Systems

Of the global final energy demand, electricity accounts for around 17% low temperature heat applications stand for 44%, whereas high temperature industrial process heat occupies 10%. Solar energy has a long history of use in the residential building sectors. The industrial and manufacturing sectors are well suited to solar thermal technology

and its application only because of the volume of energy required for process heating systems in integration. For example, the major heat requirement is for processes like different types of drying, cleaning, washing, water heating, pasteurization and sterilization and so many food processing applications. The temperature level required for these industrial processes is similar for almost all applications being below 250° C [86-88, 97-102].

5. Solar Collector Types for Process Heat Applications

Flat-Plate Solar Collector

This accumulates heat energy from incident radiation while the absorber plate absorbs and then transmits it to the working fluid, for example heat transfer oil , air, water, or aqueous glycol solution. Flat-plate collectors are popular for high absorbance efficiency of the incident radiation with good thermal conductivity and low emittance. During plant operation they provide thermal stability of the temperatures encountered. Flat-plate collectors are lighter, more durable and with cheaper capital cost. There are pipes of an isolated box where working fluids circulate to reduce heat losses.

Evacuated-Tube Solar Collector

In an evacuated-tube collector,a separate cylindrical glass envelope is provided which prevents the absorber plate from heat loss due to convection. The collector selection is dependent upon the temperature requirement of the industrial process.

Unglazed Collector

These are used for certain low-temperature applications, for example, for recovering salt from agricultural drainage water.

Vacuum-Tube Collector

In vacuum-tube collectors, pipes are placed inside vacuum glass tubes through which water circulates inside pipes. In comparison with flat-plate collectors, higher temperature range can be obtained and heat losses can be reduced more effectively.

Fresnel Collector or Parabolic Trough Collectors

The irradiation is first incidents on the reflective surfaces and then concentrated onto a solar absorber. Here, high temperature ranges above 400°C can be achieved. Concentrating collectors continually track the sunshine over the whole day and over the whole year. Primary mirrors are there to track the direct irradiation from sunlight over the time and further concentrate the sunlight onto the solar absorber tube. Inside the absorber tube, a heat transfer fluid (pressurized water, steam or thermal oil) circulates to provide thermal energy to the target process.

Table 1 represents the types of solar collectors based on their key features, concentration ratio for direct isolation and indicative temperature.

Name	Collector Type & Description	Concentration Ratio for direct isolation	Indicative Temperature
Non-concentrating Solar Pond	Stationary	C<1	300<T<360
Flat-plate Absorber	Stationary	C<1	300<T<360
Evacuated Envelope	Stationary	C<1	320<T<400
Compound Parabolic Collector	Stationary / Motion: Single Axis Solar tracking	1<C<5, 5<C<15	340<T<510, 340<T<560
Parabolic Reflector	Motion: Single Axis Solar tracking	15<C<45	340<T<560
Fresnel Reflector	Motion: Single Axis Solar tracking	10<C<40	340<T<540
Cylindrical Reflector	Motion: Single Axis Solar tracking	10<C<50	340<T<540
Parabolic Dish Reflector	Motion: Two Axis Solar tracking	100<C<1000	560<T<1200
Spherical Bowl Reflector	Motion: Two Axis Solar tracking	100<C<1000	560<T<1000
Heliostat Field	Motion: Two Axis Solar tracking	100<C<1000	600<T<2000

Table 1: Classification of solar collectors.

6. Industrial Heat Demand by Temperature Range

The analysis of the performed review studies will be useful for the industrial process heat requirement depending on the temperature ranges for many countries, which are not widely available. The analysis presented in this review paper will be useful to overcome this lack of information. However, it should be mentioned that even the industrial processes consume medium-temperature heat by using steam as a medium of working fluid; lower working temperatures would be sufficient for that purpose. Moreover, to calculate the efficiency of the integration of a solar thermal system into a manufacturing process, first the actual temperature required by the process itself should be assessed properly and should not be simply the heat carrier temperature in use. Such an approach should be followed for lowering the process energy consumption.

Table 2 represents the major industrial sectors and their application areas where low-temperature process heat is required, categorized based on process stage and temperature range. The datasets are collected from several published books and journal resources.

Sector	Process	Temperature Range (°C)
Chemicals	Biochemical reaction	20~60
	Distillation	100~200
	Compression	105~165
	Cooking	80~100
	Thickening	110~130
Foods & beverages	Blanching	60~100
	Scalding	45~90
	Evaporating	40~130
	Cooking	70~120
	Pasteurization	60~145
	Smoking	20~85
	Cleaning	60~90
	Sterilization	100~140
	Tempering	40~80
	Drying	40~200
	Washing	30~80
Paper	Bleaching	40~150
	De-inking	50~70
	Cooking	110~180
	Drying	95~200
Fabricated Metal	Pickling	40~150
	Chromaiing	20~75
	Degreasing	20~100
	Electroplating	30~95
	Phosphating	35~95
	Purging	40~70
	Drying	60~200
Rubber & Plastic	Drying	50~150
	Preheating	50~70
Machinery & Equipment	Surface treatment	20~120
	Cleaning	40~90
Textiles	Bleaching	40~100
	Coloring	40~130
	Drying	60~90
	Washing	50~100
	Fixing	160~180
	Pressing	80~100
Wood	Steaming	70~90
	Pickling	40~70
	Compression	120~170
	Cooking	80~90

	Drying	40~150
Dairy	Pressurization	60-80
	Sterilization	100-120
	Drying	120-180
	Concentrates	60-80
	Boiler feed water	60-90
Tinned food	Sterilization	110-120
	Pasteurization	60-80
	Cooking	60-90
	Bleaching	60-90
Meat	Washing,	60-90
	Sterilization	60-90
	Cooking	90-100
Flour & By-products	Sterilization	60~80
Timber By-products	Thermo diffusion beams	80~100
	Drying	60~100
	Pre-heating water	60~90
	Preparation pulp	120~170
Bricks & Blocks	Curing	60~140
Plastics	Preparation	120~140
	Distillation	140~150
	Separation	200~220
	Extension	140~160
	Drying	180~200
	Blending	120~140
Automobile	Water heating	~90
	Cleaning	~120
	Other processes	~50
Pharmacy	Different processes	7~180
Mine	Cleaning	~60
	Electro-Winning	~50
	Other processes	~80
Agriculture	Drying	~80
	Water Heating	~90
Leather	Retanning	~80
	Other processes	~90
Metal	Heating	~180
	Washing	~160

Table 2: Solar Thermal Energy for Industrial Uses.

7. Criteria for Selecting Solar Thermal Collector Type

There are some required aspects which are especially relevant and need to be considered to identify the optimal solar thermal collector technology such as space efficiency, temperature control and integration. Solar energy is affluently available where comparatively large areas are required for the collection of solar energy. Every industry is energy intensive where unused space is scarce in industrial areas. So, to use solar process heat in industries, solar-collector technology should have space efficiency with roof top installations. Another point is industrial processes are often very sensitive to temperature ranges. Definitely the solar collector systems should provide accurate temperatures according to the specific demand. Most industries use heat-carrier fluid which can supply heat to different processes. Solar process heating systems are integrated with conventional heating systems.

For integration of a solar thermal energy system into a conventional system, there could be three main methods.

1. Pre-heating of water where heat energy is required for evaporation. However, the condensate can return a high temperature so the efficiency of the non-concentrating collector is reduced.

2. Integration on the distribution level where high temperatures (mostly steam) are required so only concentrating solar collectors can be used. This provides the greatest flexibility as it is not linked to a specific process.

3. Another important way to integrate solar thermal energy is direct coupling with a specific process. But when the process is changed or stopped, it can be challenging to use the energy which is rather inflexible [1, 3, 4, 6, 8, 9].

