A review on Solar Thermal System Design, Integration, and Techno-economic Modeling for Industrial Heating and Cooling Processes

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Abstract

The utilization of solar thermal energy has been ranging from simple fire starting using a pocket mirror to the solar architecture used in various ways. Solar thermal applications are indispensable and crucial technologies with increasing attention in renewable energy research for their high energy conversion efficiency and energy storage density. Solar collectors can absorb nearly the entire solar spectrum; around 50% of the sun's energy is invisible to the human eye in the infrared spectrum, as heat. Thermal energy storage (TES) can store on average around 10, 000 kW for about 6 hours. Financially, solar thermal energy conversion systems in many locations have reached grid-parity (EUR 0.02 - 0.05/kWh for low-temperature and EUR 0.05 - 0.15/kWh for medium-temperature applications). Thus, solar heating and cooling (SHC) systems are identified as typical application areas for the huge technical potential of solar thermal integration (up to 5.6EJ in 2050) available within industries that are predominantly being met with environmentally unfriendly and less available fossil fuels. The scope of this review is, therefore, to demonstrate the state-of-the-art for basic energy generation and supply concepts of solar thermal systems for industrial application. The paper presents the basic solar thermal system design, configuration, operation, and possible integration concepts with an existing conventional system. It also describes the techno-economic mathematical models and analysis techniques for solar thermal system key performance indicators. Accordingly, this paper can be used as a brief extract and guide to systematically approach industrial solar system development projects using best practices adopted to explore the contributions of the researchers in the literature.

Keywords: Solar thermal, System design, Techno-economic modeling, SHC, Industry

1. Introduction

Solar radiation incident on the solar collector's aperture is focused on the absorber/receiver tube to heat the fluid passing through it. The heated fluid (usually air, water, or oil) is then used for applications and processes based on the specific end-use in water-heating (domestic, commercial, and industrial), space-heating, and pool heating systems (Lund et al., 2008) or to charge a thermal energy storage tank from which the heat can be drawn for use later (at night or cloudy days) (Prakash, 1994). Solar cooling is also identified as a potential application area, especially in the range of middle and small cooling capacities (Gebreyohannes et al., 2021). Solar collectors are the key components of solar thermal systems and can absorb nearly the entire solar spectrum; around 50% of the sun's energy is invisible to the human eye in the infrared spectrum, as heat (Penn State University, n.d.). Another key component of the system, Thermal energy storage (TES), is also one of the highest density energy storage systems with an average value of around 10, 000 kw for about 6 hours (Global Energy Systems Program, 2020).

As one of the identified application areas, in 1976, the U.S. Department of Energy had funded about ten Solar Heat Industrial Process (SHIP) projects as a contribution towards the commercialization of solar thermal utilization. A few years after their operation, a report summarizing the data regarding application studies, output, performances, and economic analysis of these projects was published (Brown, 1978). It was observed that there was a need to reduce cost and minimize design and installation errors. Another handbook was then released that provided a step-by-step procedure for designing SHIP systems. It also presents specific design information regarding the selection and sizing of components such as collectors, storage, piping, insulation, pumps, valves, heat exchangers, and heat transfer fluids (Uppal et al., 2015). A different report that comprises the design and integration aspects of SHIP systems and additional performance prediction procedures using computer-based simulations was also published in 1982 (Kutscher, 1983). Since then, many promising projects on SHIP have been implemented ranging from small-scale

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demonstration plants to very large systems capacities. In 2017, operating 124 new SHIP installations, totaling 192,580m² collector area was started. This increased the documented world total SHIP system by 25% in the number of installed plants and by 46% in the installed collector area. At least 624 SHIP systems, totaling 608,994m² collector areas were in operation at the end of 2017. Investigations projected the global SHIP potential to 5.6 EJ for 2050 (Gebreyohannes et al., 2021).

