Integration of Solar Process Heat in Industries

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Industrial manufacturing approaches are associated with processing materials that consume a significant amount of thermal energy, termed as industrial process heat. Industrial sectors consume a substantial amount of energy for process heating over a wide range of temperatures (up to 400 °C) from agriculture, HVAC to power plants. However, the intensive industrial application of fossil fuels causes unfavorable environmental effects that cannot be ignored. The integration of solar heat into industrial processes has proven to reduce fossil fuel consumption and to initiate a carbon-free environment, and there is an ongoing tendency towards implementing SHIP projects in a wide variety of industries. However, the research in this sector is quite minimal.

solar industrial process heat solar collectors integration layouts heat storage systems

1. Introduction

Industrial process heat refers to the thermal energy used for the treatment or preparation of substances to process manufactured products [1]. To date, the most widely used thermal energy sources in industries are fossil fuels (coal, petroleum, oil, natural gas, etc.). However, two weighty concerns evolving from the conventional fuel-based industrial processes are global warming and the limited sources of fossil fuels. Reckoning the adverse effects of conventional energy sources on the environment, there is already a growing tendency to introduce renewable energy in industrial process systems from developed to developing countries.

Depending on the geographical and economic circumstances of a country, solar thermal energy can be supplied in the form of hot water, hot air, or steam up to 400 °C for a wide range of industries. For example, conventional flat plate or evacuated tube collectors (FPC, ETC) can easily provide temperatures below 100 °C, whereas modified FPC/ETC with super high vacuum and concentrators can provide temperatures around 200 °C [2]. The types of processes also play a significant role in selecting solar collectors and the integration of solar systems into the conventional systems. The pivotal prospect of implementing solar-assisted technologies in the global industrial sectors is the higher consumption of thermal energy than electrical energy. The limited resources of fossil fuels that are presumed to last until 2060, and the increasing GHG emissions are topical issues continuously prioritizing the replacement of fossil fuels with renewable energy sources [3]. Economically developed and industrialized domains in Europe, Australia, Asia, and North America are already practicing solar-based technologies in various industries. The developing countries are also exploring policies towards zero carbon emission industrial processes [4][5]. Major common obstacles in achieving solar-assisted process heating systems in industries are the low price of fossil fuels, the high installation cost of the solar equipment, and the lack of adequate study and research required for the integration of solar technologies into existing industries to exploit the offerings of unbounded solar energy [2][6][7][8].

2. Basic Components of SHIP Systems

2.1. Solar Collectors

In a solar-based system, a solar collector plays the lead role in capturing solar irradiation and converting it to a useful form of energy such as heat or electricity, or both in a hybrid system. A solar collector acts as a heat exchanger by transferring the heat energy from falling solar radiation to the sensible heat of a working fluid. Owing to the broad range of working temperatures, nearly every type of solar thermal collector can be used in industrial process heating systems [9][10][11][12].

2.1.1. Types of Solar Collectors in SHIP Systems

Generally, three types of solar thermal collectors are recognized for industrial process use: (a) flat plate; (b) evacuated tube, and (c) concentrating collectors [13][5][12].

2.1.2. Selection Criterion for Solar Collectors

Primary selection criterion:

(a) Average operating temperature of the solar collector
(b) Optical efficiency and overall heat transfer coefficient of the collector
(c) Overall solar irradiance on the factory site
(d) Cost
(e) Availability of space and the possibility of roof integration

In the design report of SERI, the selection of solar thermal collectors is a two-step process: the primary selection and the final pick up of a suitable band [10]. There is a comprehensive analysis and a step-by-step illustration about selecting the most suitable solar collector technology for the SHIP system. Based on the data presented in the report, an algorithm was built, as presented in **Figure 1**.