8. Temperature Range for Solar Process Heat Applications

Solar heat can be integrated at the process level on heat supply level of an industrial company. At the supply level, preheating boiler feed water with the heating of a hot water circuit or production of direct steam are the main applications. These supply level applications require a high temperature which may turn as an unfavorable climate conditions. Depending on the size of the system and the industrial sector, other characteristics such as processes with integrated solar heating system were documented. 36 or 51% of installed solar heating systems were used for water heating or washing processes, 14% systems were integrated in “heating of baths/vessels”, 6% for different drying processes and 29% for other processes like car washing facilities, etc. (Task33, 2006). The temperature level required for an industrial process is crucial for the feasibility assessment, as the annual energy yield depends strongly on provided temperature. Numerous processes can be found at temperatures below 40°C, and 40°C to 60°C. The industrial processes within the temperature range of 60°C to 100°C, are of high importance as well. Figure 1 demonstrates the importance of the above mentioned temperature ranges (Task33, 2006) [12,13,16,25,26,31,32,35].

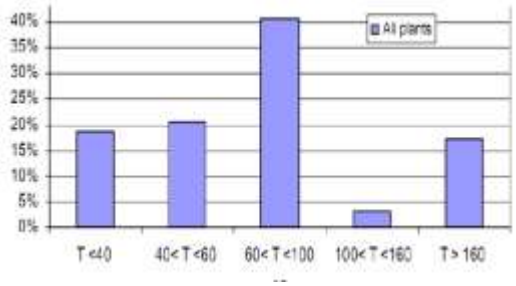

Fig. 1: Temperature level of the supported processes of existing solar heating systems (Task33, 2006) [36]

9. Typical Industrial Processes where Solar Heat is in Use

The analysis of industrial processes cannot be generalized or categorized because of the conditions, which vary too widely, for example, in food industry purification or bottle cleaning plants. Several unit operations operating in various processes and industrial sectors are given below.

9.1. Water Heating

A typical water heating process with conventional energy sources runs with smaller equipment like heat exchangers. To integrate a solar energy system, design should be focused to operate at the lowest temperature levels after increasing collector efficiency. Solar water heating (SWH) applications constitute the major part of industrial solar thermal applications, with cost effectiveness of all the currently available solar thermal technologies.

Morrison reviewed solar water heater product configurations and their markets in Australia [57]**. Esen et al.** research on the performance of two-phase solar collectors used in solar water heaters with different refrigerants [22]. **Buker et al.** reviewed past and present research work conducted on solar assisted heat pump systems used in low-temperature solar water heaters [8]. **Gautam et al.** reviewed the

basics of thus followed by the future scenario of solar water heating systems [29].

Table 3 illustrates the main industrial application areas where solar water heating system is already in use, their key features, solar collector information and also operational temperature data.

Industry	Country	Name	Industrial Operation	Solar Collector	Temperature(°C)
Automobile	South Africa	BMW Manufacturing	Paint application process	Evacuated tube collector	~90
Breweries	USA	Milwaukee Brewing Co.	Consumption	Flat plate collector	
	Germany	Hutt Brewery	Heating the brewing water	Flat plate collector	40~95
	China	Chongqing Beverage	Heating for warehouse	Evacuated tube collector	
	Saudi Arabia	Nestle Waters	Bottle washing	Flat plate collector	
Food	Mexico	Aviary Food Pellet El Paisa	Heating water	Parallel trough collector	~95
	Greece	Alpino S.A.	Hot water preheating in steam boiler	Flat plate collector	20~70
			Cleaning equipment	Other or various collectors	20~90
	Austria	Futtermittel Fruit Juice	Makeup water	Flat plate collector	
		Mogunti a Spice Making	Cleaning and production process	Flat plate collector	
	Portugal	Knoww Best Foods S.A.	Tools washing	Flat plate collector	40~45
	Spain	Montesano-canary islands	Wash meat derivatives	Flat plate collector	40~60
	Czech Republic	PETA Bohemia Pekarna Sobeslav	Bakery	Flat plate collector	10~90
	Netherlands	Perfetti van melle	Preheating of hot water and process heat	Flat plate collector	
	Jordan	Seniora Food Industries	Degreasing & cleaning requirements	Evacuated tube collector	
Textile	USA	Acme McCrary	Textile drying process	Flat plate collector	
	Greece	Allegro S.A. Childrens' clothing manufacturer	Washing machines	Flat plate collector	33~60
		Kastrinagiannis S.A.	Dyeing machines	Flat plate collector	40~90
	China	Daly Textile	Dyeing process	Flat plate collector	~55
	India	Sharman Shawls	Dyeing, bleaching & washing garments	Flat plate collector	~100
Mining	Germany	Schiffer Gmbh & Co KG	Galvanic baths	Evacuated tube collector	40~70
		Steinbach und Vallmann	Galvanic baths	Evacuated tube collector	60~80
Chemical	India	L'oreal Punne	Cleaning process	Flat plate collector	~55
Agriculture	Spain	Acuinova Andalucia S.A.	Heating Water	Flat plate collector	23~26
	China	Hongxin Aquaculture	Water Heating	Evacuated tube collector	
	Germany	Woltow	Water Heating	Parallel trough collector	
Leather	Austria	Gerberei Kolblinger	The wet process of leather retanning	Flat plate collector	
Fabricated Metal	India	SKF Technologies Mysore	Circulation	Parallel trough collector	~95
Wearing Apparel	India	Chelsea Jeans	Dyeing process	Flat plate collector	
Computer, electronic & optical products	Sweden	Bosmans Lackering	Chemical baths	Parallel trough collector	~160
Machinery	Austria	Hoval Marchtrenk	Powder coating	Flat plate collector	
		Kral Pump Factory	Space heating	Evacuated tube collector	

Table 3: Industries working with solar water heating process [101].

9.2. Drying processes

In drying processes, moisture can be eliminated from a material as a primary condition. Some other drying processes are involved in drying food, plants, fruits, textiles and mineral materials, washing and varnishing. By preheating with solar heat, the drying will generally be done with warm air. So, solar systems can work with air or water system. The potential industries that can be benefited from such solar thermal energy systems are: bricks, plants, fruits, coffee, wood, textiles, leather, malt (kiln drying of green malt).

Akoy et al. described the design features, criteria and calculation of a solar dryer for a mango factory [65]. **Fuller** describes the theoretical and technical basics of solar drying systems, evaluated the performance and discussed future developments [28]. **Mehrdadi et al.** experimentally investigated the performance of a solar dryer used in industrial drying in pharmaceutical industries [51]. **Rural Industries Research and Development Corporation** worked on developing a solar drying machine for agricultural products [47]. **Sebaii et al.** reviewed the fundamentals and research work done in solar drying systems [18]. **Lee** studied and constructed solar drying system with an evacuated tube solar collector and also evaluated the system performance with indoor and outdoor drying [45]. **Pirasteh et al.** reviewed the development of solar drying applications in industry and agriculture, energy consumption capacity and aspects of using solar dryer from multiple viewpoints [70]. **Hubackova et al.** researches on solar dryers used in fish processing in Combodia [33]. **Mustayen et al.** studied and reviewed the performance studies on different solar dryers

[61]**. Yuan et al.** researched on solar dryers used in carpet drying, thus evaluated its thermal performance [95]. **Montero et al.** researched on solar drying systems used in drying wastes from olive-oil mills [55]. **Liu et al.** reviewed 5 types of solar drying systems used in drying herbal Chinese medicine [46]. **Kumar et al.** reviewed and presented different types of solar dryers through a varied application areas and their progress [40].

Table 4 illustrates the main industrial application areas where a solar drying system is already in use, their key features, solar collector information and also operational temperature data.

