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TECHNICAL AND NON-TECHNICAL DIFFICULTIES IN SOLAR HEAT FOR INDUSTRIAL PROCESS

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Abstract: Despite of the tremendous potential in domestic, household, and industrial sector, the solar heat contribution is generally neglected in many academic and institutional projects. Thus, decision makers in many countries have paid lesser attention to solar thermal energy compared to other renewable energy solutions. Also, there is uneven level of solar thermal application in countries with similar climate and energy conditions which highlights the importance of creating public policies to go over the reasons. Nevertheless, solar thermal energy can provide a noticeable portion of the mankind energy demand which half of it is in heat form. Solar thermal technologies can be passive or active, for cooling or heating however, but still facing numerous obstruct which pursuing the dissemination of these technologies. Most of the technical difficulties have been solved with some technical limitations, while economic difficulties still counter high investment and upfront costs, legal difficulties of being permitted, and other difficulties such as lack of awareness among customers and policy makers, and insufficient training of professional, installers and designers. In this paper, an attempt to present an analysis of the barriers facing the solar integration in the industrial market from different aspects (technical, economical and others). In addition to the up-to-date solution for each problem.

Keywords: solar thermal, industrial processes, energy storage, technical barriers

INTRODUCTION

Solar heating for industrial process considered as one of the cleanest renewable energy solutions in many countries and under several climate conditions. Where a significant share of the final energy consumption is dedicated for low and medium temperatures (below 250°C) in the industrial sector. Those industrial activities have a tremendous impact on the country's economic growth, and it has 35% share of the world's growth [1]. This share can be higher in developed and growing economies such as USA 33% [2], Germany 28% [3], India 47% [4] and China 70% [5] but it depends on the level of the industrial activities in the country. Industrial sector consumes the needed demand in either electrical or thermal energy form. Where electrical portion is used for operating the electrical elements such as motors, lights, and air conditioning, while thermal energy is used for heat processes such as drying, dyeing, bleaching, etc. So that, a substantial share of the industrial energy demand is for industrial processes. However, this share varies with the industries, process type, and the manufactured products. Various industries such like textile, food, milk, beverage, pulp and paper, chemical and pharmaceutical, automobile, leather and rubber, etc., including several processes such as pressing, distillation, evaporation, pre-tanning, etc., all those processes need considerable temperature requirements that can be afforded by solar thermal system. According to those industries, a major fraction (around 60%) of the thermal energy demand is reportedly in the temperature range of 30-250°C [6].

All heat needed for processes in industry are generated typically by a heating device that generates heat then it is transferred from the source of production to the end use by a transferring mechanism which works as a distribution system. Heat process is carried out directly when the generated heat within the material itself, or indirectly where the heat is transferred by heat transfer mechanisms such as conduction, convection and radiation and this system often involves a boiler or a furnace. The example of the direct mode such as hardening and tempering, while drying and washing are examples for the indirect mode [7].

Process heating systems typically are two types: combustion-based, or electricity based. The heat is produced in the combustion-based systems by combustion of solid, liquid, or gas fuels, and then transferred directly or indirectly to the heat process. Examples of combustion-based heating systems include furnaces, ovens, and steam boilers. While the heat is produced in electricity-based heating systems by means of electrical current or electromagnetic field. Examples of electricity-based heating systems include microwave processing and infrared emitters [8].

Heat transfer media and fuels used in industrial process heating systems vary across regions and countries according to the availability of the fuels. Globally, the use of coal and liquid fuels accounts for about half of the total share of fuels used in the industrial sector. In 2020, 27%, 22%, 28.4%, 16% and only 6.6% are the shares of the liquid fuels, natural gas, coal, electricity, and renewable energy sources (solar and biomass) respectively [9]. In oil importing countries where the industrial sector demand is increasing, it would be a direct relevance to harness solar energy for not only meeting the process heating demand, but also to reduce the greenhouse gas emissions. So, it can be associated with the environmental benefits. On the other hand, the use of the heat transfer medium depends on the process and the end use requirements because the heat medium may or may not have a direct contact with the under-manufacturing product. So that, the desirable characteristics of the heat transfer medium that can be used in industry are high heat capacity, low vapor pressure, low viscosity, low corrosiveness, and high thermal stability [10]–[12].

