A REVIEW ON SOLAR THERMAL TECHNOLOGIES FOR LOW AND MEDIUM TEMPERATURE INDUSTRIAL PROCESS HEAT

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RINGKASAN: *Malaysia mempunyai potensi yang besar bagi perlaksanaan haba solar untuk proses industri terutamanya bagi aplikasi suhu rendah dan sederhana. Artikel ini membuat kajian literatur terhadap teknologi solar haba bagi proses haba industri dari segi jenis teknologi pengumpul suria untuk suhu operasi rendah dan sederhana, potensi aplikasi dalam sektor industri yang terpilih dan jenis proses industri. Kemudian, ia membincangkan tentang potensi proses pemanasan solar ini khususnya di Malaysia berdasarkan data permintaan tenaga. Ia juga membincangkan bagaimana tenaga solar boleh disepadukan ke dalam proses haba industri. Akhir sekali, artikel ini membentangkan empat loji demonstrasi proses haba suria yang telah dipasang di seluruh dunia.*

ABSTRACT: Solar heat for industrial process has a large potential to be implemented in Malaysia especially for low and medium temperature application. This article reviews solar thermal technologies for industrial process heat in term of type of solar collector technologies for low and medium operation temperature, its potential application in selected industrial sectors and type of industrial processes. Then, it discusses the potential of this solar process heat specifically in Malaysia based on the energy demand data. It also provides information on how the solar energy can be possibly integrated into industrial process heat. Finally, the article presents four solar process heat demonstration plants that have been installed worldwide.

KEYWORDS: Solar heat for industrial process, low and medium temperature, solar collectors, solar heat integration, Malaysia's potential

INTRODUCTION

Malaysia's National Energy Balance 2013 (Malaysia, 2013) reported that total final energy consumption for Malaysia in 2013 was 51,584 ktoe. According to sectors, 43.3 % of this final energy consumption was used by transport, 26.2 % by industry, 14.4 % by commercial/residential, 14.1 % from non-energy use and 2 % from agricultural sector. Focusing on industrial sector alone, the heating requirement accounts for a large portion i.e. 67 % of the total energy use from the fossil fuel, and the balance was for electricity. Looking at this figure, a significant energy from fuel can be reduced if some portions of the heating use in industry is supplied by Renewable Energy (RE).

The enabling policy framework and support programmes in Malaysia for RE have focused on grid electricity power generation over thermal applications despite the facts that large portion of the energy is expended for meeting heating requirement especially in industrial sector. Moreover, many programmes, incentives and Research, Development and Innovation (R&D&I) activities related to solar energy in Malaysia have been emphasised mainly on solar photovoltaic (PV) for electricity generation and much less on heat application. Furthermore, apart from domestic solar water heaters, the government does not yet have policies, incentives or standards that specifically aim at larger-scale solar thermal system applications in commercial buildings or in industrial applications.

Malaysia is located in the equatorial region and has a tropical rainforest climate. The tropical climate has been categorized as having heavy rainfall, constantly high temperature and relative humidity throughout the year. Being a country that is close to equator, Malaysia naturally has abundant sunshine and thus solar irradiance. It is reported that annual average daily solar irradiations for Malaysia were from 3.73 kWh/m^2 to 5.11 kWh/m^2 (Engel-Cox, 2012) with the highest usually recorded in March or April and the lowest is in November or December during monsoon season. Northern region and few places in East Malaysia have the highest average daily solar radiation. With this plenty of sunlight throughout the year, Malaysia has big potential for solar energy application.

Given the fact that 30 % of the total industrial process heat demand requires temperature below 100 ^{o}C (ECOHEAT, 2006), which can be met by commercially available solar thermal collectors, in principle the potential of solar thermal in industry is enormous (Mat, 2015). Furthermore, industrial sector has more than 80 % of untapped potential of energy efficiency in the period to 2035 as reported in the New Polices Scenario by International Energy Agency (IEA) (IEA, 2014b).

This paper reviews solar thermal technologies for industrial process heat in term of type of solar collectors, its potential application in selected industrial sectors, process, operating temperature, and possible points for solar heat integration. It also provides several examples of solar process heat plants in several countries.

SOLAR THERMAL COLLECTOR TECHNOLOGIES FOR PROCESS HEAT

Solar collector in a solar thermal system is a component that absorbs solar irradiation as heat and transfers the heat to a working fluids such as water, air and thermo oil. The heat carried by the working fluid is then used to provide hot water, steam or space heating.

There are three major categories of solar thermal collectors i.e. 1) non-tracking (stationary), 2) single-axis tracking and 3) two-axis tracking collectors (Kalogirou, 2003). The major types of collector that can be used for industrial process heat are from the non-tracking category and one-axis -tracking collectors like scheffler dish, parabolic trough collectors and Fresnel collectors (Kalogirou, 2003). Three types of collectors that fall into stationary category are: 1) flat-plate collectors, 2) evacuated-tube collectors and 3) stationary compound parabolic collectors. The flate plate collectors are designed for low temperature (< 100 ^{o}C), meanwhile evacuated-tube collectors are for medium temperature (100 ^{o}C – 400 ^{o}C) application. The non-tracking and one axis parabolic trough collectors (PTCs) are used for medium and high temperature (> 400 ^{o}C) industrial process heat. On the other hand, two-axis tracking collectors such as parabolic dish reflector (PDR) and heliostat field collector are used to produce steam for power generation. Table 1 shows the type of solar thermal collectors and their suitable applications.