Industry	Country	Name	Industrial Operation	Solar Collector	Temperature(° C)
Breweries	Germany	Newmarketer Lammsbraw	Drying process	Air collector	~60
		Carriers & Sons	Drying	Air collector	~43
Food	USA	Keyaqa Orchards	Walnuts Drying	Air collector	~43
		Kreher's Poultry Farms	Drying of chicken Eggs	Air collector	
		Stapleton Spence Fruit Packing Co.	Rehydrate Dried Foods	Unglazed Collector	
		Sunsweet Dryers	Prune Drying	Air collector	10~15
	India	Kaveri Agricare Pvt. Ltd.	Drying Coir Peat	Air collector	~105
	Costa Rica	Coopeldos	Coffee Drying	Air collector	40~45
	Panama	Duren Coffee	Coffee Drying	Air collector	40~45
	China	Gengli Fruit Drying	Fruit drying	Air collector	50~70
	Indonesia	Malabar Tea Drying	Tea drying	Air collector	~35
Mining	Austria	Korner Kvk	Preheating, drying	Flat plate collector	50~80
Agriculture	India	AMR dal Mill	Drying of Pulse	Air collector	65~75
	Romania	Aroma Plant Romania	Drying of Medicinal Plants	Air collector	
	USA	Sonoma Country Herb Exchange	Drying of Herbs	Air collector	
	Germany	Krimmer	Drying of Wild Flower Seeds	Flat plate collector	
Leather	India	Leo Leather	Chemical mixing, drying	Flat plate collector	
Fabricated Metal	Germany	Lackiercenter Shulte	Drying Chamber	Evacuated tube collector	
	Portugal	Silampos S.A.	Drying finished product	Parallel trough collector	50~160
Tobacco	Argentina	Grammer Solar Argentina	Drying of tobacco	Air collector	
Rubber & Plastic Products	Thailand	Inter Rubber Latex Co. Ltd.	Drying of natural rubber	Air collector	
Concrete	Austria	Leitt Beton Gmbh	Drying of pre-fabricated concrete components	Flat plate collector	
Furniture	Austria	Carpenting Hamminger	Wood Drying	Flat plate collector	25~115
Repairing & Installation	Germany	Lackiererei Vogel	Drying process	Evacuated tube collector	22~24,60~70

Table 4: Industries working with solar drying process [101].

Fig.2. Copendos, Costa Rica coffee drying process [79].

9.3. Preheating processes

Solar thermal energy is ideal to use for preheating processes with low-temperature applications. Waste heat, compressed air compressors, cooling equipment, gas engines might serve as alternative heat source. Typical examples can be: warm water and boiler feed water.

Celuppi et al. studied and analyzed the performance of 4 vacuum solar collectors for boiler water preheating [10]. **Esen et al.** investigated the performance of heat pump integrated solar space heating system [19, 20]. **Kabeel et al.** reviewed the designs, and further improvement methods for solar air heater to reduce fuel consumption [37].

Table 5 illustrates the main industrial application areas where a solar preheating system is already in use, their key features, solar collector information and also operational temperature data.

Industry	Country	Name	Industrial Operation	Solar Collector	Temperature(° C)
Breweries	USA	Gatorade	For soft drink production	Flat plate collector	~35
	Germany	Brauerei Hald (brewery for beverages)	Preheating of bottles	Flat plate collector	40~120
		Newmarketer Lammsbraw	For drying process	Air collector	~60
	Czech Republic	Cider House Hostetin	Cider before pasteurization & for bottle washing	Flat plate collector	
Food	Mexico	Durango Dairy Company	Boiler Preheating	Parallel trough collector	20~95
	Spain	Industria Alimnetaria Alcoyana	Boiler feed water for	Flat plate collector	40~130
		Metadero Montesierra	Boiler feed water	Flat plate collector	40~60
		TE-PE S.A.	Boiler feed water	Flat plate collector	40~130
	Netherlan	Perfetti van	Hot water	Flat plate	

	ds	melle	and process heat	collector	
	China	Gengli Fruit Drying	For fruit drying	Air collector	50~70
Textiles	China	Jiangsu Printing & Dyeing	For printing & dyeing process	Evacuated tube collector	~50
Mining	Austria	Korner Kvk	Preheating, drying	Flat plate collector	50~80

Table 5: Industries working with solar preheating process [101].

9.4. Steam Heating Process

Solar steam heating is done with conventional energy sources runs with smaller equipment like heat exchangers. To integrate a solar energy system, the design should be focused on operating at the lowest temperature levels after increasing collector efficiency. These applications constitute the major part of industrial solar thermal applications, with cost effectiveness of all the currently available solar thermal technologies.

Haagen et al. investigated the solar process steam systems installed in the pharmaceutical industry, RAM pharmaceuticals in Jordan [48]. **Valenzuela et al.** analyzed the numerical results obtained from the thermal-hydraulic behavior of solar fields producing steam using parabolic-trough collectors under different design conditions [93].

Table 6 illustrates the main industrial application areas where a solar steam heating system is already in use, their key features, solar collector information and also operational temperature data.

Industry	Country	Name	Industrial Operation	Solar Collector	Temperature(° C)
Food	USA	Frito Lay	Steam for Heating	Parallel trough collector	~243
	Switzerland	Emmi Dairy Saignelsgier	Different drying processes	Parallel trough collector	140~180
Textile	India	Purple Creations	Steam processing & washing	Other or various collectors	
Chemical	China	Solar steam boiler for procter & gamble (Tianjin)	Steam generation	Parallel trough collector	~130
Fabricated Metal	Germany	Alanod Solar	Production of saturated steam	Parallel trough collector	~143

Table 6: Industries working with solar steam heating process [101].

9.5. Pasteurization and sterilization process

Dairy industries can utilize solar energy for process operations as they operate with no day off. Among the solar food processes, pasteurization and sterilization are the energy-intensive ones where major difference is the phase of the medium. Pasteurizing bottled requires a heat transfer medium because it is impossible to apply a direct heat exchange. The heat transfer medium can be connected to a solar thermal plant for pasteurizing and sterilization. It can be for liquid food, packaged food, devices, and other process streams.

Aiken et al. designed and developed a prototype solar water pasteurizer system with integral heat exchanger [2]. **Paull** submitted a report on solar pasteurization on water used for washing fruit and vegetable [68]. **Rabab et al.** fabricated and tested the performance of low temperature solar milk pasteurizer [73]. **Osama et al.** carried out a TRNSYS simulation to find a potential solar collector for sterilization applicationsm depending on industrial area [66].

Table 7 illustrates the main industrial application areas where a solar pasteurization or a solar sterilization system is already in use, their key features, solar collector information and also operational temperature data.

Fig. 3. 706 kW solar thermal plant in dairy industry in Greece [94].

Industry	Country	Name	Industrial Operation	Solar Collector	Temperature(° C)
Breweries	Austria	Gangl Fruit Juices	Pasteurization	Flat plate collector	95~105
	Austria Mexico	Metbrauerei Newwirth	Pasteurization, sterilization	Flat plate collector	50~95
		Dairy Plant Ladonita	Pasteurization	Parallel trough collector	60~95
Food	Mexico India	Nestle Dairy Plant	Pasteurization	Parallel trough collector	80~95
		Nestle Dairy Plant-Lagos ds Moreno	Pasteurization	Parallel trough collector	80~95
		B.G. Chitale	Pasteurization of milks	Other or various collectors	~150
	India Austria	Indian Institute of Horticulture	Pasteurization of straw	Other or various collectors	80~100
		Mahanand a Dairy	Pasteurization of milks	Other or various collectors	~120
		Milma Dairy	Pasteurization of milks	Flat plate collector	
		Krispl Fruit Juice	Pasteur crates washing space climate	Flat plate collector	~80

Table 7: Industries working with solar pasteurization process [101].

9.6. Washing processes

Washing processes require a bulk of warm water, which provides an excellent opportunity to use solar thermal energy in practically all commercial sectors like bottles, barrels and containers in the food industry, metal parts and varnishing, galvanizing and enameling surfaces, and textile industry, business enterprises, laundries etc.