Steam is the most used heat transfer medium in the industries which accounts for 37% and 33% in the USA and UK respectively [13]. The reason beyond it, that it has a high energy density compared to hot water and thermal oils, it can be stored in large quantities, and it can be transferred at constant temperature. Therefore, it accounts for a significant amount of the used energy in in the industrial sector. For example, the fuel used for generating steam in pulp and paper, chemical manufacturing, and diary are 84%, 47% and 50-60% respectively.

Even though, using hot water as a medium in the industrial processes also have a significant share due to its easy operation and maintain, but it requires a large distribution pipe diameter as compared to steam. Thermal oils are also used in industry due to its capability of operating under low pressures since its evaporation temperature can reach up to 300°C. However, it costs more, and it has lower specific heat capacity than water. Finally, hot air is used in drying applications, tea, and paper manufacturing [14].

Solar energy is one of the most sustainable energy resources and it is promising as an alternative source for thermal applications and power generation in both domestic and industrial sectors [15]-[16]. The thermal conversion of the solar energy can have higher efficiency up to 70% compared to the electrical conversion. Even for power production, the efficiency of the photovoltaic systems have 15-20% system efficiency, compared to 20-25% for thermal systems [17]. Therefore, use of solar thermal energy for industrial processes meets the increased industrial energy demand.

IEA (International Energy Agency) has established the solar heating and cooling program (SHC) back in 1977 to promote all the aspects of solar thermal energy utilization. These collaborative activities involve experts from Europe union and IEA member countries. For example, Task 33 (conducted between 2003 to 2007) showed the huge potential for using heat in industry and the importance of opening a new market sector to integrate solar thermal systems into the industrial processes. This integration requires further improvement and development of the solar thermal system's components to fulfill the stipulated requirements [6].

Task 49 (conducted between 2012 to 2015) reported that globally 30% of the industrial heat demand is needed at temperature below 100°C, while in the EU27 28% of the overall energy demand is heat below 250°C [18]. In this task 120 operating solar thermal systems are reported worldwide with total capacity of 88 MW_{th} which equals 125,000 m^2. The three main tasks in this project were:

≡ to optimise the processes and the solar thermal system (e.g., lower the process temperature, control safety issues etc.),
≡ system optimization (e.g., Pinch analysis), and
≡ integration of the solar thermal energy based on exergetic considerations.

Finally, Task 64 (started 2020-2023) focuses on process temperatures from above ambient up to 400-500°C aiming to help solar technologies becoming a reliable part of process heat supply systems. The key objective of this task is to promote, identify, and verify the role of solar heating systems in combination with other heat supply technologies (fossil and non-fossil) [19].

Selecting an appropriate solar collector technology for process heat demand in industry usually relays on four factors:

≡ operating temperatures
≡ annual solar yield
≡ solar collector efficiency, and
≡ costs [20]-[21].

Mainly three different types of solar collector technologies are being utilised in the solar industrial applications – flat-plate (FPC), evacuated tubes (ETC), and concentrators. Usually, water and air are used as heat transfer medium within the collector loops, while sometimes water needs to be mixed with glycol to avoid freezing and burst in case there is a drop down in the ambient temperature below 0°C. Solar air collectors are being used in food processing industry to reduce the heat losses that happen due to using fossil fuel to dry food materials in open air. FPCs and ETCs are used for low temperature industrial applications [22], while solar concentrators can produce process temperatures up to 300°C, which is available in several designs such as parabolic dishes or troughs and linear Fresnel reflector [23].