In the following sub-section, this paper will focus on the technology of flat plate and evacuated tube collectors that are suitable to be used for industrial process heat which requires low and medium heating temperature. This is also because these type of collectors are suitable to be applied in countries such as Malaysia which has high cloud coverage and diffuse solar radiation. The potential of solar thermal for process heat in Malaysia will be discussed further in the next section of this paper.

Table 1. Type of solar collectors and its application (Faninger, 2010; Kalogirou, 2003; Mekhilefa, 2011)

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)	Possible Application
Stationary	Flat plate collector (FPC)	Flat	1	30-80	Pool heating, crop drying, low temp. industrial process heat
	Evacuated tube collector (ETC)	Flat	1	50-200	water, space heating, space cooling, med. temp. industrial process heat
	Compound parabolic collector (CPC)	Tubular	1-5	60-240	water, space heating, space cooling
Single-axis tracking			5-15	60-300	
	Fresnel lense tracking (FLC)	Tubular	10-40	60-250	high temp. industrial process heat
	Parabolic trough collector (PTC)	Tubular	15-45	60-300	high temp. industrial process heat
	Cylindrical trough collector (CTC)	Tubular	10-50	60-300	high temp. industrial process heat
Two-axis tracking	Parabolic dish collector (PDS)	Point	100-1000	100-500	power generation
	Heliostat field collector (HFC)	Point	100-1500	150-2000	power generation

Note: temp. (temperature), med. (medium)

Flat Plate Collectors

Flat plate collectors are the most commonly used collectors in Europe, which is the second largest market place for solar thermal collectors after China. It is reported that, 83.8 % of solar thermal installed capacity in Europe in 2013, being the flat plate collectors (Mauthner, 2015). This is mainly because the flat plate collectors are cheaper, require less maintenance and suitable for delivering thermal energy at temperatures between 30 ^{o}C to 80 ^{o}C (Cottret, 2010). Construction of a typical flat plate collector consists of glazing covers, absorber plates, insulation layers and recuperating tubes which is filled with heat transfer material such as water or water/glycol mixture (Tian, 2013) as shown in Figure 1. The principle of the flat plate collector is: when the solar irradiation hit the surface of the collector, the radiation will pass through the transparent cover and reach the absorber plate. The radiation is then absorbed by the plate and converted into thermal energy which is then transferred to the heat transfer material fluid within the tubes.

A standard flat plate collectors have high heat losses and not suitable for higher operation temperature (Cottret, 2010). Therefore, some efforts to improve the performance of flat plat collector in reducing thermal losses and keeping high optical efficiency were carried out. Some technological improvements include replacing the single glass by multiple and different kind of glasses and anti-reflective coating (Dagdougui, 2011; Ehrmann, 2012), modelling a gas-filled flat plate collector (Vestlund, 2009), improving structure by integrating heat pipe (Wei, 2013) and choosing better material for heat transfer (Chen, 2010).

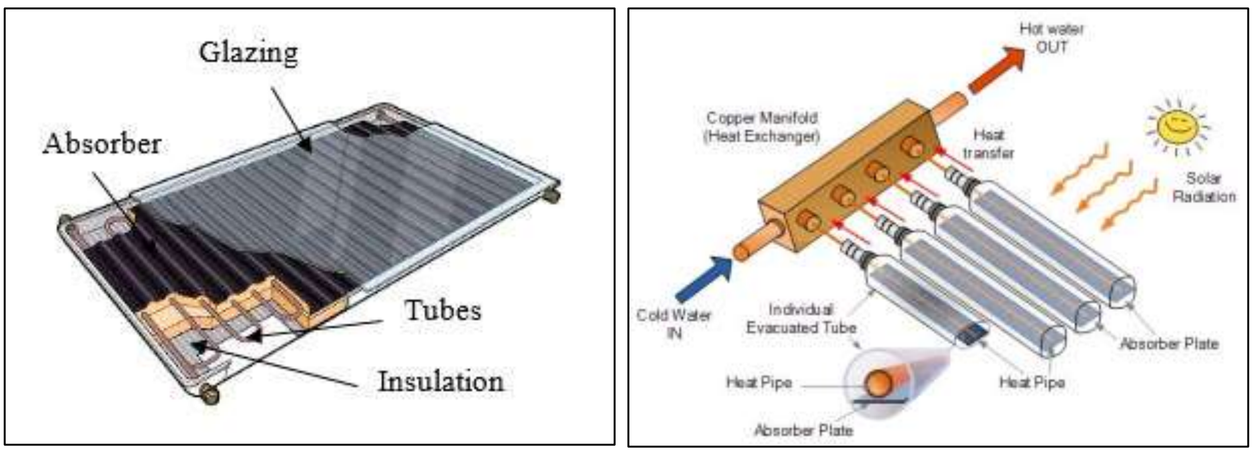

Figure 1. Construction of flat plate collector (left) (Trust, 2015) and evacuated tube collector (right) (Tutorials, 2015)

Evacuated Tube Collectors

Evacuated tube collectors are the predominant solar thermal collector technology worldwide in 2013 with a share of 70.5 % from total solar thermal installed capacity (Mauthner, 2015). This figure is mainly contributed by China which is the biggest user of evacuated tube collectors, as well as the world largest installed capacity of solar thermal. Evacuated tube collectors are designed to operate at higher temperature than flat plate collector ranging from 50 ^{o}C to 130 ^{o}C (Cottret, 2010). The manufacturing process, mechanical complexity and material selection of the evacuated tube collectors are more expensive than the flat plate collectors (Trust, 2015). This is also due to the design of collectors' housing that is made of a vacuum glass tubes to reduce and eliminate convection and conduction thermal losses. Furthermore, the glass tube is used because it able to withstand the stress of the vacuum. A typical construction of evacuated tube collector is shown in Figure 2.