Fig. 4. Washing demonstration plant in Austria [95].

Table 8 illustrates the main industrial application areas where a solar washing system is already in use, their key features, solar collector information and also operational temperature data.

Industry	**Country**	**Name**	**Industrial Operation**	**Solar Collector**	**Temperature(°C)**
Automobile	India	Mahindra Vehicle Manufacturers	Engine components	Other or various collectors	~120
Breweries	Greece	Achaia Clauss S.A.	Bottle Washing	Flat plate collector	45~60
	Germany	Hofmuhl Brewery	Bottle washing	Evacuated tube collector	20~110
		Brauerei Hald (brewery for beverages)	Cleaning	Flat plate collector	40~120
	USA	Brown's Brewing Co.	Cleaning	Flat plate collector	
	France	Bourdoil	Bottle cleaning	Flat plate collector	15~70
	Czech Republic	Cider House Hostetin	Bottle washing	Flat plate collector	
	South Africa	CBC Brewing	Cleaning process	Flat plate collector	
	Austria	Metbrauerei Newwirth	Bottle washing,	Flat plate collector	50~95
		Petter Vineyard	Bottle washing	Flat plate collector	20~90
		Gangl Fruit Juices	Bottle cleaning,	Flat plate collector	95~105
	Saudi Arabia	Nestle Waters	Bottle washing	Flat plate collector	
Food	Greece	Tyras S.A.	Washing of cisterns and lorries	Flat plate collector	
		Mevgal S.A.	Cleaning equipment	Other or various collectors	20~90
		Plektemboriki Kritis S.A.	Cleaning Olives	Flat plate collector	40~90
	USA	Adams Farm Slaughterhouse	Cleaning	Flat plate collector	
		Battenhill Valley Creamery	Cleaning	Flat plate collector	
		Prestage Foods	Cleaning	Flat plate collector	60~82
	Austria	Eidvogel Hubert Bernegger	Fish Transportation trucks		
		Krispl Fruit Juice	Washing space	Flat plate collector	~80
		Moguntia Spice Making	Cleaning	Flat plate collector	
	Israel	Golan Winery	Barrel Washing	Flat plate collector	~95
	India	Kwality Walls Inccream	Cleaning	Flat plate collector	
	Portugal	Knoww Best Foods S.A.	Tools washing	Flat plate collector	40~45
	Spain	Montesano-Jerez de los caballero	Raw product reception washing	Flat plate collector	40~45
	France	Bonilait Dairy	Cleaning	Flat plate collector	~80
	Germany	Edmund-gourmet foods	Rinsing & Cleaning of bottle plants	Flat plate collector	20~60
	Jordan	Seniora Food Industries	Cleaning requirements	Evacuated tube collector	
Textile	Greece	Allegro S.A. Childrens' clothing manufacturer	Washing machines	Flat plate collector	33~60
	India	Purple Creations	Washing	Other or various collectors	
		Sharman Shawls	Washing garments	Flat plate collector	~100
Wearing Apparel	Vietnam	Saitex Jeans	Jeans washing process	Flat plate collector	
Mining	South Africa	Anglo Plant-brakfontein	Cleaning	Flat plate collector	
		Anglo Plant-middlepunt	Cleaning	Flat plate collector	
		BHP Bolliton wolwekrans colliery	Cleaning	Flat plate collector	~60
		Northern Platinum's Booysendal Mine	Cleaning	Flat plate collector	~60
		Xstrata Elands Mine	Cleaning	Evacuated tube collector	~60
Chemical	India	L'oreal Punne	Cleaning process	Flat plate	~55

				collector	
	Austria	MAPAG	Cleaning of samples	Flat plate collector	~60
Fabricated Metal	France	Viessmann Faulquemont	Cleaning bath	Evacuated tube collector	~60
Transport Equipment	India	Harite Seatings Systems Limited	Cleaning automobile parts	Evacuated tube collector	55~60

Table 8: Industries working with solar washing and cleaning process [101].

10. Currently used Solar Industrial Process Heat Systems-Sector-wise analysis

10.1. Automobile Industry

Automobile industries operate different types of production process which consume a vast amount of energy as electricity or heat. Energy sources used in automobile production processes are mainly electricity, petroleum products like natural gas and other sources.

Currently South Africa, India and Spain are employing solar process heating systems in their production systems. The operations are heating water used in the paint application process, washing the engine components in automobile manufacturing unit, bodyworks pre-treatment line and bodyworks sheet surface preparation. Different types of solar collector are in use here and the maximum temperature that can be achieved is 120**°C.** Typical production processes in the automobile industry which require heat energy explained below in detail, with the temperatures required in the process and the thermal energy transfer medium as hot water, hot air or pressured steam.

Zahler et al. investigated a solar-driven convection system installed in as automobile factory in Germany [96]. **Uppal et al.** reviewed solar industrial process heating systems in use in Indian automobile industries based on the most energy intensive process stages [90]. Table 9 depicts similar research on solar industrial process heating systems in use in automobile industries.

Year	Global Analysis/Country Specific	Existing SHIP Analysis	Reference
2012	Germany	Solar-driven convection oven	[97]
2015	India	CST technologies based on process stages	[90]

Table 9: Literature review for SIPH in automobile industries.

Table 10 presents the country-wise operational industries where solar process heat is in use and their manufacturing specifications.

Country	Name	Industrial Operation	Solar Collector	Temperature(°C)
South Africa	BMW Manufacturing	Hot water used in the paint application process	Evacuated tube collector	~90
India	Mahindra Vehicle Manufacturers	Washing the engine components in automobile manufacturing unit	Other or various collectors	~120
Spain	Nissan Avila	Bodyworks pre-treatment line	Flat plate collector	
	FASA Valladolid	Bodyworks sheet surface preparation for the welding process & before the painting	Flat plate collector	~50

Table 10: Existing SHIP in automobile industries [101].

10.2. Breweries

In the brewing industry, solar thermal can be used for processes such as: steam generation, malting process, stopping germination of grains, air cooling, conservation with hot air, power supplying of washing machines, withering and kiln processes. Malting plants and breweries consume heat for their thermally driven processes at temperature level ranges between 25°C and 120°C. It seems feasible to supply heat at this temperature level which is not higher than the actual amount required but in reality it is often decided by the consumer needing the highest temperature. Several European countries, China, South Africa and USA are contributing for reduced carbon di-oxide emission by involving solar process heating in breweries. The respective process operations include: washing and cleaning, which is most widely used with maximum temperatures of 120°C. Then comes the preheating of bottles done with air collector or flat-plate collector which delivers maximum 60°C temperature. There could be several operations like cooling of wine cellar (95°C), pasteurization and sterilization. These processes are categorized briefly on Table 12.

Lauterbach et al. reviewed solar process heating system integration problems and also their potential in breweries [43]. **Mauthner et al.** suggested solution to the integration problems of solar industrial process heating systems working from flat-plate solar collectors in brewing [49, 50].

Table 11 presents the country-wise operational industries where solar process heat is in use and their manufacturing specifications.