In the literature, the reported potential of harnessing solar energy in industrial processes are very large, while so far, the actual installed capacity is very small due to several reasons. In this study we are focusing on categorizing these barriers and providing the most up-to-date solutions for eachs case. The reported barriers based on the most recent literatrue are:

≡ difficulties in itergating solar process heating systems in existing industries
≡ optimising process heating streams
≡ lare scale industries are rather lesser in numbers, compared to the majority of the industrial units which requires tailormade solutions for each case study
≡ high upfront costs for small and medium enterprises (SMEs)
≡ unavailability of competent, qualified designer and installers
≡ lack of compact thermal energy storage solutions
≡ unavailability of adequate regulatory support and policy comapred to photovoltaic and solar thermal genergation solutions.

The present work will focuse on highlighting the most essential reasons in details and to give a solution for each of it.

BARRIERS TO DIFFUSION

Worldwide, industrial process heat accounts for more than two-thirds of the total energy demand in industry, where half of this demand is for heat temperatures below 400°C.

Currently, approximately 41% of the industrial primary energy consumption is covered by petroleum, and approximately 40% by natural gas. Therefore, by 2030 there is an energetic potential to provide around 15 EJ of solar thermal heat which account for 10% of the industrial energy demand. The potential markets for solar thermal systems are typically in the food, textile, transport, machinery, pulp, and paper industries, where approximately 60% of the needed heat temperature is below 250°C. One of the biggest barriers is the structure of the industrial sector.

Concerning large scale industries, which considered as energy-intensive factories, the bottlenecks are the difficult integrating of solar heat into existing process heat streams, and the lack of familiarity with the targeted technology. While for SMEs, which account for 95% of the industrial enterprises, need to be tailor made design to meet with the specific energy demand at specific location and circumstances. For SMEs, the feasibility study of this kind of projects is low, but it is hampered by the high upfront costs. However, the increasing costs and volatility of fossil fuel prices improve the potential of deploying solar thermal technology [17].

— TECHNICAL BARRIERS

Stagnation handling

Solar heating systems must operate totally reliably in all circumstances and conditions that may happen. Solar thermal applications in general must cope with the phenomenon of stagnation therefore, it requires specific technical solutions. Stagnation describes the case of a solar thermal system where an interruption happens in the flow of the collector loop and more solar radiation is absorbed by the solar thermal collector therefore the fluid in the collector loop is heated up to a temperature where the absorbed energy equals the heat losses. In low temperature applications, stagnation considered as a reliability issue so that, the use of solar thermal energy in medium-to-high temperature applications (mainly solar concentrator technology) require further importance of stagnation/overheating prevention strategies.

In comparison to conventional heating technologies, the solar thermal system cannot be simply shut down to prevent any extra heating in case of technical defects, lack of heat demand, or power blackout. Different effects during regular operating conditions have to be avoided depending on the solar collector concept such as preventing the heat transfer medium being released to the atmosphere in case of high-pressure state, as well as preventing too high temperatures that may damage the solar collector parts or the solar collector loop. For small to medium scale residential solar thermal systems typically, pressure release valve can be replaced by expansion vessels or simple heat dissipaters mounted in the collector loop [24]. While for industrial applications designed for higher supply temperatures with more efficient solar thermal collectors, other strategies should be applied such as active cooling devices for de-focusing (in case of tracking system) or overheating prevention. This solution guarantees a long term, low-maintenance, reliable operating conditions.

If the stagnation is an accepted operating mode in the process heat, extra measures must be added to prevent the solar loop components from being severely damaged by the high pressure or temperatures caused by stagnation.

As a solution for the stagnation for small domestic hot water systems, the expansion vessels are the state of the art, while for medium-scale solar systems inexpensive simple aluminium finned-tube heat exchanger can significantly reduce the steam in the primary loop as in Figure 1a. This solution can dissipate around 750-1000 W/m. If this solution is not sufficient to protect the temperature-sensitive components from steam, then passive evaporative air coolers can dissipate higher energy with small surface heat exchanger as in Figure 1b. The big advantage of this system that it can work independently of the electrical supply.