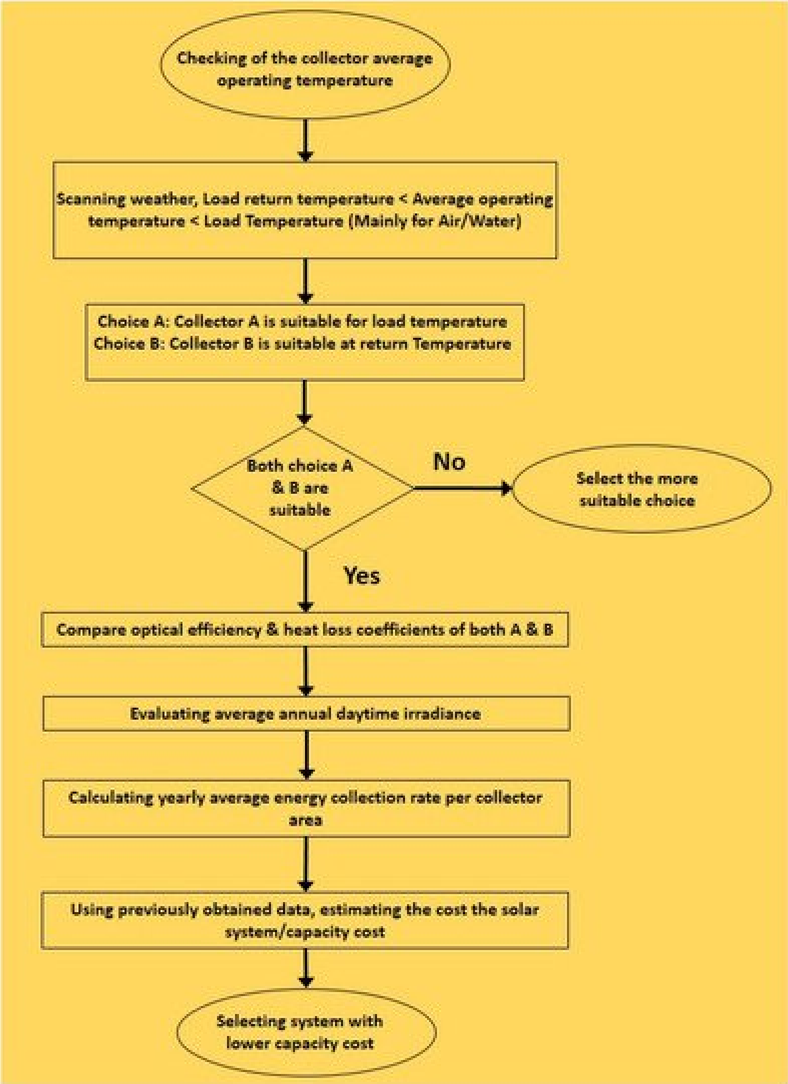

Figure 1. Steps to select a preferable solar collector for a SHIP system, modified from TR-253-1356 by SERI [10].

2.1.3. Heat Exchangers

Heat exchangers are mechanical systems that transfer heat energy between two or more fluids and are crucial elements for various industrial processes. Heat exchangers can be classified according to the heat transfer method, whether the two fluids are in direct contact or not, the number of participating fluids, compactness of the surface, design aspects, fluid flow arrangements, and the mode of heat transfer. Some of the important types of heat exchangers for industrial process heating purposes are shell and tube heat exchangers, plate-type heat exchangers, spiral plate heat exchangers, lamella heat exchangers, and extended surface heat exchangers. Shell and tube heat exchangers are tubular heat exchangers and are extensively used in chemical industries and power plants for space heating and cooling purposes. Plate-type heat exchangers are best suited for food, beverage, dairy, juice, alcohol, and pharmaceutical industries. Of the other types, lamella heat exchangers are widely used in chemical, paper and pulp, and general industrial processes, whereas spiral plate heat exchangers are used in cellulose factories as kettle reboilers [14].

2.1.4. Piping Systems

Piping systems for industrial plants are of two categories: process piping systems and utility piping systems. Process piping systems are of two types, primary systems and secondary systems. Primary piping systems are directly involved in the treatment of material, secondary piping systems are related to the further refining of the material, and utility piping systems are for maintaining and aiding the primary piping systems [15].

2.1.5. Storage Systems

A consistent problem in solar industrial process heating systems is the inconsistency between the demand and the supply of solar power due to unpredictable weather conditions. Hence, an energy storage system has the potential to enhance the thermal performance and effective regulation of SHIP systems. Energy can be in several forms, such as chemical, electrical, or thermal, and it is possible to store every form of energy using a special kind of device called an energy storage/accumulator. However, the thermal energy storage system (TES) is the best-suited technology for solar process heat in industries and power plants. Based on storage media, TES is classified into three types: (1) sensible heat storage; (2) latent heat storage, and (3) chemical heat storage [16][17][18].

3. Basic Integration Layouts of SHIP Systems

3.1. Solar Hot Air Systems

Hot air systems are very capable of meeting industrial process heating requirements. Examples include drying of food products, preventing deterioration of food products, maintaining and upgrading product quality, and easing the transportation of food products. [2]. Hot air systems can be direct or indirect. A direct hot air system has a very simple layout with a solar collector to heat the air and a pump to deliver the heated air to the process. An auxiliary heater can be used if the temperature of the heated air fails to meet the process requirement. In an indirect solar hot air system, the heat energy is provided to the air via a heat exchanger

3.2. Solar Hot Water Systems

3.2.1. Direct Solar Hot Water Production System

A direct solar hot water system is like a direct solar hot air system with the process water being the working fluid that passes through the solar collector. A direct solar hot water system can be with or without storage. Based on the piping layout, a direct solar hot water system with storage for a non-freezing working fluid can have four classifications: Four-Pipe Storage, Two-Pipe Storage, Multiple Tank Storage, and Variable-Volume Storage Configuration.