Country	Name	Industrial Operation	Solar Collector	Temperature(°C)
Greece	Achaia Clauss S.A.	Bottle washing in winery	Flat plate collector	45~60
USA	Barrington Brewery & Restaurant	Brewing process	Flat plate collector	
	Brown's Brewing Co.	Cleaning	Flat plate collector	
	Gatorade	Preheating the water for soft drink production	Flat plate collector	~35
	Milwaukee Brewing Co.	Hot water consumption	Flat plate collector	
France	Bourdoil	Bottle cleaning with tap water	Flat plate collector	15~70
	GICB Wine Cellers	Cooling of wine celler	Evacuated tube collector	70~95
Germany	Brauerei Hald	Cleaning & thermal	Flat plate collector	40~120

	(brewery for beverages)	preheating of bottles		
	Hofmuhl Brewery	Brewing water, bottle washing, defrosting & space heating	Evacuated tube collector	20~110
	Hutt Brewery	Heating the brewing water	Flat plate collector	40~95
	Newmarketer Lammsbraw	Preheating the ambient air for drying process	Air collector	~60
South Africa	CBC Brewing	Brewing water & cleaning process	Flat plate collector	
China	Chongqing Beverage	Heating for warehouse in winter, hot water supply for production in other seasons	Evacuated tube collector	
	Coca cola Shanghai	Other process heating	Evacuated tube collector	
Czech Republic	Cider House Hostetin	Preheating of cider before pasteurization & for bottle washing	Flat plate collector	
Austria	Gangl Fruit Juices	Bottle cleaning, pasteurization	Flat plate collector	95~105
	Goess Brewer Mashing Process		Flat plate collector	80~90
	Metbrauerei Newwirth	Bottle washing, pasteurization, sterilization	Flat plate collector	50~95
	Petter Vineyard	Wine cooling, bottle washing	Flat plate collector	20~90
Saudi Arabia	Nestle Waters	Hot water for bottle washing	Flat plate collector	
Tunisia	Winery Grombalia	Solar cooling by feeding an ammonia-water by absorption chiller	Fresnel collector	~110,~160

Table 11: Existing SHIP in breweries [101].

Year	Global Analysis/Country Specific	Existing SHIP Analysis	Reference
2009	Germany	SHIP systems in Hutt Brewery were analyzed	[43]
2014	Global	3 large scale solar thermal systems are analyzed	[49,50]

Table 12: Literature review for SIPH in brewing.

To utilize the organic matter from brewing residues, optimized heat recovery can supply its thermal energy demand over resources. Theoretically, the full energy potential is not utilized so the pathway is the conventional means of energy. However, the conversion of heat from energy gained from renewable energy resources can ensure environment friendly beer production process for future. To increase the overall energy efficiency, the integration of solar heat energy gained from solar thermal collector technologies can be considered as a prospective alternative to fulfill the demands of typical low temperature process heat.

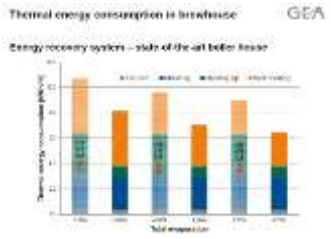

Fig. 5. Thermal processes and associated process temperatures in malting plants and breweries [49,50].

10.3. Food Industry

The most common industrial processes where industrial process heat in the medium temperature range is in use are: pasteurizing, sterilizing, hydrolyzing, drying, evaporation, distillation, cleaning and washing; each of which is in the scope of food industry. The food industry is identified as the dominant industrial sector now a day for solar process heating systems. Most of the countries in Europe, North America, South America and Asia use industrial process heating systems in their own industries. The dominant ones are Mexico, USA, Greece, India, Spain, and Austria. The common process operations in food industries are water heating, pasteurization, cleaning, preheating, drying and cooking. Flat-plate solar collectors and parallel-trough collectors are generally in use here. Currently food industries are dealing with maximum 243°C where most of them are low-temperature process heat applications summarized in Table 14 below. Table 13 lists existing research and review describing solar industrial process heating systems in food industries.

Year	Global Analysis/Country Specific	Existing SHIP Analysis	Reference
2009	India	Indian technologies and applications were analyzed	[67]
2011	Global	Integration feasibility analysis by mathematical modelling	[72]
2012	Global	Different devices in use with solar energy	[24]
2013	Global	Discussed the potential of SHIP	[27]
2013	Global	Different devices are analyzed	[14]
2013	Global	Small and medium scale industry thermal energy requirements	[63]
2016	Global	Estimates the potential of SHIP through greenhouse-gas mitigation	[80]

Table 13: Literature review for SIPH in food industries.

Kalogirou gave an overview on the solar industrial process heat potential in the food industry through solar collector analysis, annual energy gain and economic analysis [39]. **Palaniappan** described the roof mounted solar hot air technology adopted in various food processing systems in India [67]. **Desai et al.** discussed different devices in use with solar energy in the dairy industries [14]. **Ramos et al.** studied parabolic trough solar collector based solar process heat applications in Mexico [74]. **Eswara et al.** reviewed the solar food

processing technologies based on solar collectors, concentrators and dryers in food processing [24]. **Sharma et al.** investigated the potential of solar industrial process heating integration in Indian dairy industry through solar radiation analysis [80]. **Quijera et al.** evaluated the feasibility of integrating solar thermal system into dairy industries by mathematical modeling [72].

Table 14 presents the country-wise operational industries where solar process heat is in use and their manufacturing specifications.

Country	Name	Industrial Operation	Solar Collector	Temperature (°C)
Mexico	Aviary Food Pellet El Paisa	Heating water	Parallel trough collector	~95
	Dairy Plant El Indio	Process heat	Parallel trough collector	20~95
	Dairy Plant Ladonita	Pasteurization	Parallel trough collector	60~95
	Durango Dairy Company	Boiler preheating	Parallel trough collector	20~95
	Food Pellet Plant	Cooking	Parallel trough collector	40~95
	Matalan Dairy	General process heating	Parallel trough collector	80~100
	Nestle Dairy Plant	Pasteurization	Parallel trough collector	80~95
	Nestle Dairy Plant-Lagos ds Moreno	Pasteurization	Parallel trough collector	80~95
USA	Adams Farm Slaughterhouse	Cleaning	Flat plate collector	
	Battenhill Valley Creamery	Cleaning	Flat plate collector	
	Carriers & Sons	Drying	Air collector	~43
	Frito Lay	Steam for heating	Parallel trough collector	~243
	Keyaqa Orchards	Walnuts drying	Air collector	~43
	Kreher's Poultry Farms	Drying of chicken Eggs	Air collector	
	Prestage Foods	Cleaning	Flat plate collector	60~82
	Stapleton Spence Fruit Packing Co.	Rehydrate dried foods	Unglazed Collector	
	Sunsweet Dryers	Prune drying	Air collector	10~15
Greece	Alpino S.A.	Hot water preheating in steam boiler	Flat plate collector	20~70
	Mandrekas S.A.	Preservation of yogurt making temperature	Flat plate collector	40~45
	Mevgal S.A.	Hot water for cleaning equipment	Other or various collectors	20~90
	Plektemboriki Kritis S.A.	Cleaning olives	Flat plate collector	40~90
	Tyras S.A.	Washing of cisterns and lorries	Flat plate collector	20~80
India	B.G. Chitale	Pasteurization of milks	Other or various collectors	~150
	Indian Institute of Horticulture	Pasteurization of straw	Other or various collectors	80~100
	Kaveri Agricare Pvt. Ltd.	Drying coir Peat	Air collector	~105
	Kwality Walls Inccream	Cleaning and making sugar solution	Flat plate collector	
	Mahananda Dairy	Pasteurization of milks	Other or various collectors	~120
	Milma Dairy	Pasteurization of milks	Flat plate collector	
	Panchmahal Dairy	Preheat boiler feed	Flat plate collector	
	Tapi Foods	Preheat boiler feed	Other or various collectors	
France	Bonilait Dairy	Cleaning	Flat plate collector	~80
South Africa	Chalmar Beef Pty(Ltd)	Ablution	Flat plate collector	
Costa Rica	Coopeldos	Coffee drying	Air collector	40~45
Switzerland	Cremo S.A.	Milk processing, Coffee creme Production	Parallel trough collector	~150,~110
	Emmi Dairy Saignelsgier	Steam for different drying processes	Parallel trough collector	140~180
	Lesa Dairy	Milk processing	Parallel trough collector	
Panama	Duren Coffee	Coffee drying	Air collector	40~45
Germany	Edmund-gourmet foods	Rinsing & cleaning of bottle plants	Flat plate collector	20~60
Austria	Eidvogel Hubert Bernegger	Washing of fish transportation trucks		
	Fleischwaren berger	Cooking	Flat plate collector	30~95
	Futtermittel Fruit Juice	Heating of makeup water	Flat plate collector	
	Krispl Fruit Juice	Fruit pasteur crates washing space climate	Flat plate collector	~80
	Moguntia Spice Making	Hot water for cleaning and production process	Flat plate collector	
China	Gengli Fruit Drying	Heating air for fruit drying	Air collector	50~70
	Meihao Food Processing	Sterilization by hot water	Evacuated tube collector	~80
Israel	Golan Winery	Barrel washing	Flat plate collector	~95
Portugal	Knoww Best Foods S.A.	Hot water for tools washing	Flat plate collector	40~45
Indonesia	Malabar Tea Drying	Tea drying	Air collector	~35
Spain	Industria Alimnetaria Alcoyana	Preheating of boiler feed water for olive preparation	Flat plate collector	40~130
	Metadero Montesierra	Preheating of boiler feed water	Flat plate collector	40~60
	Montesano-canary islands	Hot water used for wash meat derivatives	Flat plate collector	40~60
	Montesano-Jerez de los caballero	Raw product reception washing	Flat plate collector	40~45
	TE-PE S.A.	Preheating of boiler feed water	Flat plate collector	40~130
Italy	Nuova Sarda Industria Caaseria	Other process heating	Fresnel collector	~200
Czech	PETA Bohemia	Hot water for	Flat plate	10~90