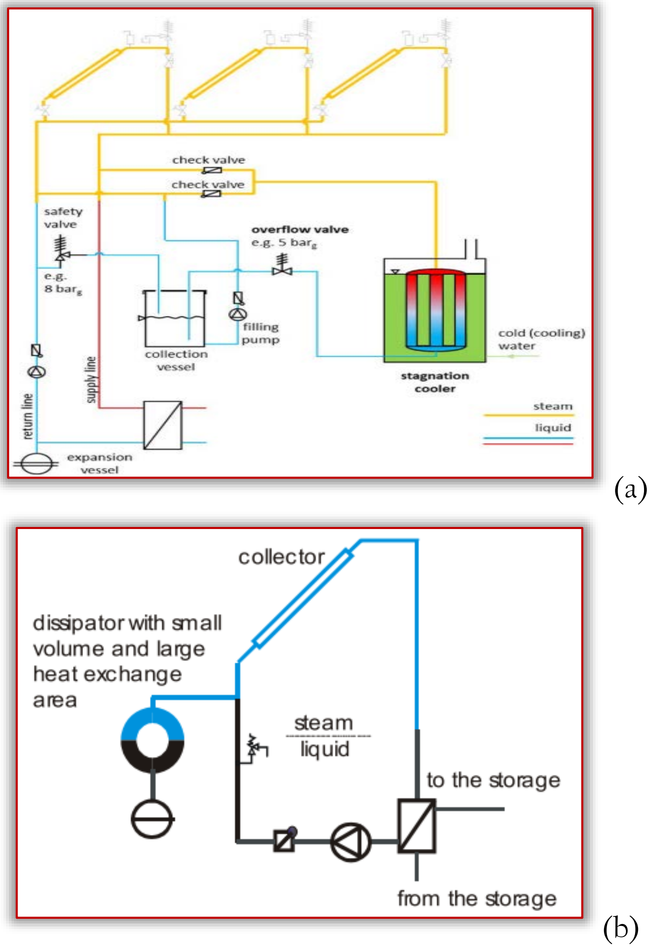


Figure 1.(a) Evaporative cooler (b) Passive heat disspators [24]

Overheating prevention

As soon the operation temperature is exceeded in solar thermal system, the overheating occurs as in Figure 2. It could happen for several reasons such as: if the energy delivered by the solar collectors exceeds the heat demand and the storage capacity, or if there is a failure in the controlling system. If there are no precautions, the collectors or the whole collector loop will be damaged, or it will reach to stagnation temperature. So that, the collector loop components must be chosen carefully to meet the operating conditions.

In case if stagnation is not an accepted operating mode in the process heat, then overheating prevention is a must to prevent the solar thermal system from temperatures and pressure stress caused by stagnation.

The stagnation temperature occurs when the thermal energy output of the solar thermal collector $\dot{Q}_{coll}$ drops to zero where $\dot{Q}_{coll}$ is represented by the following equation:

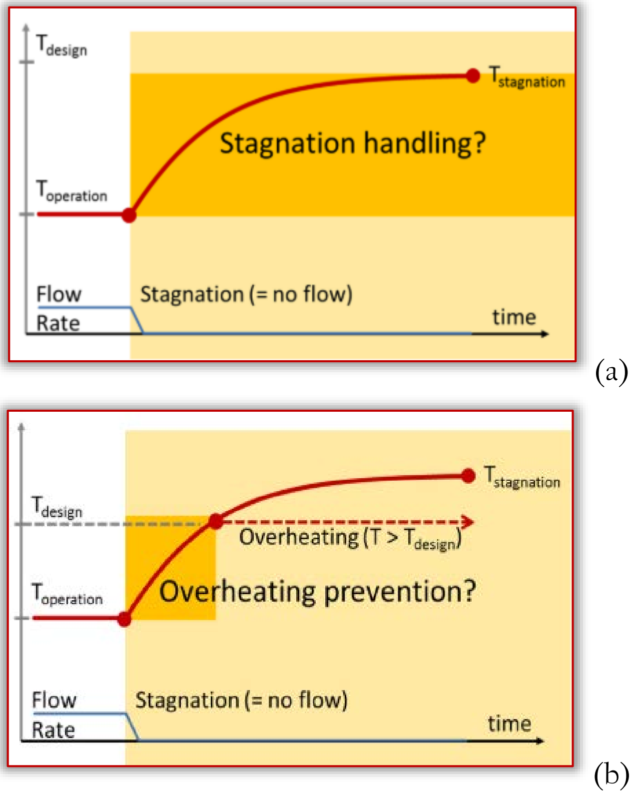
$$\dot{Q}_{coll} = A.G.(\eta_0 - a_1.\frac{(T_{m,f}-T_a)}{G} - a_2.\frac{(T_{m,f}-T_a)^2}{G}) \qquad (1)$$