In a preceding couple of decades, though the dominant means for supplying cooling capacities have been compression refrigeration systems driven by electrical energy, the use of sorption refrigeration machines, which can be driven with thermal energy in the temperature range of 55-180°C have been used to supply cooling. Having been commercially available, absorption chillers are also mature and reliable technologies (Gebreyohannes et al., 2021). Currently, there is increasing use of solar cooling solutions for large public and private buildings as well as industries. According to (Justus et al., 2005), more than 100 commercial solar cooling systems with a cooling power of 9 MWth are reported in Europe. These systems show high potential in energy saving compared with conventional electric systems. By the end of 2015, an estimated 1,350 solar cooling systems were installed worldwide (Gebreyohannes et al., 2021).

Financially, the total investment costs for solar thermal systems, with few exceptions and differences at the national levels range from EUR 180 - 500/m^2. This equates to solar thermal systems in the range of EUR 450 - 1100/kWth and leads to an average energy cost of EUR 0.02 - 0.05/kWh for low-temperature and EUR 0.05 - 0.15/kWh for medium-temperature applications and is comparable to grid-parity in many locations (Gebreyohannes et al., 2021).

The aim of this paper is, therefore, to present a comprehensive review of several possible designs and integration prospects of solar thermal systems for industrial application. The methods and techniques for the techno-economic modeling of the systems are also briefly explained in the following sections. A systematic review method was established with two major steps included in the review process: (i) collection of system installation concepts and (ii) collection of system techno-economic modeling techniques. Hence, the study helps as a quick installation and modeling guide for Solar Heating and Cooling (SHC) installations of industries depending on the thermal energy requirements.

2. System installation concepts

2.1. Solar thermal applications and energy flow

Most of the energy consumed by the industrial sector is either in the form of thermal or electrical energy. Thermal energy is mainly used in process heating applications (cooking, washing, dyeing, bleaching, drying, etc). There is also increasing energy consumption for refrigeration and air conditioning, especially in the range of middle and small cooling capacities.

Solar thermal energy is often assumed as some unique source that must have complex technology to convert it to useful work. However, solar thermal energy is no different from any other type of thermal energy. Different temperatures and operating temperature ranges can be obtained depending on the collector setup and working fluid. This heat can then be applied for several thermal processes that would normally be driven by some other heat source such as natural gas, propane, or electric resistance heat. Cooling needs are also an excellent fit for solar thermal energy because of the often synchronous nature of the energy source and load schedule (Gebreyohannes et al., 2021). The energy collected by the solar field and stored in the warm reservoir can be used for process heating and driving thermal chillers. When not enough solar energy is available a traditional heating and cooling system can be started to produce the required heating and cooling effect (Burckhart et al., 2014). A typical schematic diagram of the thermal energy flow and distribution for heating and cooling applications is shown in Figure 1.

2.2. Basic system designs and configurations

i. Low-temperature systems

The system consists of an array of non-concentrating solar collectors, a circulating pump, and a storage tank. It also includes the necessary controls and thermal relief valve, which relieves energy when the storage tank temperature is exceeding a preset value. When the stored water temperature is above the required process temperature, it is mixed with mains water to attain the required temperature. If no water of sufficient temperature is available in the storage tank, its temperature is topped up with an auxiliary heater before use (Schmitt, 2016). A schematic of a typical diagram of a low-temperature solar system is shown in Figure 2. This once-through system (i.e. no hot water returns to the storage tank) is what usually happens in many industrial applications. The used hot water is replaced by mains water.