Republic	Pekarna Sobeslav	bakery	collector	
Netherlands	Perfetti van melle	Preheating of hot water and process heat	Flat plate collector	
Jordan	Seniora Food Industries	Hot water for degreasing & cleaning requirements	Evacuated tube collector	

Table 14: Existing SHIP in food industries [101].

10.4. Paper Industry

The Indian paper industry accounts for about 2.6% of the total production of paper in the world. Fuel consumption in the paper industry in India comprises electricity, biomass, coal and petroleum fuel. To reduce greenhouse gas effects, fossil fuel consumption needs to be reduced besides maintaining the required energy supply to the paper industry, which can only be achieved by improving the fuel utilization efficiency and substituting the fossil fuel by harnessing renewable sources of energy. 75% of the total energy used in paper industry is essential for process heating at low and intermediate temperatures. Processes like bleaching and washing with hot water, pulping, drying, and boiler feed water heating consume most of the process heat, using heat transfer medium like water, steam, air or oil depending on specific process requirements. The paper industries still lack proper attention to reduce greenhouse gas emissions through proper utilization of renewable energy resources. Only in India B.S. paper mill is using solar heat for different process operations using various collectors integrated into the system with a maximum achieved temperature of 98°C (Table 16). There are a few literatures on SIPH in the paper industries (table 15).

Year	Global Analysis/Country Specific	Existing SHIP Analysis	Reference
2015	India	Potential estimation of SHIP	[79]
2016	India	potential estimation of SHIP and corresponding carbon-di-oxide emissions mitigation	[81]

Table 15: Literature review for SIPH in paper industries.

Sharma et al. analyzed solar industrial process heating potential in paper industry in several research works. They had a preliminary assessment to estimate the SHIP potential by classifying paper mills, estimating the annual process heating requirements, analyzing solar radiation availability [79, 81].

Country	**Name**	**Industrial Operation**	**Solar Collector**	**Temperature(°C)**
India	B.S. Paper Mill	Different process applications	Other or various collectors	90~98

Table 16: Existing SHIP in paper industries [101].

10.5. Pharmaceutical Industry

The pharmaceutical industry has a substantial energy demand for producing pharmaceutical products, and for the formulation of the final product. The process temperature ranges around 160°C – 180°C and depends on the process and the specific product. In Jordan this pharmaceutical industry contributes for around 20% to the manufacturing GDP. Pharmaceutical industries are identified as most promising industrial sector for European and North American countries where economy is dependent upon these kinds of industries. Now a days only Egypt and Greece are dealing with solar process heating based pharmaceutical industries for process steam generation and cooling, where several other operations operate at low temperature (Table 18). Table 17 lists the research on solar industrial process heating systems in pharmaceutical industries.

Year	Global Analysis/Country Specific	Existing SHIP Analysis	Reference
2014	Jordan	Solar process steam for RAM pharmacy	[48]

Table 17: Literature review for SIPH in pharmaceutical industries.

Haagen et al. estimated the solar process heating potential in the steam generation process in pharmaceutical industries [48].

Country	**Name**	**Industrial Operation**	**Solar Collector**	**Temperature(°C)**
Egypt	El Nasr Pharmaceutical	Production of process steam	Parallel trough collector	~173
Greece	Sarantis S.A.	Warehouse cooling	Flat plate collector	7~45

Table 18. Existing SHIP in pharmaceutical industries [101].

10.6. Textile Industry

The textile industry requires a continuous supply of water like most of other industrial sectors, mainly for the dying process. The temperature requirement for the water is not only at a normal level but also at a higher level like 80°C, which requires a considerable amount of heat energy. If conventional energy sources are used consequently for water heating, environmental impacts will also increase as a consequence. Solar water heating using solar process heat is a potential candidate to replace conventional fossil fuel sources in the textile industry to substantially reduce the environmental impact. Among the seven countries where textile industries are equipped with solar process heating systems, Greece, China and India are dominant ones. Water heating is the common process operation working with flat-plate collectors to obtain a maximum 100°C temperature. Other process operations include solar preheating, painting and textile production processes which are summarized in Table 20. Table 19 describes the literature on textile industry based process heating systems.

Year	Global Analysis/Country Specific	Existing SHIP Analysis	Reference
2006	Pakistan	Alternating solution to solar water heating	[59]
2008	Turkey	Experimental investigation of solar water heating	[58]
2013	Global	Small and medium scale industry	[74]
2015	Global	A medium scale industry	[30]

Table 19: Literature review for SIPH in textile industries.

Muneer et al. investigated the thermal performance of two differently constructed solar water heaters to find out the potential in textile industries [58, 59]. **Ramos et al.** studied parabolic-trough solar collector based solar process heat applications in Mexico [74]. **Frey et al.** monitored the results of the solar industrial process heating systems installed in the textile industry of Germany based on real-time operational data [30].

Country	**Name**	**Industrial Operation**	**Solar Collector**	**Temperature(°C)**
USA	Acme McCrary	Hot water for textile drying process	Flat plate collector	
Greece	Allegro S.A. Childrens' clothing manufacturer	Hot water for washing machines	Flat plate collector	33~60
	Kastrinagiannis S.A.	Hot water directly for dyeing machines	Flat plate collector	40~90
China	Daly Textile	Water heating for dyeing process	Flat plate collector	~55
	Jiangsu Printing & Dyeing	Solar preheating for printing & dyeing process	Evacuated tube collector	~50
Vietnam	Grammer Solar Vietnam	Textile production process	Air collector	
Spain	Harlequin	Painting	Flat plate collector	
Germany	Meiser Textile	Other process heating	Parallel trough collector	~140
India	Purple Creations	Iron the children's garments-steam processing & washing	Other or various collectors	
	Sharman Shawls	Hot water requirements for dyeing, bleaching & washing garments	Flat plate collector	~100

Table 20: Existing SHIP in textile industries [101].