where:

$\dot{Q}_{coll}$	Thermal output of the collector	[W]
A	Collector area	[m^2]
η_0	Conversion factor (peak efficiency)	[%]
a_1, a_2	Heat transfer coefficients	[Wm^{-2}k^{-2}]
$T_{m,f}$	Mean fluid collector temperature	[°C]
T_a	Ambient temperature	[°C]
G	Solar irradiance on collector plane	[Wm^{-2}]

The stagnation temperature is reached when $\eta_0 = 0$ and the $T_{m,f} = T_{stg}$:

$$T_{stg} = \frac{\sqrt{G.\eta_0.a_2+(\frac{a_1}{2})^2-a_1}}{a_2} + T_a \qquad (2)$$



(a)

(b)

Figure 2. Temperature over time of stagnation in case of (a) T_{design} > $T_{stagnation}$ (b) T_{design} < $T_{stagnation}$ [24]

To prevent overheating, the concept always has to address the lowest design temperature of all the parts of the collector loop. For a parabolic trough collector, overheating will have different causes and effects. Because during the overheating process the cooling system and the absorber tubes will be affected based on the design temperature. In general, the affected parts are as in Table 1.

Table 1. Overheating effect on system components

The component	The effect
The pumping system	Non-metallic components and rubber seals will be damaged
The absorber	The coating will start to degenerate
Collector tubes	Permanent deformation may occur
Thermal oil	Oil may lose its efficiency
The piping system	Rubber seals will crumble, and leaks appear in the system

As a solution for the overheating and the stagnation, in industrial-scale solar systems, every closed circuit filled with heat transfer medium is equipped with expansion valves which are able to absorb the expansion of the medium in case there is a temperature increase. Moreover, a safety valve which is pressure controlled is obligatory in all scenarios, that opens in case when the defined maximum operating pressure is reached and then release the evaporated transfer fluid. In this case, the opened valves lead to a partial emptying of the loop from the heat transfer fluid, this causes addition costs and maintenance. While in small-scale systems (such as domestic hot water), the expansion vessels are designed to absorb both the collector fluid expansion and the vaporized fluid. This means larger vessels, thus costs more.

In large-scale solar systems, such as district heating system, it is designed in a way that there is a constant base heat demand that the solar heat supply does not exceed. In this case, the stagnation occurs only by a power outage or a technical malfunction which means rarely to happen. While in industrial-scales, stagnation happens more frequently due to company holidays, process dependencies and weekend shutdowns therefore, low maintenance is inviable and overheating prevention and stagnation handling must be guaranteed.

The strategies developed to manage the stagnation and the expansion are either to design the system similarly to conventional small-scale systems which are able to cope with steam (stagnation handling), or to avoid the evaporation of the heat transfer medium (overheating prevention).