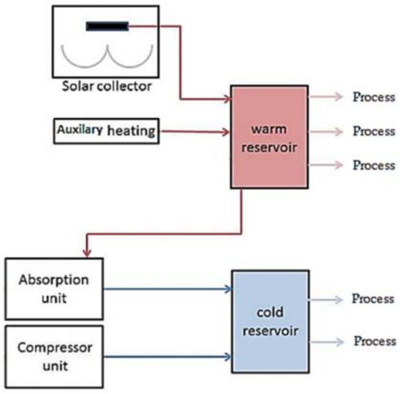


Fig. 1: Flow of thermal energy for heating and cooling processes

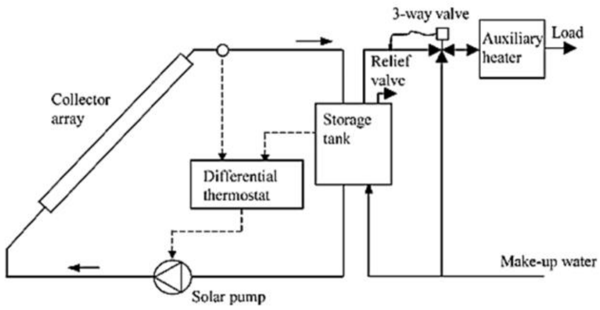


Fig. 2: Low-temperature solar system using a non-concentrating solar collector

In the case of low-temperature applications, higher efficiencies are achieved due to the low input temperature to the solar system. Thus, low technology collectors can work effectively and the necessary load supply temperature has little or no effect on the solar system performance. The system would need to be pressurized to allow storage at temperatures higher than 100 ^{0}C (Schmitt, 2016).

ii. High-temperature systems

Schematics of typical solar concentrator-based systems integrated with the backup boiler, with and without thermal energy storage are illustrated in Figure 3.

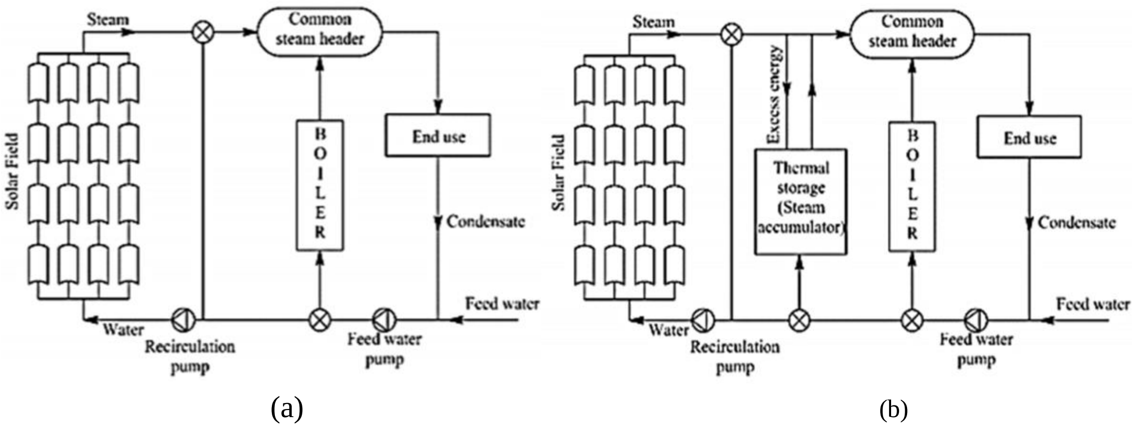
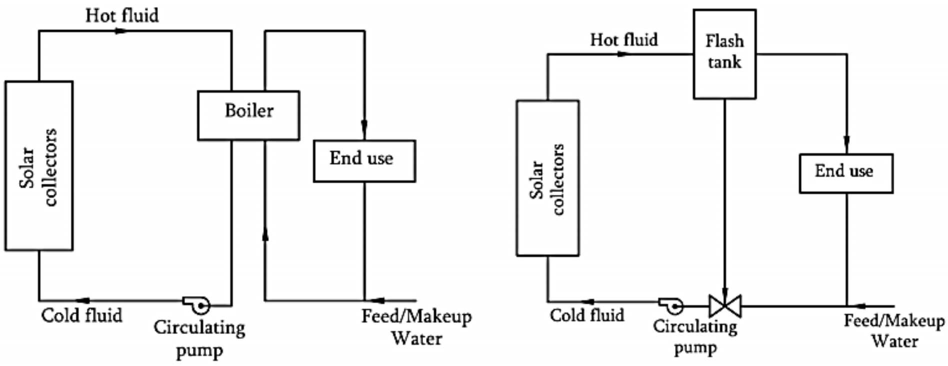


Fig. 3: High-temperature solar systems (a) with and (b) without provision of thermal storage