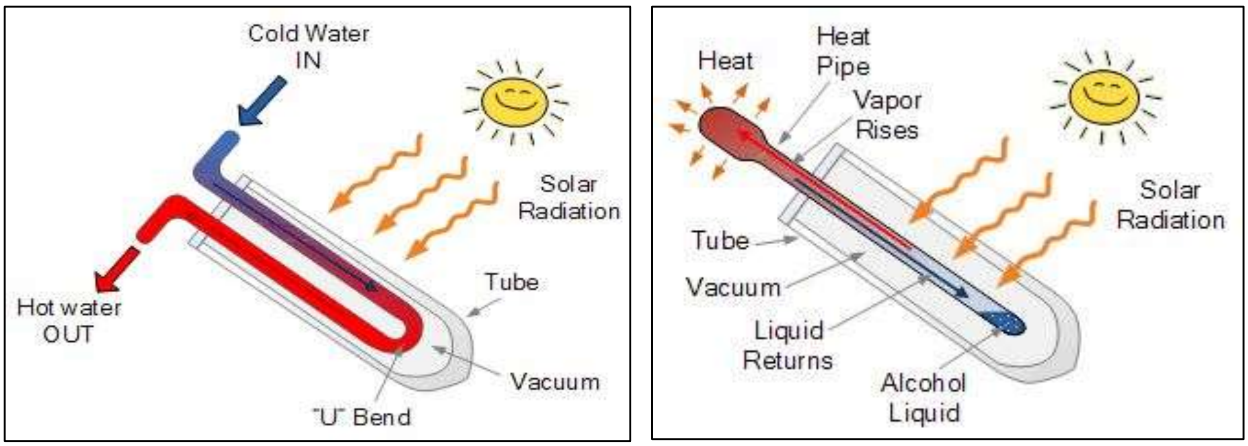

Figure 2. Direct flow (left) and heat pipe evacuated tube collector (right) (Tutorials, 2015)

There are two types of evacuated tube collectors i.e. 1) direct flow and 2) heat pipe collector. The direct flow evacuated tube collectors use an evacuated tube inside a U-shape tube. In direct flow evacuated tubes, there are two heat pipes running through the centre of the tube, one is flow pipe and the other one is the return pipe. A heat absorbing reflective plate is in between the flow and the return pipes through the solar collector tubes. The heat pipes and the reflector pipe are made out of copper with a selected coating material. Both the absorber plate and the heat transfer tube are made vacuum sealed inside a glass tube. This is shown in Figure 2. The heat transfer material is usually fluid and this fluid runs through concentratic tube-in-tube or a U-shaped tube to the base of the glass bulb and then returns to the header.

A heat pipe evacuated tube collectors contains alcohol or water in a vacuum which is used to absorb the energy from the sun. Due to presence of the vacuum, the alcohol or water will evaporate at a low temperature of 25 ^{o}C to form a vapour. This vapour then rises up to the top of the collector tube, heating it up and transfer the heat to the solar fluid. After the heat transfer process completed, the vapour condenses back to a liquid and flows down back to the bottom of the collector tube.

SOLAR HEAT FOR INDUSTRIAL PROCESS

Solar heat for industrial processes is still in the infancy stage of development, but is considered to have a huge potential for solar thermal applications. It was reported that in 2006, there were 90 operating solar thermal systems for process heat worldwide, with a total capacity of about 25 MWth (35,000 m^2) and this figure accounts for only 0.02 % of the total solar thermal installed capacity worldwide (IEA, 2008). The figure had increased in 2014 as 120 operating solar thermal systems for process heat have been installed worldwide which is equivalent to a total capacity of about 88 MWth (125,000 m^2) (IEA, 2014a). Nevertheless, a huge potential is still available as more than 80 % of untapped potential of energy efficiency is seen for the industries in the period to 2035 (IEA, 2014b). This is supported by a study (Lauterbach, 2012) that estimates the potential of solar heat in industrial process in five European countries i.e. Austria, Italy, Netherlands, Portugal and Spain is in the range of 3.0 % to 4.5 % of the industrial heat demand and in total of 16.7 TWh (IEA, 2008).

Solar Heat Potential in Industrial Sectors

Majority of the solar thermal application today i.e. 94 % is for domestic hot water systems (Mauthner, 2015). Although the domestic sector offers a great potential demand for solar thermal application, the industrial sector should not be left out. This is due to two important factors (IEA, 2008). First, the industrial sector covering about 26 % of the final energy consumption in Europe in 2012 (Agency, 2015). Second, the major share of heating energy needed in industrial sector is for low (20 ^{o}C – 100 ^{o}C) and medium temperature (~250 ºC) (Schnitzer, 2007), which is a temperature that could be supplied by available solar thermal technologies (Kalogirou, 2003). A study by (ECOHEAT, 2006) reports that 30 % of the total industrial heat demand requires temperature below 100 ºC and 60 % requires temperature above 100 ºC. These percentages can be further breakdown into low temperature below 100 ºC (30 %), medium temperature between 100 ºC to 400 ºC (27 %) and high temperature over 400 ºC (43 %) (ECOHEAT, 2006) as shown in Figure 3. A slightly different fraction of temperature range is reported for Germany (Lauterbach, 2012) i.e. 21 % is for process heat lower than 100 ºC, 8 % is for temperature range of 100 ºC - 200 ºC, a small percentage is for application between 200 ºC - 300 ºC and the biggest portion i.e. 65 % is needed at temperature over 500 ºC.