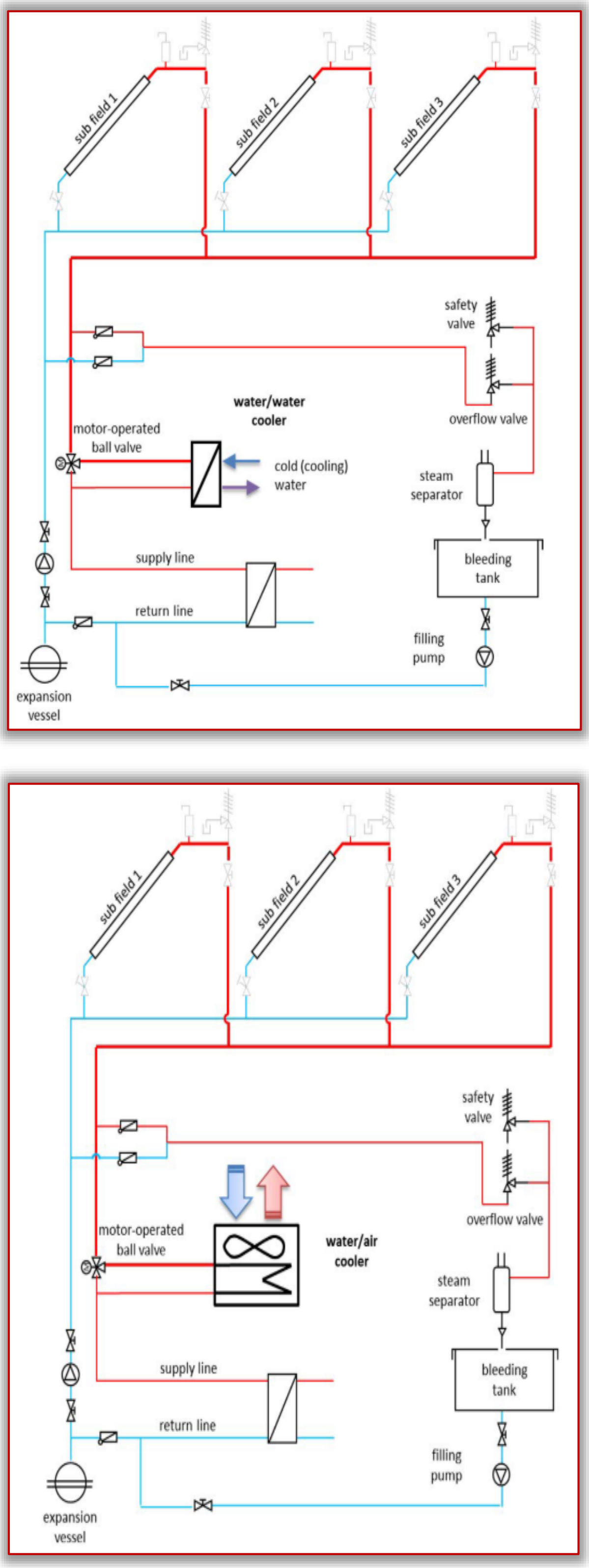
To prevent overheating there are different embedded protections in the collector concept, it is divided into three main categories:

≡ mechanically embedded systems such as flaps or heat dissipating methods
≡ material embedded such as thermo-tropic coating works as absorber and
≡ proper designed heat pipes.

If the emptying behaviour is unfavorable conditions on the system or collector level, active re-cooling devices should be used to prevent overheating in the system components (e.g., valves, pumps, membrane, etc.). In case of stagnation and overheating happens due to lack of heat demand in the solar process heat applications, which is the most critical issue, this solution is very efficient and reliable.

However, it depends on electricity so it will not function during outages in case there is no emergency power supply.

Or an additional safety valve can be mounted which may cause a partial emptying of the loop. There are two main types of it: water/water heat exchanger, or water/air heat exchanger [25] as in Figure 3.



(a)

(b)

Figure 3. Active cooler in the solar primary loop
(a) water/water (b) water/air

Another solution to avoid steam generation is to full drain the system at pre-defined temperature. When the heat supply from the collector cannot be used or stored or when the supply heat from the solar collector field is not sufficient, the solar loop pump stops and then the entire collector field is automatically drained to a drain-back tank as in Figure 4. When the solar irradiation is again sufficient, the solar pumps switched on and the collector loop is filled again with water so that the normal process starts in a few minutes. This system has a big advantage since it uses only water as a heat transfer fluid, therefore there is no ageing or maintenance which was associated with glycol-filled circuits. This system is a simple and reliable design with much experience in the small and medium systems and limited practical experience with the large-scale systems. In cold climates where there is a potential of frost, this can be a special challenge for this system.