In concentrator-based systems, steam is generated in indirect and direct methods. In the indirect method, the heat transfer medium is heated in the solar collector loop and is then supplied to generate steam indirectly in the end-use loop. The indirect steam generation method can be in two different types of designs: unfired boiler (heat exchanger) based and flash boiler-based systems. In the unfired boiler-based system heat transfer fluid (e.g. water and air) is heated in the solar collector loop to provide the required heat that could be used to convert a secondary fluid to generate steam, pressurized hot water, or hot air as per the requirements of the end-use (Figure 4a). In the flash boiler-based system, pressurized water is heated in the solar collector loop and is passed through a throttling valve. Due to the pressure change in the valve, a part of it is converted into steam (Figure 4b). This steam is transported to the end-user as per the requirements. The rest of the water is re-circulated through the collector field. Make-up water is fed from the feed water tank. In this case, a circulating pump is used in the loop that always maintains the pressure of water to prevent boiling in the collector loop and piping (Sharma et al., 2017).



(a) (b)

Fig. 4: Indirect steam production systems (a) Unfired boiler-based, (b) Flash boiler-based

In the direct (in situ) method, the water is boiled in the solar collector loop. In the case of partial heating, water is circulated through a steam drum where steam is separated from the water. Feed/Make up water is supplied to the steam drum or mixed with the re-circulated water at a rate regulated by a water level controller as shown in Figure 5 (Sharma et al., 2017).

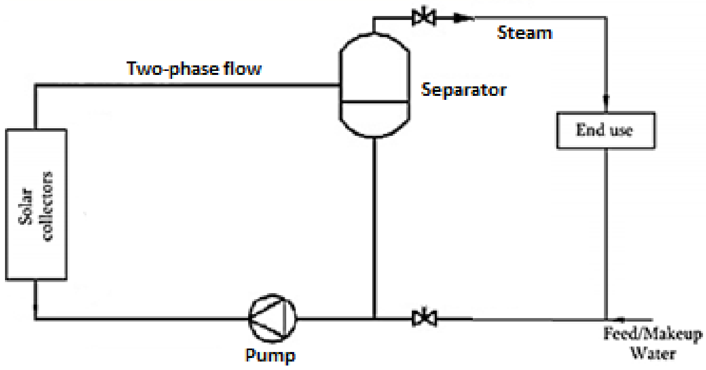
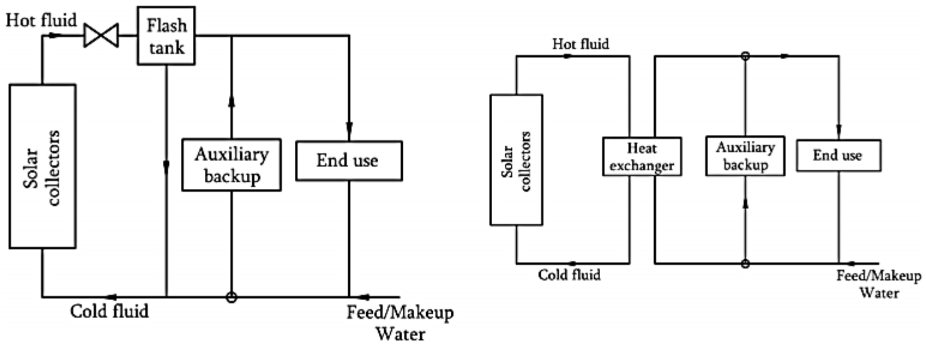