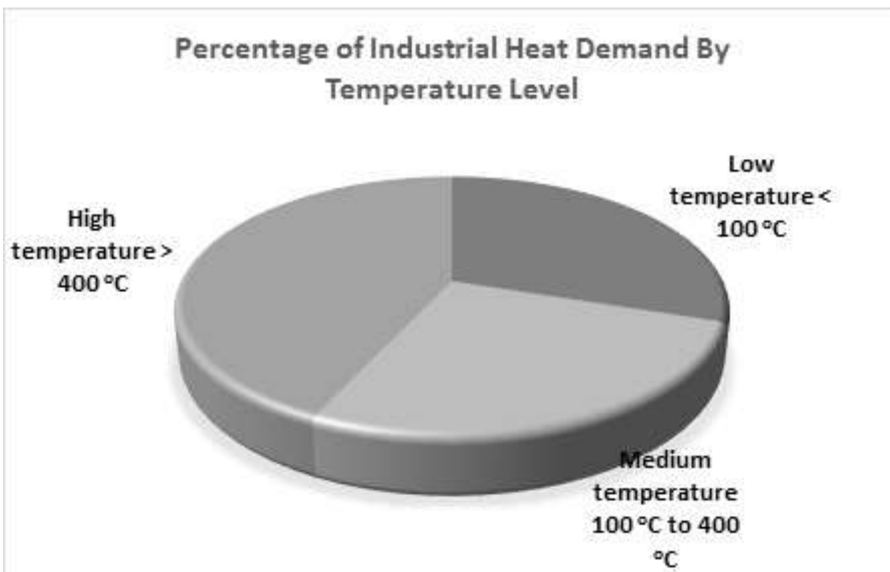

Figure 3. Share of Industrial Heat demand according to temperature level (ECOHEAT, 2006)

A survey conducted by (IEA, 2008) has identified several potential industrial sectors and industrial processes where the solar thermal could be optimally and efficiently used. These sectors and processes are identified based on the continuous heating demand needs and the temperature level of the processes that is compatible with the operating temperature of solar thermal collectors. The sectors include food (including wine and beverage), textile, transport equipment, metal and plastic treatment and chemical. The most suitable industrial processes include cleaning, drying, evaporation and distillation, blanching, pasteurization, sterilisation, cooking, melting, painting, and surface treatment. Another study (Kalogirou, 2003) states that most of the energy used for industry in Cyprus is from the food industry and the manufacture of non-metallic mineral products. Among the food industries, milk and breweries industries have great potential to employ solar process heat as the industries involve applications such as drying, cooking, cleaning, extraction and many others. Other potential industrial sectors with its corresponding suitable process and operating temperature level (Weiss, 2015) are shown in Table 2.

Table 2. Potential industrial sectors with suitable industrial processes and temperature level (Weiss, 2015)

Industrial Sector	**Process**	**Temperature Level [ºC]**
Food and Beverages	Drying	30 - 90
	Washing	40 - 80
	Pasteurizing	80 - 110
	Boiling	95 - 105
	Sterilising	140 - 150
	Heat Treatment	40 - 60
Textile Industry	Washing	40 - 80
	Bleaching	60 - 100
	Dyeing	100 - 160
Chemical Industry	Boiling	95 - 105
	Distilling	110 - 300
	Various chem. Processes	120 - 180
All sectors	Pre-heating of Boiler Feed-water	30 - 100
	Heating of factory buildings	30 - 80

Note: chem. (chemical)

Solar Heat Potential Impact for Malaysia's Industry

A similar trend of final energy consumption by industrial sector in Europe was seen in Malaysia (Malaysia, 2013) i.e. 26.2 % of the total final energy demand in 2013 was used by industry. This shows that Malaysia's industrial sectors also has a great potential for solar thermal application. In contrast with statistic reported for Cyprus (Kalogirou, 2003), most of the industrial energy demand in Malaysia are from chemical and followed by food, beverages and tobacco in second place (Malaysia, 2013) as shown in Figure 4. Table 2 indicates that low and medium temperature solar process heat are suitable for industrial sectors in Malaysia. This is supported by the fact that Malaysia's climate with significant amount of cloud and has Direct Normal Irradiance (DNI) below the required amount of concentrating collectors to be economically feasible i.e. 1,900 – 2,000 kWh/m^2/year is not suitable for producing heat at higher temperature (Affandi, 2013).

A simple calculation can be used to generalize the potential impact of solar process heat in Malaysia on fuel's savings and CO_2 emission. Assuming 5 % of the industrial heat for temperature below 100 ^oC were supplied using solar thermal; a 1,577 GWh amount of energy from fuel could be saved which translates into 394,358 tonnes CO_2 emission reduction from fuel oil. This equivalent to 1.8 MWth (405,718 m^2) installed capacity. These figures with assumptions used to derive them are shown in Table 3.