The Four-Pipe Storage Configuration is suitable for space heating and residential applications. One disadvantage is that the collector inlet temperature might exceed its limit as the collector is fed from the mixed tank at a temperature nearly that of the load supply. However, controlling this system is very convenient irrespective of the application area.

A two-pipe storage layout is a modification of the four-pipe arrangement with both the inlet and outlet pipes amalgamated to pass through a single storage tank. Such systems provide better performance than the four-pipe storage configuration by solving the problem of an excessively heated collector inlet. Nevertheless, one big disadvantage is that the solar collector and the storage cannot supply heat energy at the same time unless the load flow rate is higher than the collector flow rate.

A multiple tank storage arrangement provides better performance than a two-pipe storage configuration by keeping the collector inlet temperature under the load supply temperature when there is no load. Such aspects allow this system to have a better thermocline state. Nevertheless, such systems are quite expensive and involve heat loss.

A variable volume storage system delivers better performance than the other three configurations. Such systems consist of two variable storage tanks, one for hot fluid and the other for cold fluid. In no-load conditions during the daytime, cold water passes through the solar collector and is stored in the hot tank. In the off-period, hot water can be taken out of the hot tank for use. However, a variable storage system does not provide good performance in cloudy weather.

3.2.2. Indirect Solar Hot Water Production System

An indirect solar hot water system has quite a simple layout with a solar collector, two fluid loops, and a heat exchanger. In an indirect solar water system, antifreeze protection usually involves the application of an antifreeze solution/heat oil in the solar collector loop.

3.3. Steam Generation Systems

An indirect steam generation system usually consists of a collector loop with a heat transfer fluid to produce heat energy to be transferred via a heat exchanger to another fluid (normally water or air) to produce steam/hot air/hot water under pressure as per industrial process requirement.

4. Approaches towards Solar Industrial Process Heat Integration

4.1. Solar Heat Integration Methodologies

Suitable design propositions and appropriate integration layouts have always been a core subject of investigation for researchers to obtain better performance from SHIP integration. There are several approaches for the development and evaluation of suitable solar heat integration methodologies, such as time-slice model (TSM), time average model (TAM), total site analysis (TSA), and pinch analysis.

Industrial processes can be both continuous and batch processes. In batch processes, the heat exchange between the hot and cold utilities is limited [19]. Depending on the mode of operations, not all of the integration approaches can provide the same solution.

Pinch technology is a popular and widely used methodology for the perusal of industrial processes, more particularly to locate the least permissible temperature difference between the hot and cold utility. The term pinch analysis derives from the term pinch technology, and also refers to the use of mechanisms, Socratic methods, and algorithms to reach the pinch point and thus find the most suitable integration concept for financial savings. Linhoff and Flower, and Umeda et al., first introduced pinch analysis as two individual research groups [19][20].

For batch processes, two commonly used approaches are the Time Average Model (TAM) and Time Slice Model (TSM), both developed by Kemp and Macdonald [21][22][23]. Both TAM and TSM methodologies were originated from pinch technology; however, the main distinction between them is the consideration of time factors such as process scheduling or time availability. In TAM, the operations of a batch process occur ignoring the sequence, and at any time. In TSM, the beginning and the finishing time of the involved operations can be integrated, and, within these slices, heat integration can be performed as a continuous process [19][24].

Another design approach is Total Site Analysis (TSA), which involves thermal profiles of the source and sinks site i.e., the total site, as developed by Dhole and Linnhoff in 1993. In the TSA method, grand composite curves (GCCs) of the associated processes of a central system are used to build the site source-site sink profiles (SSSP) which help to reach the optimal design considerations.