10.7. Minerals processing

Solar process heating technologies can be used for moderate temperature heating and steam generation, which are useful processes in the minerals processing industries. These SHIP applications would be particularly convenient in remote mines where fuel costs are much more significant than in urban areas. Low-temperatures gas or liquid heating can be achieved with solar thermal systems. Solar heating systems with fluid temperatures range up to 150°C can be easily achieved with non-concentrating technologies while temperatures up to 400°C can be achieved using simple CST technologies. Potential applications of CST in minerals processing can be divided into process group- thermal processes, chemical processes, and carbothermic reduction processes. Solar thermal processes include solar kiln development for thermal decomposition of limestone ($CaCO_3$) to produce lime (CaO) at up to 1130°C. Solar thermal heating of air for industrial applications has also been proposed, for example a material with high thermal conductivity and heat capacity might be used to form a heated permeable bed using solar thermal energy. Heated air then passes through the bed where temperatures of up to 850°C can be achieved. Preheated air can be used for metallurgical smelting processes like regenerative heating. Cowper stoves, the best-known high-temperature application, produce air heating for blast furnaces for iron production. SolarGas (CSIRO, New South Wales, and Australia) is natural gas reformed using CST energy to produce carbon monoxide and hydrogen gas (syngas) etc. CSIRO has developed the process to meet thermal energy requirement from solar energy. South Africa, Chile, Austria and Germany are dominant and vibrant mining based industrialized countries where solar process heating system is already built in and operated in mines, mostly for cleaning, mining, water heating operations. Other mine specific operations involve- copper electro-winning process, nickel bath, degreasing chemicals with flat-plate collector and evaporated-tube collector (Table 22). The mining sector still lacks where there are huge scopes for low-temperature, medium-temperature and also high-temperature solar process heating systems to get integrated for reducing greenhouse gas emissions. According to the mining industries, there are very few solar process heating systems (Table 21).

Year	Global Analysis/Country Specific	Existing SHIP Analysis	Reference
1999	Global	Replacement of Hall-Heroult process by solar process heat	[60]
2013	Australia	Potential processes identification by temperature range	[15]
2015	Australia/ Northern Territory	Considering Northern Territory's potential for solar power	[5]

Table 21: Literature review for SIPH in mining industries.

Dinter et al. studied the potential of solar industrial process heat on the ferroalloy industry, depending on energy requirements, sizing of collector fields and financial evaluation [15]. **Murray** proposed an intermediate A1N compound to replace the Hall-Heroult process

through solar process heat [60]. **Eglinton et al.** studied concentrated solar thermal integration's potential in medium and high temperature process stages in mineral industries [11]. **Baig et al.** investigated the potential of concentrated solar power in remote mine sites in the Northern Territory of Australia [5].

Country	Name	Industrial Operation	Solar Collector	Temperature(°C)
South Africa	Anglo Plant-brakfontein	Cleaning	Flat plate collector	
	Anglo Plant-middlepunt	Cleaning	Flat plate collector	
	BHP Bolliton wolwekrans colliery	Mining & Cleaning	Flat plate collector	~60
	Northern Platinum's Booysendal Mine	Mining & cleaning	Flat plate collector	~60
	Xstrata Elands Mine	Mining & cleaning	Evacuated tube collector	~60
Chile	Codelco Gabriela Mistral	Electro winning Process	Flat plate collector	~50
	Minera Constanza	Electro winning Process	Flat plate collector	
Cyprus	Hellenic Copper Mine	Industrial mining, leaching, extraction	Flat plate collector	
Austria	Gillich Galavanic	Degreasing & removal of lacquer from metal parts in baths	Evacuated tube collector	~75
	Korner Kvk	Preheating, drying	Flat plate collector	50~80
India	Kangaroo India Limited	Nickel bath	Flat plate collector	
Germany	Hustert Galvanic	Heating thermal baths for electroplating	Evacuated tube collector	~80
	Schiffer Gmbh & Co KG	Hot water for galvanic baths	Evacuated tube collector	40~70
	Steinbach und Vallmann	Hot water for galvanic baths	Evacuated tube collector	60~80

Table 22: Existing SHIP in mineral industries [101].

10.8. Manufacturing of Chemical Products

There are various chemical production processes that require heat at a relatively low temperature level where primary preheating steps with other energy sources are supplementarily used by solar energy. There are areas within solar industrial process heating in the chemical industry that work exclusively at a low-process temperature. The most common processes where solar water heating is in use are water heating, steam heating, cleaning and painting process with flat-plate collector where currently the maximum attained temperature is 130°C (Table 24).

Country	Name	Industrial Operation	Solar Collector	Temperature(°C)
India	L'oreal Punne	Hot water for cleaning process	Flat plate collector	~55
Austria	MAPAG	Cleaning of samples for analytical lab	Flat plate collector	~60
Egypt	Pachin Paints Co.	Heating of chemicals	Flat plate collector	~50
Germany	Penzkofer Autolackiererei	Painting process	Air collector	
China	Solar steam boiler for procter & gamble (Tianjin)	Steam generation	Parallel trough collector	~130

Table 23: Existing SHIP in chemical industries [101].

Meier et al. developed solar chemical reactor technology for reducing carbon di-oxide emissions in the lime and cement industry. Table 23 presents the country-wise operational industries where solar process heat is in use and their manufacturing specifications [52].

Year	Global Analysis/Country Specific	Existing SHIP Analysis	Reference
2014	Spain	Process heat driven vegetable preservation	[85]
2015	Global	Solar process heating systems in agricultural industries	[34]

Table 24: Literature review for SIPH in agricultural industries.

10.9. Agricultural Industry:

Solar industrial process heat is used extensively in the agricultural and fisheries industries from different countries, mainly for drying of agricultural products, water heating using different types of solar collectors which vary based on plant capacity and temperature-range requirements. Most of the industries have low-pressure temperature range applications with air collector, flat-plate collector, parallel trough-collector, etc. (Table 25). Table 24 describes the literature on such agricultural industries.

Country	Name	Industrial Operation	Solar Collector	Temperature(°C)
India	AMR dal Mill	Drying of pulse	Air collector	65~75
Spain	Acuinova Andalucia S.A.	Heating water	Flat plate collector	23~26
Romania	Aroma Plant Romania	Drying of medicinal plants	Air collector	
China	Hongxin Aquaculture	Water heating	Evacuated tube collector	
USA	Sonoma Country Herb Exchange	Drying of herbs	Air collector	
Mexico	Buenavista Greenhouse	Space heating	Parallel trough collector	
Germany	Krimmer	Drying of wild flower seeds	Flat plate collector	
	Woltow	Water heating	Parallel trough collector	

Table 25: Existing SHIP in agricultural industries [101].

Rural industries research and Development Corporation worked on developing a solar drying machine for agricultural products [47]. **Silva et al.** worked on the solar process heat driven vegetable

preservation industry by thermal treatment and canning in Spain [85]. **Hussain et al.** reviewed solar process heating systems used in agricultural industries [34].

10.10. Manufacturing of Leather products

Several Asian countries like Thailand, China, India and other countries are operating with solar process heating based leather production. Manufacturing industries of leather products principally involve the retanning process and water heating for solar industrial process heat utilization. The evacuatedttube collector is mostly suitable for these types of operations (Table 26).

Country	Name	Industrial Operation	Solar Collector	Temperature(°C)
Thailand	Ayuttaya Tannery	Retanning process	Evacuated tube collector	~80
	Sadesa Leather	Retanning process	Evacuated tube collector	
Austria	Gerberei Kolblinger	Hot water for the wet process of leather retanning	Flat plate collector	
China	Heshan Bestway Leather	Retanning process	Evacuated tube collector	~70
India	Leo Leather	Chemical mixing, drying	Flat plate collector	
Kenya	Nairobi Tannery	Retanning process	Evacuated tube collector	
Vietnam	Saigan Tantec	Retanning process	Evacuated tube collector	~70
Greece	Tripau-katsouris leather treatment factory	Leather treatment	Flat plate collector	48~84

Table 26: Existing SHIP in leather industries [101].

10.11. Fabricated Metal Industries

In fabricated metal industries in mostly European countries solar process heat is used for water heating, process drying and cleaning processes, which are the most widely used solar heat driven processes. The maximum attained temperature is 180°C operated with various types of solar collectors (Table 27).