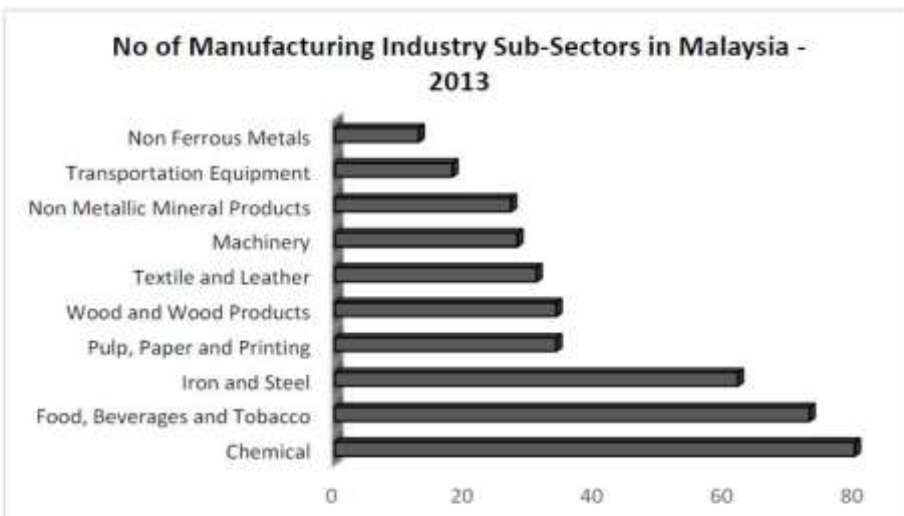

Figure 4. Number of manufacturing industrial sub-sectors in Malaysia in 2013

Table 3. Potential impact of solar thermal on energy savings from fuel and CO_2 emission for Malaysia

Malaysia's Scenario			**Assumption**
Total energy for heating in industrial sector in 2013	105,162,182	MWh	1 ktoe = 11,630 MWh
30 % uses heating energy less than 100 ^oC	31,548,654	MWh	30 % of industrial sector uses process heat < 100 ^oC

Every 5 % conversion to solar thermal	1,577,433	MWh	5 % heating energy from solar thermal
Reduction of CO_2 emission	394,358	ton CO_2	1 kWh = 0.25 kgCO_2 Emission - Oil
Annual expected energy generation from 4.5kW/m^2 solar thermal system	3.89	MWh/m^2	Industrial practice based on 4 hours daily sun radiation for 270 days a year at 4.5 kW/m^2 annual and 80 % efficiency
Total area collector	405,718	m^2	
Installed capacity of solar thermal	1,826	MWth	1 m^2 = 4.5 kW solar thermal installed capacity

Integration of Solar Heat into Industrial Process

Integration of solar heat into industrial process involves a complex operation than the conventional heat supply system. It requires studying and analyzing the existing heat supply system and determining the potential energy savings, energy flows and temperature levels of the process that could lead to optimizing the economic, technical and energy impact of the system (Cottret, 2010).

There are several ways of solar thermal that can be integrated into the industrial process. First, since the central system for heat supply in industry is providing hot water or steam at a pressure corresponding to the highest temperature needed among the different processes (180 ^oC - 260 ^oC), thus, solar systems can be integrated with the conventional heat supply system for preheating water used for processes or for steam generation (Kalogirou, 2003). In this conventional heat supply system, the solar thermal can also be directly coupled to an individual process that has a lower temperature than the central supply (Kalogirou, 2003). These are shown in Figure 5.

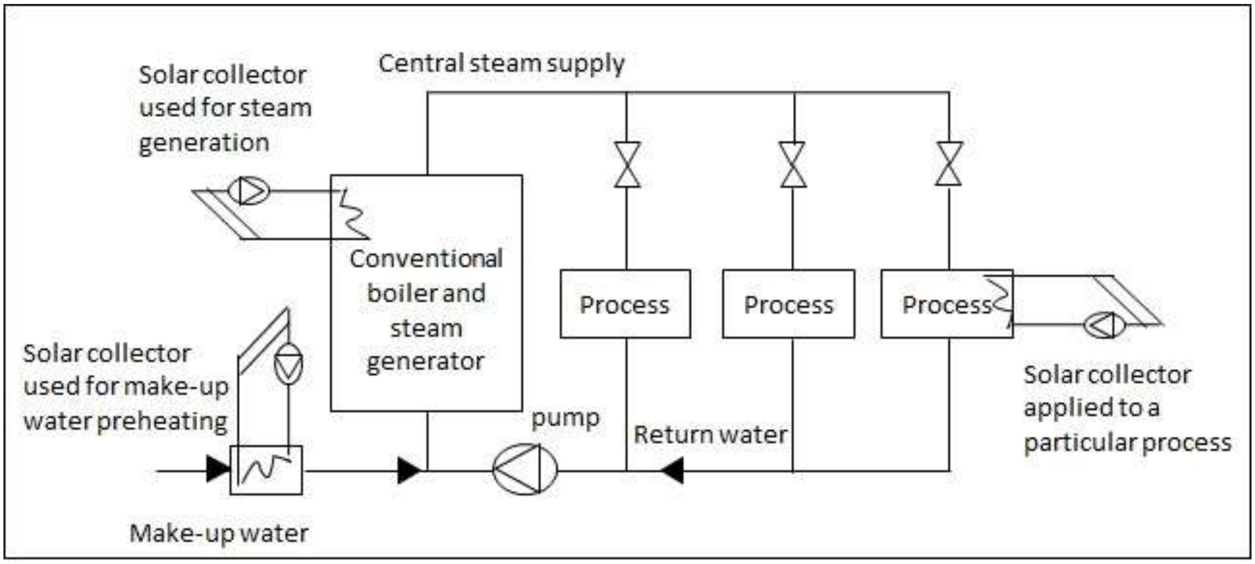

Figure 5. Solar thermal integration in the conventional heat supply system (Kalogirou, 2003)

Solar thermal can also be integrated directly into existing heating system of the industrial process (Cottret, 2010) as shown in Figure 6. For this integration to be working properly, it requires the solar system operates at the same temperature as the existing heating system. Another possible way of integrating solar system in the conventional heat system is to integrate it directly to the process heat (Cottret, 2010) as shown in Figure 7. Such integration requires another heat transfer if the temperature from the solar collectors is different from the temperature of the heating medium.