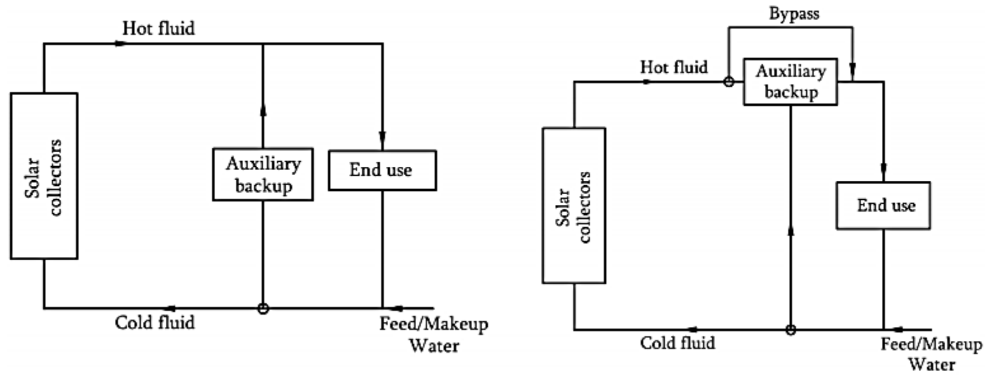
Fig. 5: Direct steam production system in a solar collector

A solar thermal system should enable continuous operation for meeting the process heating and cooling demand. This is possible with hybrid solar thermal systems where auxiliary boilers backup the system and ensure delivery of steam at a required temperature and pressure even in off-sunshine hours. Depending on the process heating and cooling demand and other requirements, the aforementioned solar thermal systems can be configured in parallel or series modes as per the requirements of the application shown in Figure 6 and Figure 7 (Sharma et al., 2017).



(a) (b)

Fig. 6: Indirect steam production configurations with auxiliary backup in parallel for (a) Flash boiler, (b) Unfired boiler



(a) (b)

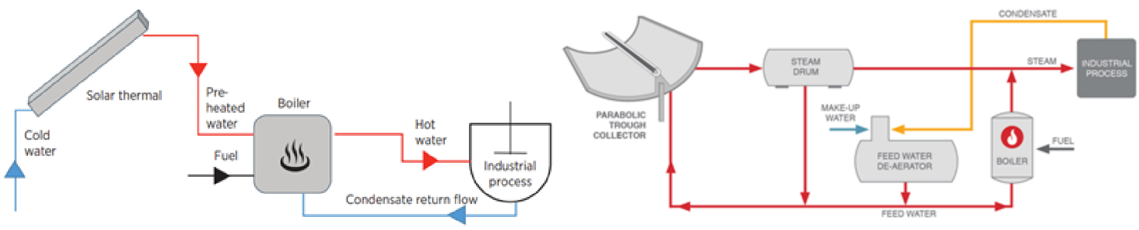
Fig. 7: Direct (in situ) steam production configurations with auxiliary backup in (a) Parallel, (b) Series

2.3. Basic system integration concepts

Perhaps the most common difficulty in the use of solar energy in a continuous operation is how and where to integrate it. A manual has been developed by the International Energy Agency (IEA) summarizing the guidelines for integrating solar systems with conventional systems (Aidonis et al., 2005). Different suitable integration concepts and configurations are identified by the guidelines for the integration of solar heat on supply and process levels. On the supply level, the respective heat transfer medium and integration point directly leads to a possible integration concept. On the process level, the category of a heat sink in combination with its conventional energy supply is decisive for the integration concept (Muster et al., 2015). Both direct and indirect integration configurations are applicable for integrating solar energy in the processes of existing industries.

Hot water or low-pressure steam at medium temperatures (less than 150 ^{0}C) can be used either for preheating of water (or other fluids) or for steam generation or by direct coupling of the solar system to an individual process processes such as washing, dyeing, etc. working at temperatures lower than that of the central steam-supply. The central system heat supply in most industries uses hot water or steam at a pressure matching to the highest temperature needed in the different processes. Typical maximum temperatures are about 180 – 260 ^{0}C (Schmitt, 2016).

In Figure 8 and Figure 9 two means (i.e. supply and process) for the direct integration of solar heating are shown. Figure 8a illustrates the solar array acting effectively as an inline heat exchanger preheating the water, or heating fluid, returning from a process before entering the heat source or boiler. In Figure 8b the flow can be diverted such that instead of using the heat source or boiler, the heat can be provided by the solar array (Epp et al., 2017; Schweiger et al., 2015).