4.2. Steps to Identify the Optimal Integration Points

Although various industrial sectors are becoming interested in implementing SHIP projects, most of the solar heat integrations have been made by paying more attention to developing the collector's design, categorizing industries by similar unit operations, conceptual assumptions regarding the overall heat demand, the temperature level of the processes, the production rate of the factories on a monthly/yearly basis and the statistics from single demonstration plants. Specific instructions for the integration of solar thermal process heating systems in existing industrial plants are not firm yet. However, some general guidelines have been constructed, as published by the International Energy Agency under task 49 of The Solar Heating and Cooling Programme (IEA SHC Task 49), based on the Ph.D. thesis of Bastian Schmitt [25]. Some major steps were established along with some leading factors as presented in **Figure 2**. For the overall grouping of SHIP integrating systems, three leading parameters were identified, such as the assessment of the existing integration strategies, heat transfer medium, and the difference in the heat integration between the supply level and process-level. Besides, clear distinctions between supply level and process-level were found to be necessary for identifying the specific boundary conditions of suitable solar process heat integration in industries [25][26].

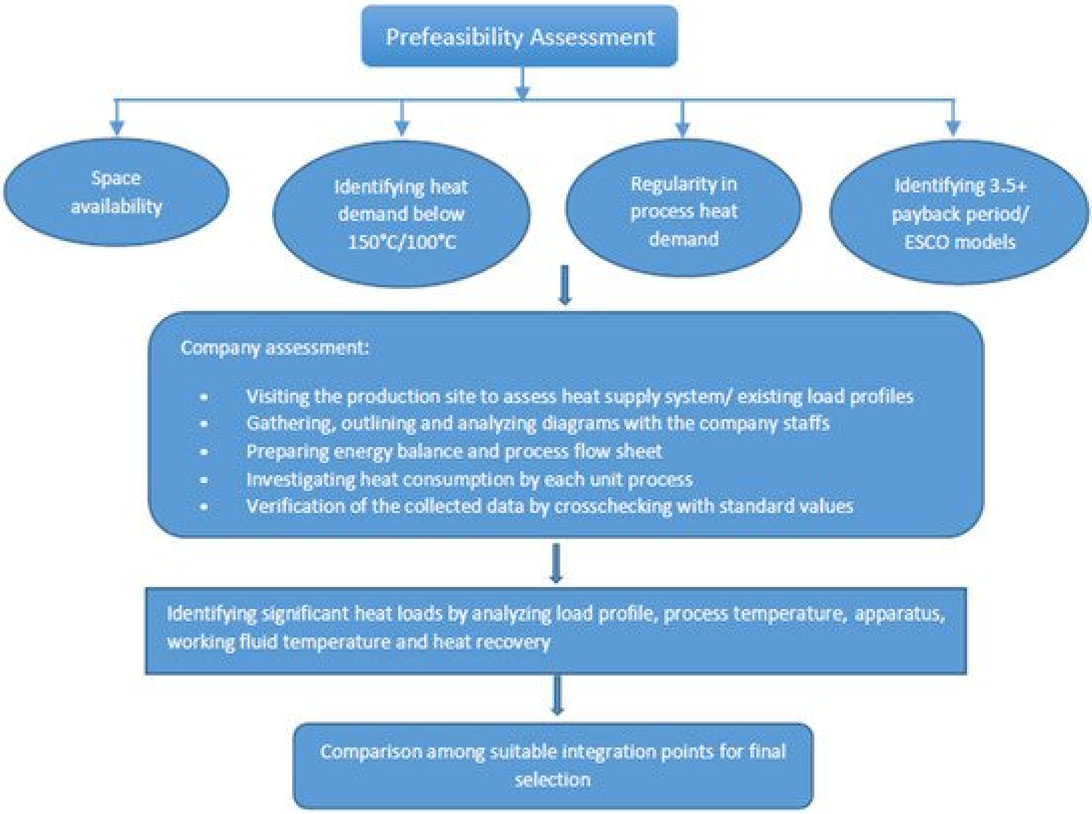

Figure 2. Steps towards the selection and identification of suitable integration points of solar process heat integration in industries. Modified from [26][27].

5. Status of Integration Parameters of Solar Process Heat in Existing Plants

SHIP projects are being carried out worldwide in a wide range of industries and power plants. The most promising industrial sectors for solar process heat integration are food, textile, and mining. According to the ship plant database, a very useful online portal, developed by AEE-Institute for Sustainable Technologies (AEE INTEC), about 346 plants exist in 44 countries worldwide. In 2020, countries having the highest number of SHIP installations were China, Mexico, Germany, India, and Spain, with a total number of 30, 16, 10, 3, and 3 projects, respectively. Other important countries were Belgium, Austria, Cyprus, Italy, Malaysia, Morocco, the Netherlands, and Turkey [28][29][30].

5.1. Global Integration Scenario in the Food Industry

The food industry is the most prominent industrial sector, including the food manufacturing, beverage, and agriculture sectors, for solar integration with low-temperature processes (<150 °C). Together, food and beverages share 47% of the total globally installed projects [28]. In the agriculture sector, solar process heat is gaining the potential for greenhouse heating in horticulture and for preserving fruits and vegetables. The most common operations in the food industry include general process heating, pasteurization, cleaning, cooking, space heating, and drying [31][32][33].