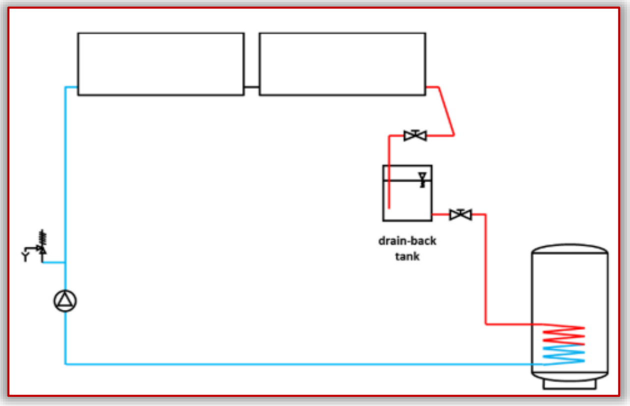


Figure 4. Drain-back system

In case of concentrating and tracking collectors, the defocusing is the easiest solution to prevent both overheating and stagnation. This occurs due to moving the receiver out of the beam radiation using an algorithm implemented in a programmable logic controller (PLC) which controls the movement of the collector. It works when the mass flow of the heat fluid stops or when a specific temperature is reached, the collector moves to a new position where less solar radiation is absorbed, therefore the temperature will decrease, and no overheating is produced.

Night cooling is a hydraulic concept that enables the solar thermal storage tank to unload during the night hours. In case there is no heat demand is needed in the upcoming days or the storage tank is fully loaded, the solar heat generated during the daytime can be dissipated during the night by circulating the hot water from the top of the tank through the entire solar collector field (only applicable for FPCs), therefore it operates like a large radiator during the nighttime.

The efficiency of the night cooling depends on the efficiency of the solar collector field, the temperature of the thermal fluid, and the ambient conditions (wind speed, temperature, and cloudiness). For cold climates such as central Europe, an Austrian brewery Goess uses night cooling to dissipate 80% of the gained solar thermal during the daytime under clear night conditions, while 20-25% during unfavorable conditions (sultry weather, no wind, cloudy).

Process integration

Process integration or Pinch analysis is an engineering filed that seek to reliably produce a product considering the minimum energy inputs. To reduce the economic inefficiencies and optimise the solar collectors, the variability of the energy supply must be quantified based on ambient temperature, daily solar radiation, and available storage opportunities.

If the solar thermal systems designed to provide all the heat demand, the manufacturer must align the production to match the supplied energy, or to store it for later use. One the other hand, solar system can be designed to supply a portion of the total required energy and the rest can be fulfilled by a complementary source. For the available commercial low-temperature solar collectors, it can be an effective solution for pre-heating purposes.

Energy storage options

Large-scale thermal energy storages are a budding market, but it can compensate the absence of the sunlight. For low and medium temperatures (up to 250°C) the storing medium can be a heat transfer fluid such as hot water or oil. Wile for high temperatures, storing the heat becomes more difficult, requires alternative mediums and storing material, and more costly.

The only practical solution for high temperatures is molten nitrate salt (220 to 565°C) which has proven its reliability at commercial scales. Nevertheless, the national renewable energy laboratory (NREL) develops heat transfer fluid that sustain and operate at temperature 0 to 1300°C. This is a step forward since the thermal loss from the heat storage tank was up to five times greater than originally expected during the 70s and 80s.

— NON-TECHNICAL BARRIERS

Cost

The economic viability of a solar thermal system depends significantly on two main factors:

- the initial cost of the installation and
- the prices of the alternatives.

High upfront payments usually prevent industrial companies from investing in new technologies, even if the long-term lifetime costs would be lower. Nevertheless, the costs for solar thermal systems are decreasing annually, and the financial investment in solar technology are more stable than many types of fossil fuels. Due to this, the biggest driver of the solar thermal systems is the prices of the alternatives such as coal, natural gas and oil. As the prices of these alternatives fluctuate and become more expensive, as it is easier to justify the investment in solar technology. Due to the high volatility of fossil fuel, some manufacturers accept to have high upfront costs with a predictable payback period.