(a) (b)

Fig. 8: Direct integration of heat from solar array (a) non-concentrating (b) concentrating

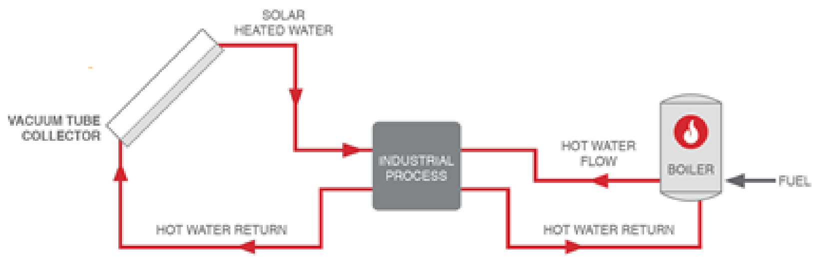


Fig. 9: Direct integration of solar heat into a process

There are some arguments for and against using direct integration as shown in Figure 8 and Figure 9. Typically the setup cost for these systems tends to be relatively low; however, they do require continuous control and by their nature limit the size of the solar array to ensure that they do not provide energy at a higher temperature than is required by the process. Furthermore, these systems will only function during the day. These shortcomings can be overcome by the use of an indirect, storage-based system as shown in Figure 10. By installing an intermediate storage tank, heat can be added to the tank by the solar array and used as required. As such the system does not need to be continuously controlled as with a direct system and by adding a storage vessel heat can be stored and used during periods of low or no solar radiation. The main drawback of an indirect system is that they tend to have a higher initial cost and also a longer payback time (Anderson et al., 2008).

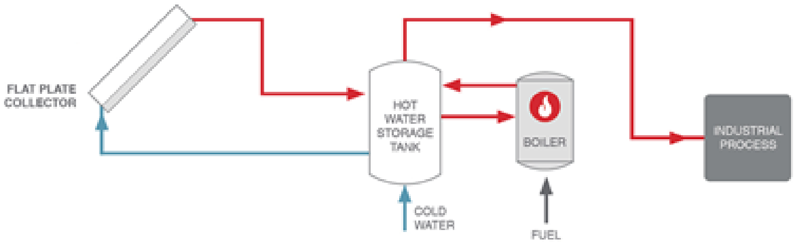


Fig. 10: Indirect heat integration from a solar array utilizing a storage system

One common method used in the determination of where heat sources should be integrated into a process is the pinch method. The pinch method uses combined heating and cooling curves as a graphic representation of heat and temperature demand in process industries. It shows the pinch point above which it is required for heat to be added and below which cooling is necessary. The minimum allowed temperature difference (ΔT_{min}) between hot and cold streams limits the maximum heat that can be transferred in a heat exchanger (March, 1998; Brunner et al., 2008a).

Tab. 1: Typical ΔT_{min} values for various processing industries

Industrial Sector	**Experience ΔT_{min} values (^{0}C)**
Oil Refining	20 - 40
Petrochemical	10 - 20
Chemical	10 - 20
Low-temperature processes	3 - 5

Table 1 confirms that the use of solar energy is ideally suited for low-temperature process application, as SHC systems would be able to deliver energy both above and below this point. The task is finding the optimal network of heat exchangers, external heaters, and external coolers for the capital and annual operating costs. In practical applications, $\Delta T_{min} \neq 0$ is always valid. To cut the size of the heat exchanger into an acceptable level with a reasonable price, it is expected that there always exists a temperature difference.

3. System techno-economic modeling

As mentioned earlier, the choice of configuration or design of a solar system is typically based on the specific requirement of process heating and cooling. Another important consideration is the economic viability of the systems. Many studies involving new design and integration concepts of industrial solar systems have been reported in the literature. Analytical formulae to evaluate the annual useful energy supplied by these design and integration configurations have been developed. These formulae internalized the effect of system parameters or variables such as characteristics of solar collector, storage tank, heat exchanger, piping, flow rates, and user demand/load. This approach can also be used for analysing system performance. These results are expected to be useful in performing sensitivity and optimization studies (Collares-Pereira et al., n.d.; Klein et al., 1976; Klein et al., 1979; Klein et al., 1975; Brunner et al., 2008b; Hess et al., 2010; Evans et al., 1997; Aidonis et al., 2005; Wallerand et al., 2016; Baniassadi et al., 2015; Walmsley et al., 2015; Baer et al., 1985; Gordon et al., 1982; Collares-Pereira, Gordon, Rabl, et al., 1984; Kulkarni et al., 2007; Kulkarni et al., 2008).