Country	Name	Industrial Operation	Solar Collector	Temperature(°C)
Germany	Alanod Solar	Production of saturated steam	Parallel trough collector	~143
	Lackiercenter Shulte	Heating of painting & drying chamber	Evacuated tube collector	
Austria	Julius Blum	Heating of pre-treatment washbasins of the coating device	Evacuated tube collector	~85**
Spain	Pincasa	Heat oven	Other of various collectors	~180
Portugal	Silampos S.A.	Process wash & drying finished product	Parallel trough collector	50~160
India	SKF Technologies	Heat the water for	Parallel trough	~95
	Mysore	circulation	collector	
France	Viessmann Faulquemont	Heating up an alkaline cleaning bath	Evacuated tube collector	~60

Table 27: Existing SHIP in fabricated metal industries [101].

10.12. Other Manufacturing Industries

Different countries in Europe, south-east Asia and from Africa are using solar industrial process heat for their core industries like tobacco, wearing apparel, wood, plastic, manufacturing of electrical or mechanical equipment, furniture production units or different sorts of repair and installation houses. The most widely used industrial processes here are drying, washing, water heating, cooking etc. Exceptions include degreasing wheels, volcanizing cables and conditioning tobacco. Most of the processes operate within low-temperature range applications using flat-plate collector or evacuated-tube collector (Table 28) [52,65,70,75,78].

Industry Type	Country	Name	Industrial Operation	Solar Collector	Temperature(°C)
Tobacco	Argentina	Grammer Solar Argentina	Drying of tobacco	Air collector	
	India	India Tobacco DIvision	Conditioning of tobacco	Air collector	~95
Wearing Apparel	India	Chelsea Jeans	Hot water dyeing process	Flat plate collector	
	Vietnam	Saitex Jeans	Solar heat for jeans washing process	Flat plate collector	
Wood	Spain	Instituto del corcho	Cork cooking	Other or various collectors	~110
Rubber & Plastic Products	Thailand	Inter Rubber Latex Co. Ltd.	Drying of natural rubber	Air collector	
Concrete Components	Austria	Habau Concrete Component Production	Heating of formwork of wooden planks, drying of concrete components	Flat plate collector	16~25
		Leitt Beton Gmbh	drying of pre-fabricated concrete components	Flat plate collector	
Computer, electronic & optical products	Sweden	Bosmans Lackering	Hot water for chemical baths that provide gold plating for radio cabinets	Parallel trough collector	~160
Manufacturing of Electrical Equipment	India	Bergen Solar	Integrated in existing processes	Other or various collectors	120~140
		Hindusthan Vidyut Products	Volcanizing of cables	Other or various collectors	~85
Manufacturing of Machinery	South Africa	ABB Longmeadow	Other process heating	Flat plate collector	
	Austria	Hoval Marchtrenk	Solar hot water for powder coating	Flat plate collector	
		Kral Pump Factory	Hot water space heating & cooling	Evacuated tube collector	

	India	Wheels India	To degrease the wheels before the final painting	Evacuated tube collector	
	Switzerland	Zehnder Group AG	Heating the pre-treatment washbasins of the coating device	Evacuated tube collector	~90
Transport Equipment	India	Harite Seatings Systems Limited	Cleaning automobile parts before painting	Evacuated tube collector	55~60
Furniture	Austria	Carpenting Hammingeer	Wood Drying	Flat plate collector	25~115
Repairing & Installation	Germany	Lackiererei Vogel	Heat cabins from and generate hot air for drying process	Evacuated tube collector	22~24,60 ~70

Table 28: Existing SHIP in other different type manufacturing industries [101].

11. Summary and Future Research Scope

Table 29 summarizes the current literature reviews of solar industrial process heat applications in different aspects like integration at supply level or process level, process heat integration feasibilities based on simulation and cost analysis. But no such work gives an extensive survey on all industries based on their operations/processes where a solar process heating system is currently in use, based on their available thermal energy generation capabilities, including solar collector types and highest amount of process heating temperature that can be achieved through solar heat in that particular area. This paper will certainly be a valuable resource to the literature which summarizes the potential industrial sectors, potential process heating operations for creating a future zero-carbon emission industrial zone.

Literature work	**Potential industrial sectors/ process identification**	**Feasibility analysis/ Integration problems**	**Modelling and simulation**	**Experimental investigation**	**Solar collector type, temperature requirements**
Weiss et Al.[94]	3 key sectors	Solution to integration problems	No	No	N/A
Kalogirou[38]	No	No	TRNSYS simulation	No	Paraboli c-trough collector
Esen[21]	No	No	No	Yes, based on different refrigerants	Vacuum -tube collector
Schnitzer et Al.[77]	5 key sectors,8 key processes	System integration feasibilities	No	No	N/A
IEA SHC TASK 33[36]	10 key sectors	No	N/A	N/A	N/A
Mekhlief et Al.[43]	11 key sectors, 6 key processes	No	No	No	N/A
Lauterbach et Al.[44]	7 key sectors, 3 key processes	Feasibility and cost analysis	TRNSYS simulation	No	No
Lauterbach et Al.[42]	No	No	Yes	Yes	N/A
Pietruschka et Al.[69]	No	No	Simulation for control and optimization	No	3 different collectors
Vajen et Al.[91]	4 key sectors	System integration feasibilities	No	No	No
Calderoni et Al.[9]	No	Feasibility study and economic analysis	No	No	No
Montes et Al.[56]	No	No	No	Yes	Paraboli c trough collector
Frein et Al.[27]	No	No	No	Yes	N/A
Schramm et Al.[78]	No	Storage systems	Yes	Yes	4 systems
Silva et Al.[83]	No	Economic analysis and optimization	No	No	Paraboli c trough collector
Silva et Al.[85]	No	Uncertainty and sensitivity analysis	No	No	Pataboli c trough collector
Larcher et Al.[41]	No	No	No	Yes	Paraboli c trough collector
Coccia et Al.[11]	No	No	No	Yes	Paraboli c trough collector
Schmitt[65]	No	System integration by load profile	No	No	No
This Research	**11 key sectors, 6 key processes**	**No**	**No**	**No**	**Yes**

Table 29: Comparison among the methodologies of the related works.

For sustainable energy development in future, the crucial factor is reducing the carbon di-oxide emission thus reducing the consumption of non-renewable fuels. To limit the utilization of fossil fuels in today's industrialized world, it is obviously necessary to involve renewable energy sources to supply both process heat and electricity in industries. Electricity generation from solar energy is already widely in use. But supplying heat energy to run industrial process operations is still very limited in operation. A major drawback for lack of implementing solar process heating systems is significant capital cost of installation- which is a barrier for small and medium scale industries. To get a clear overview about the efficiency of solar industrial process heating system- industrial process operations should be analyzed through simulation to see whether solar process heat can generate the required temperature to run the plant, throughout its working time per day or its lifetime. To prove the reduction in greenhouse gas emission and calculate the impact upon the future environment, industry-specific or industrial-process specific lifecycle assessment can be carried out which will help to understand and commercialize the solar process heating system for reducing amount of fossil fuel consumption. An industry-wise or industrial-operation specific lifecycle inventory model can be created based on inventory database for further impact assessment. Lifecycle costing analysis can also give indication to manufacturers and consumers whether installing a solar process heating system can help their business or not.

12. Conclusion

In this review paper, existing industrial processes are categorized for the identification of typical applications for solar process heat and also future opportunities to integrate solar heat in the heat supply level of an industrial company. Industrial process-heat systems are analyzed

in this paper with respect to collector technologies and demand temperatures. These results are applicable to every country within the same industry type along with similar weather and economic conditions. Solar energy should be given a chance even if the costs may not be so favorable, because of the depleted oil reserves, and increasing oil prices.

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