The solar thermal system can be more cost effective when it is tailored to the specific case study of the plant. On the factory level, large-scale system can benefit from the scale economies to lower the investment costs, leading to increase the viability of the project. While on the national level, when the installed capacity gets doubled, the estimated costs can be reduced by approximately 20%.

Here governments play a major role by applying subsidies which will not only reduce the upfront costs, but also strengthen the willingness of householders and enterprises tending towards solar which has been proven that it works properly, in addition to its attribution of a public good. Besides the direct increasing of energy security and reducing greenhouse emissions, subsidies accelerate the cost reduction of growing climate friendly technologies by learning by doing process and the deployment of the early market stage. It should be noted that “stop-and-go” polices have proven a disastrous result of emerging market, since the support was not long enough to create a difference in the costs.

Thus, if there is no long-term strategies or goals for deploying solar thermal technologies, governments and industry have no way to estimate the progress and the chart path which lead to a sustainable, and mature solar thermal market.

Variability

Renewable solution like wind and solar energy can be predicted at a high degree of confidence. In industries that require 24/7 demand, the availability of solar energy can lead to a serious challenge [26]. The reliability of the supplied heat from the solar thermal system is a paramount concern to several industries, where an unanticipated disruption in the supply demand can lead to an economically devastating. Solar thermal technology is a reliable solution but not always available therefore, it can be a good solution for industries that do not require a constant production, or for whom the available radiation creates a good matching with the heating requirements. On the other hand, solar thermal collectors have an annual output for less than 1000 working hours, more likely to be 500-700 hours, compared to photovoltaic (PV) and concentrated solar power (CSP) for 1000 and 2000-2500 hours, respectively. It is serious also when the demand is low or zero during summertime, while the supply at its peak, in this scenario solar thermal systems are not suitable solution.

Legal and behavioural barriers

Split incentives are one of the most important barriers which arise for solar thermal technology both in rental and new construction markets. Building’s owners and property developers have little incentive to invest in solar thermal solution while renting their properties since the return of investment will go to the occupants. In theory it can be solved by making a financial arrangement between the landlord and the tenant so they can share the benefit. While in practice it is harder to solve due to the high transaction costs and the market inertia.

Other scenarios happen in large companies where decision makers think that they may not benefit from the savings resulting from the installation of solar thermal system. While in existing collective dwellings if the owner has his own system, it will be hard decision to modify the installation for solar heat and probably it still requires permitting from the other owners since they have only one roof.

Therefore, experts consider solar thermal technologies for dwellings generally possible only in new constructions.

Legal barriers vary from country to country, where following national or local regulations, ground mounted, or roof mounted installation will require permits. There are consequences of having a permit request such as procuracy procedures and costs for the application and the lawyers.

CONCLUSIONS

For several industrial sectors such as textile, metals and plastics, paper and pulp, chemicals, food processing etc., the share of thermal energy demand for various processes such as drying, cleaning, distillation, blanching, pasteurising, sterilising, cooking, surface treatment etc., it can be efficiently provided by solar thermal collectors due to its low and medium temperature range. There is a tremendous potential of adopting solar heat for industrial processes in most of the countries worldwide. The potential of implementing solar heat in European industry estimated at approximately 260 PJ which corresponds 143-180 million m^2 of collector area. However, the disseminated and reported levels are relatively low due to several barriers representing the large gap between the potential and the installed capacity.

In this paper we discussed the most important barriers technically such as the overheating and the stagnation and non-technically such as the upfront costs particularly in SMEs, and the lack of subsidies and appropriate promotional initiatives. Contemporary solar collectors for providing solar heat are available in the market such as FPC and ETC that can provide low temperatures, while several solar concentrating technologies (such as linear Fresnel reflector, parabolic trough, etc.) can produce an intermediate temperature reaches up to 300°C. Also, we discussed the solution for each barrier.

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