3.1. System yield assessment

The annual system yield is the most important value for assessing the economic feasibility of a solar thermal system besides system cost. This yield is influenced by many factors like temperature level, load profile, collector type, and location. There are many solar energy analyses in different papers and articles. A typical and simplified layout of solar thermal system with process steam production, primary and secondary circuits are made together combined, is shown in Figure 11 as a case study (Manfrida et al., 2009; Santbergen et al., 2010a; Gupta et al., 2010; Adnan M. Shariah et al., 1995; A.M. Shariah et al., 1999; Zondag, 2008; Santbergen et al., 2010b; Sarhaddi, Farahat, Ajam, & Behzadmehr, 2010; Zondag et al., 2003; Duffie, 2013; Sarhaddi, Farahat, Ajam, Behzadmehr, et al., 2010).

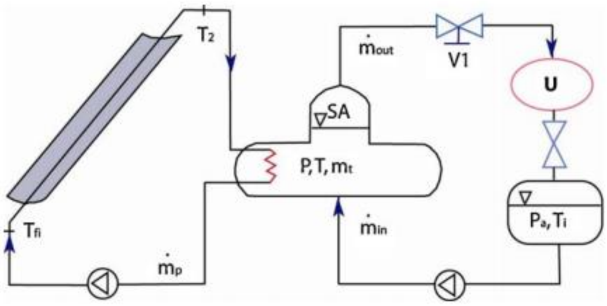


Fig. 11: Schematic diagram of a typical solar thermal system

In Figure 11, heat is transmitted from the primary circuit to the secondary circuit. The water vapor of the secondary circuit is stored in Steam Accumulator (SA). This model is assumed as a perfectly stirred adiabatic system, where heat is controlled by two limiting liquid levels with a liquid-vapor separation interface. Saturated steam is delivered to the thermal end-user or production plant (U) from the top of the SA at a mass flow rate of m_{out}. Water comes into the SA at its bottom after leaving the condensate recovery tank of U with a mass flow rate of m_{in} at sub-cooled conditions. When heat demand is increased by the user, the system valve V1 is opened to increase the system flow rate. During this transient period, the level in the SA falls and SA is depressurized to produce flash steam. To restrain this level from dropping below the minimum limit, more heat has to be provided by the solar collector or the condensate mass flow rate has to be raised. The former is dependent on weather conditions. On the other hand, if no heat is extracted from the SA ($m_{out} = 0$), the continuous heat input from the primary circuit and the condensate inlet mass flow rate ($m_{in} \neq 0$) leads to a rise in the SA filling level. Considering common conditions for steam production, a limitation for the SA filling level and operating pressures should be included.

The mass balance equation of the SA and the energy balance for the dynamic model of the SA, under the assumption of no thermal stratification, can be written as summarized in Table 2.

Tab. 2: The mass balance, energy balance, and system yield for the dynamic model of the SA

Mathematical Equation	Remark
$\dot{m}_{PT} = \frac{dM}{dt} = \dot{m}_{out} - \dot{m}_{in}$	$\dot{m}_{PT}$ is mass flow rate exiting from the system accumulator (kg/s)
$\frac{du}{dt} = \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + \dot{Q}_c$	$\dot{m}_{out}$ is mass flow rate exiting from the SA (kg/s)
$\frac{du}{dt} = \dot{Q}_{SC} - \left(\dot{Q}_{PT} + \dot{Q}_{VAP}\right) + \dot{Q}_c$	$\dot{m}_{in}$ is mass flow rate coming into the SA (kg/s
	h_{in} and h_{out} are enthalpies of $\dot{m}_{in}$ and $\dot{m}_{out}$ (kJ/kg)