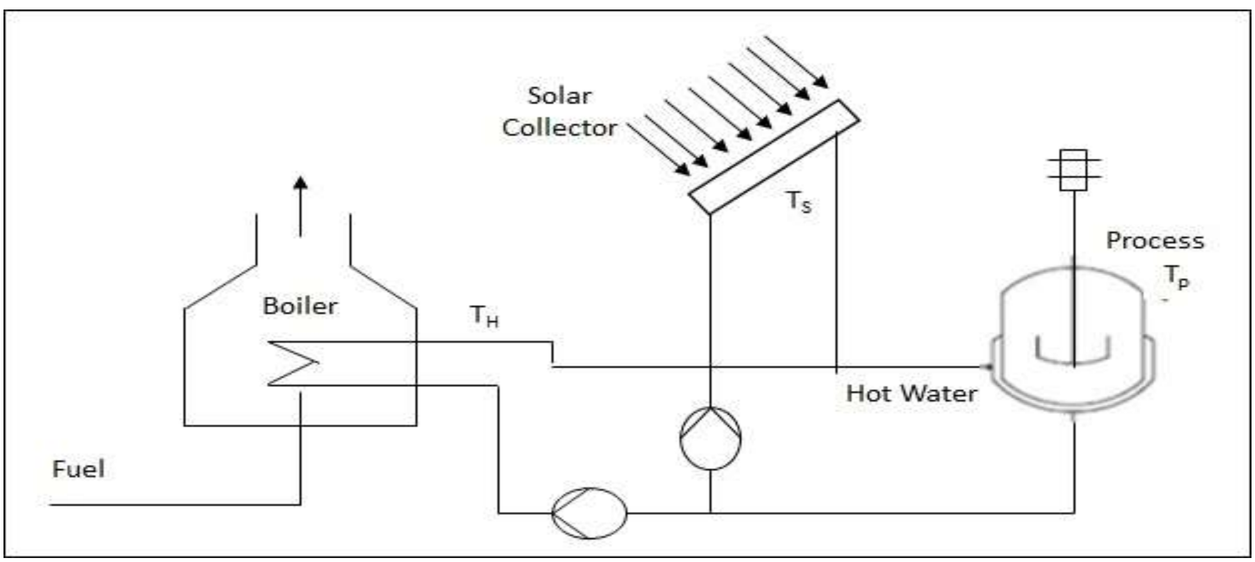

Figure 6. Solar thermal integration directly to the existing heating system (Cottret, 2010)

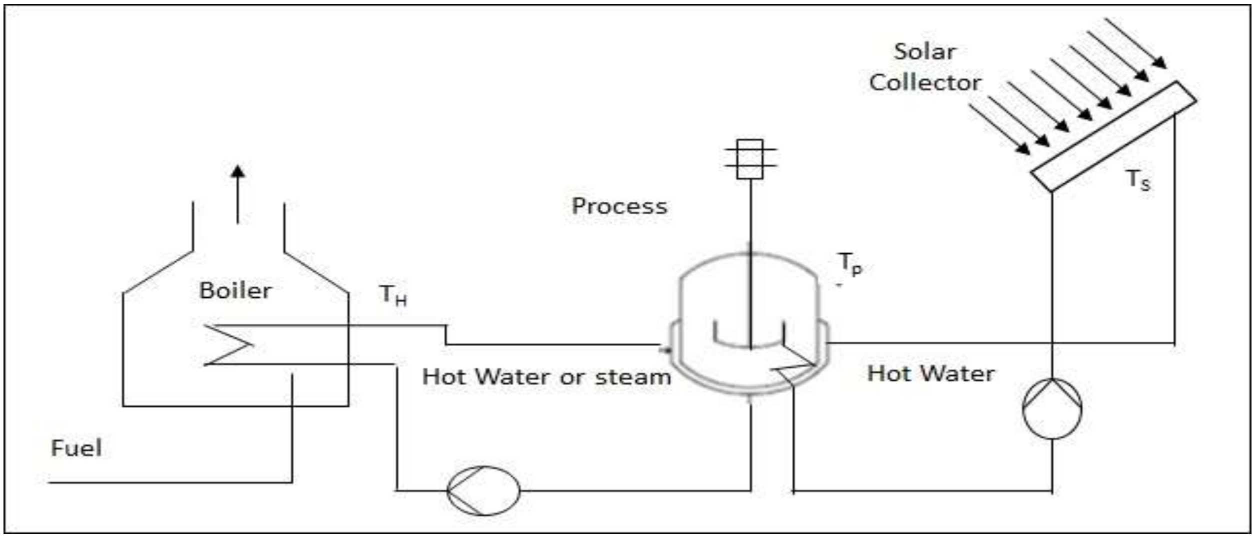

Figure 7. Solar thermal integration directly to the process heat (Cottret, 2010)

A guideline to integrate solar heat into industrial process has been developed by IEA Solar Heating Cooling (SHC) in Task 49 (Muster, 2015). More theoretical analysis on solar heat integration in industry can be found using mathematical model and pinch analyses for fish can industry in (Quijera, 2013; Quijera, 2014) and dairy industry in (Schnitzer, 2007; Quijera, 2011), using static model for textile industry in (Freina, 2013) and using transient analysis for brewery in (Lauterbach, 2014) and dairy industry in (Walmsley, 2015).