5.2. Global Integration Scenario in Textile & Leather Industry

The textile and leather industry is an emerging sector in solar process heat integration. The installed thermal capacity in this sector is 26 MW_{th} which is 5% of the globally installed thermal capacity for solar heat integration. Mostly applied operations include retaining, bleaching, and process heating.

5.3. Global Scenario of SHIP Integration in Mining Industries

The mining industry is another dominating sector for solar thermal integration and has the highest share of installed thermal capacity (78%). The main operation includes cleaning, extraction, and process heating. Of the world's largest three SHIP plants, two are in the mining industry (Oman and Chile). There is a total of 14 mining plants currently in operation with eight plants having solar process heat integration at the process level and four plants at the supply level [34].

5.4. Comparison of the Supply Level, Process Level, and Other Point Integration of Solar Industrial Process Heat in Percentile

As discussed in the previous section, a distinction between process level and supply level integration is required for checking the suitability of solar process heat integration in certain industrial sectors. In industries, solar process heat integration generally occurs at the supply level, process level, and other points designed by process suitability.

In the food manufacturing, beverage, and agriculture industry, most of the solar process heat integration occurs at the supply level compared to the process level, which is clear from the following figure. Process heating operation (general and other) has the highest number of projects with supply level integration (38 projects), followed by cleaning (18 projects), pasteurization (12 projects), cooking (8 projects), and space heating (6 projects).

However, process-level integration is higher than supply-level integration for the drying operations in the Food industry. The percentage of integration in this sector is 51% for supply-level integration, 27.3% for process-level integration, and 22.6% integration at other points.

In the textile and leather industry, solar integration at other integration points is slightly higher than the supply level or process-level for the process heating operation. There is no supply-level integration for cleaning operations. For retanning operations, solar integration at the process level and other points is higher than process-level integration. However, the total percentage of the supply-level and process-level integration shares the same value (26%) for this sector.

In the mining industry, supply-level integration is higher than both process-level and other integration points for the general and other types of process heating operation. However, for cleaning and extraction operation, all the integrations are at the process level. The percentage of integration for the mining industry is 28.5% supply-level integration, 57.1% process-level integration, and 14.25% integration at other points.

The chemical and pharmaceutical industry is another emerging sector with a total of 21 globally installed projects [34]. In this sector, supply-level integration for process heating operation is much higher (10 projects) compared to process-level and other integration points (four projects). However, there is no supply level integration for drying, cleaning, cooling, and painting operations. The percentage of integration in this industry is 52.3% supply-level integration, 28.5% process-level integration, and 19% integration at other points.

Solar process heat integration in the transport sector is not extensive. In this sector, the process-level integration is a little higher (44%) than supply-level integration (33%). For cleaning and surface treatment there is no supply-level integration.

In the field of wood, paper, and rubber products manufacturing, solar heat integration is implemented only in two processes: process heating and drying. For process heating operations, the highest integration occurs at other optimal points followed by supply-level integration. For the drying process, one project has supply-level integration and another project has process-level integration.

In basic/fabricated metal and metal products manufacturing, most of the integrations are at the process level and other points compared to supply-level integration. For drying, extraction, and cooling operations, all solar integrations are at the process level and other optimal points. The percentage of integration in this industry is 18.7% supply-level integration, 31.3% process-level integration, and 50% integration at other points.

In the sector of electronics and machinery manufacturing, solar process heat is integrated only for process heating, surface treatment, and cooling operations.

There is only one project with supply-level integration for process heating operations in the production of electronic equipment. In the industry of machinery manufacturing, all of the solar integrations are at the process level and other integration points.

6. Conclusions

Considering the environment, economics, and technological development, proper utilization of renewable sources of energy in the industrial sector is both logical and congruent. Beginning in the late 1970s, although solar process heat integration for industrial purposes had not yet made any breakthrough, the concept was continuously gaining research interest and spreading steadily throughout industries worldwide. Solar process heat integration in industries has the potential for creating a carbon-free environment, but the process is at its early stage. The analysis clearly shows that successful SHIP projects are more likely to be achieved by deep analysis of integration point selection among other l factors such as the development of the solar collector and use in suitable industries. As process-level integration is relatively arduous, it might discourage solar integration. So, future research has the full scope to target the evaluation of more feasible integration arrangements at the process level. The efficiency of supply-level integration can be enhanced by optimizing the heat distribution network.

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