$\dot{Q}_{SC} = \dot{m}_{in}(h_{in} - h_s)$	$\dot{Q}_c$ is heat rate to heat transfer fluid in the solar collector (kW)
$\dot{Q}_{PT} = (\dot{m}_{out} - \dot{m}_{in})h_s$	$\dot{Q}_{sol}$ is heat rate from the sun to the solar collector (kW)
$\dot{Q}_{VAP} = \dot{m}_{out}(h_{out} - h_s)$	I is the solar irradiance, A is solar collector area (m^2)
$\dot{Q}_c = \eta_c \dot{Q}_{sol} = \eta_c AI$	$\dot{Q}_{PT}$ is the energy required to compensate for any inlet or outlet flow imbalance (kW)
$Total\ Input\ Energy = IA + pump\ work$	$\dot{Q}_{VAP}$ is the energy necessary for heating the required flow rate $\dot{m}_{out}$ from saturated liquid to saturated steam condition (kW)
$\eta_{sys} = \dfrac{\dot{Q}_{PT} + \dot{Q}_{VAP} + \dot{Q}_{SC}}{Total\ Input\ Energy}$	$\dot{Q}_{SC}$ is the heat supply for starting the sub-cooled water thickened coming from the user with a flow rate $\dot{m}_{in}$ up to saturated liquid condition (kW)
$SF = \dfrac{Q_{Sol}}{Q_U}$	h_s enthalpy of saturated steam (kJ/kg)
	η_c and η_{sys} are a collector and system efficiency
	SF is a solar fraction
	Q_U is heat load (process demand)

3.2. Economic considerations

The method of annual saving and payback period are mainly used to check the economic feasibility of systems (S. A. Kalogirou, 2004; *TRNSYS 17*, 2009; Florides et al., 2002; S. Kalogirou, 1996). The mathematical equations for economic considerations are summarized in Table 3.

Tab. 3: Economic parameters of the system

Mathematical Equation	Remark
$C = C_s + C_o$	C is the total annual cost or a purchase cost at the end of year N
$C_s = C_f + C_a A + C_v V$	C_s is investment costs of the solar system
$P = \dfrac{F}{(1+d)^N}$	C_o is the operation cost (maintenance and parasitic costs are considered)
$F = C(1+i)^{N-1}$	C_f is collector area independent cost
$PW_N = \dfrac{C(1+i)^{N-1}}{(1+d)^N}$	C_a is collector area dependent cost
$FS = 365\ \dfrac{days}{year}\left(SF * \dfrac{Q_U}{day} * C_{FL}\right)$	A is collector area
	C_v is the cost of storage per m^3 of storage volume
	V is a storage volume
$SS = FS + Extra\ savings$	P is the present value of money
$PW_{LCS} = \sum_{N=1}^{N} \dfrac{SS}{(1+d)^N}$	F is cash flow occurring N years from now
	d is a discount rate
	N is occurring years from now

$PP_{year} = \frac{Capital\ Cost}{Annual\ Savings}$	i is annual inflation rate (the value of money is decreasing over time) PW is total present worth (or discounted cost) FS is fuel saving SF is the solar fraction C_{FL} is the cost rate of conventional fuel SS is solar saving LCS is life cycle saving PP is payback period

4. Concluding remarks

Solar thermal energy is getting attention for its technical (energy collection efficiency and storage density) and economic advantages. Due to the huge technical potential for solar thermal integration, industrial heating and cooling processes can be considered as the potential application areas for solar thermal energy. There are different system design, configuration, and integration concepts of a solar thermal system for meeting the industrial process heating and cooling demand. The principles of the mathematical models for conceptual design, virtual prototyping, and economic analysis of the system are the key performance indicators. Hence, this paper has reviewed and discussed these aspects to briefly extract a systematic approach and guide to be adopted for industrial solar system development projects given the boundary conditions of solar resource and process demand profiles.

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