DEMONSTRATION OF SOLAR THERMAL PLANTS FOR LOW AND MEDIUM TEMPERATURE PROCESS HEAT

In this section, four solar process heat plants installed worldwide at various type of industries for low and medium temperature application are presented. These demonstration plants are gathered from the database for applications of solar heat integration in industrial processes created by AEE INTEC (INTEC, 2015).

Fleischwaren Berger Solar Thermal Plant For Meat Industry, Austria

A 746.9 kW_{th} solar thermal capacity has been installed by Fleischwaren Berger CmbH & Co. KG in 2013 for processing and preserving of meat and production of meat products. The installation uses flat plate collector and occupies 106.7 m^2 gross installed collector area in Sieghartskirchen, Austria (Figure 8). The produced thermal energy is used for feed water preheating (30 °C up to 95 °C) for steam production and ham cooking and hot water preheating from about 40 °C up to 70 °C for drying the air conditioning systems. The point of solar heat integration is at point A1- integration on supply level for heating of make-up water as in Figure 9.

Figure 8. 746.9 kW_{th} solar thermal plant for meat industry in Austria (INTEC, 2015)

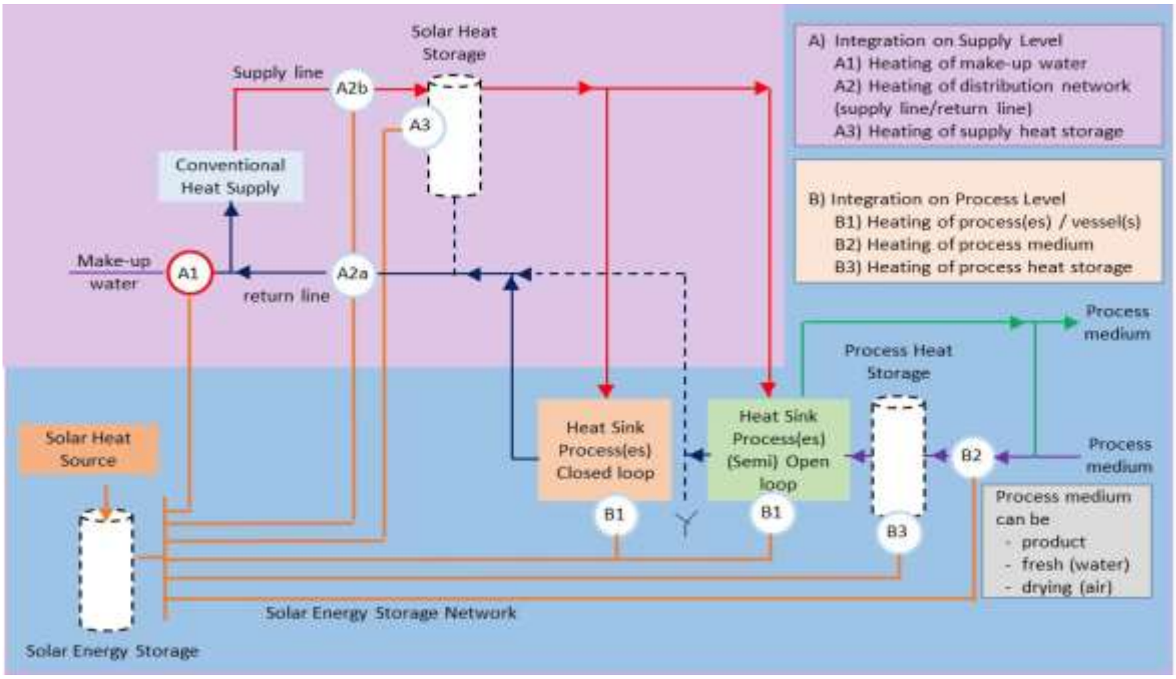

Figure 9. Solar heat integration point for Fleischwaren Berger plant (INTEC, 2015)

Goess Brewery Solar Thermal Plant for Beverage Industry, Austria

A 1,064.0 kW_{th} solar thermal capacity has been installed by Brauerei Goss in 2013 in a beverage manufacturing industry. The solar collector is a flat plate type with gross installed collector area of 1,520 m^2 in Brauhausgasse, Austria (Figure 10). The solar heat integration is in mashing process and make-up water for temperature process between 80 ^oC to 90 ^oC. The point of solar heat integration is at point B1- integration on process level for heating of process/vessel as in Figure 11.

Figure 10. 1,064 kW_{th} solar thermal plant for beverage industry in Austria (INTEC, 2015)

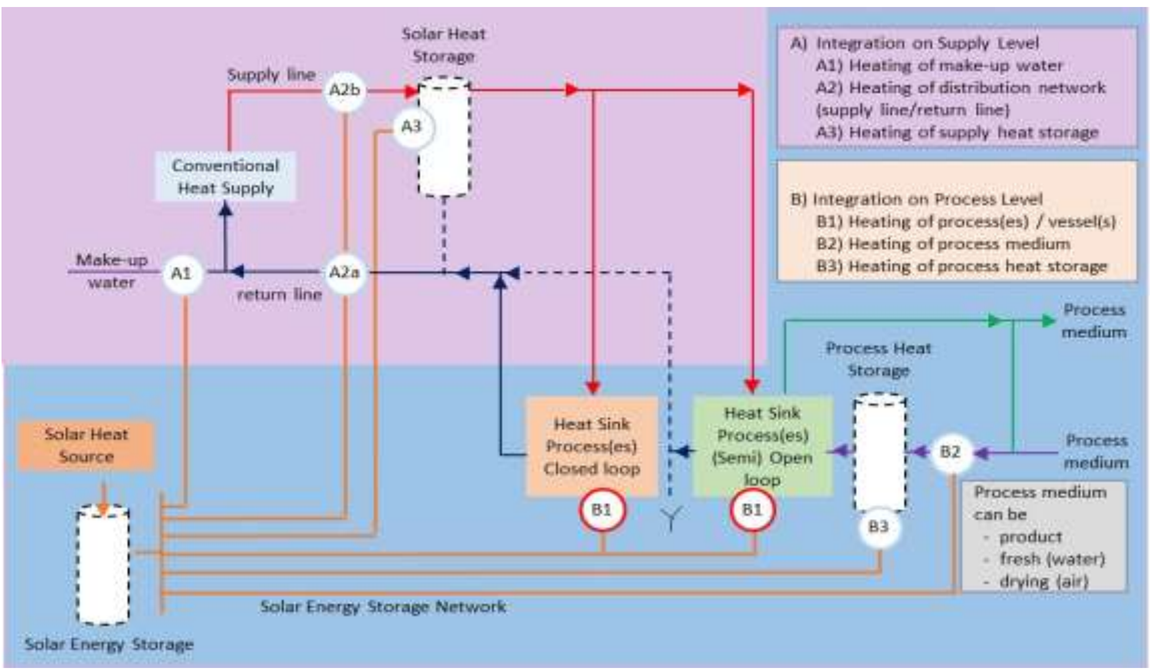

Figure 11. Solar heat integration point for Goess Brewery Plant (INTEC, 2015)

Harita Seating Systems Solar Thermal Plant for Transportation Industry, India

Harita Seating Systems has installed a 360 kW_{th} solar thermal system in 2015 in a transport manufacturing industry. The system uses evacuated tube collector with gross installed collector area of 754.8 m^2 in Belagondapalli, India (Figure 12). The point of solar heat integration is at point B1- integration on process level for heating of process/vessel as in Figure 13. The integration involves installing erecting coil type heat ex-changer inside the process tanks. The produced thermal energy is used for cleaning automobile parts before painting at the temperature range process of 50 °C to 60 °C and temperature range solar loop of 70 °C to 95 °C.

Figure 12. 360 kW_{th} solar thermal plant for transportation industry in India (INTEC, 2015)

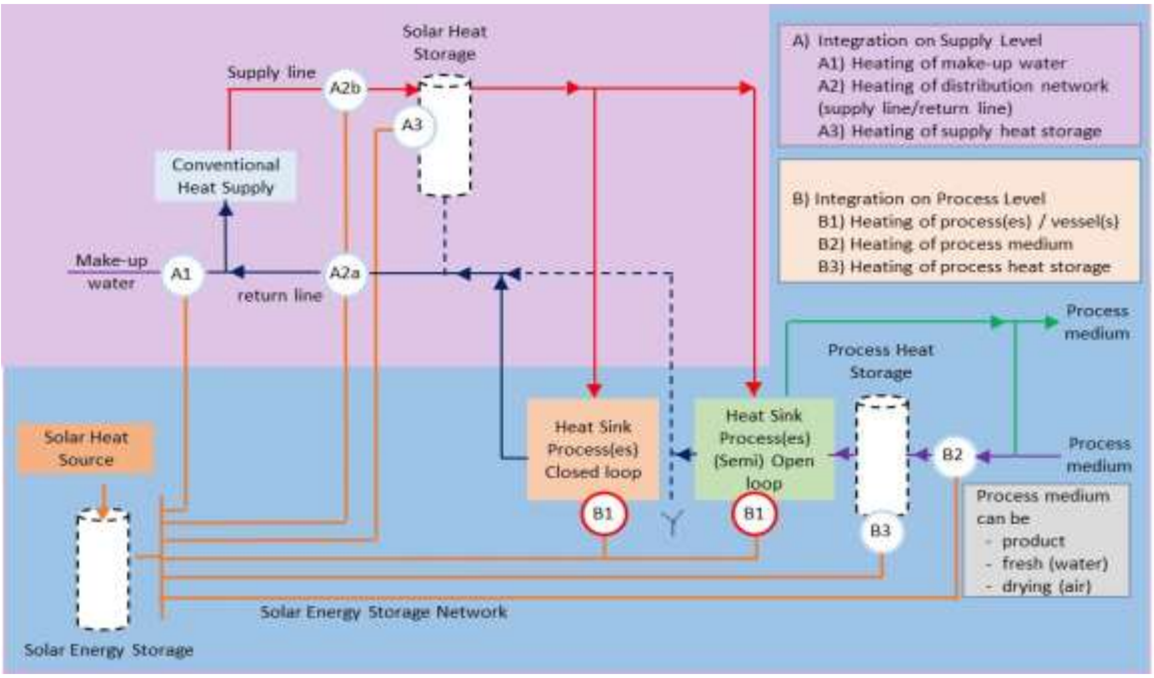

Figure 13. Solar heat integration point for Harita Seating Systems Plant (INTEC, 2015)

Zehnder Group AG Solar Thermal Plant for Machinery and Equipment Industry, Switzerland

Zehnder Group AG has installed a 276.64 kW_{th} in 2012 in a machinery and equipment manufacturing industry. The installation uses evacuated tube collector with gross installed collector area of 395.2 m^2 in Aargau, Switzerland (Figure 14). The produced thermal energy is used for heating of the pretreatment washbasins of the coating device. The integration point is at supply line i.e. point A2b – heating of distribution network as in Figure 14. The temperature solar loop is 90 ^oC out of the collector.

Figure 14. 276.64 kW_{th} solar thermal plant for machinery and equipment industry in Switzerland (INTEC, 2015)

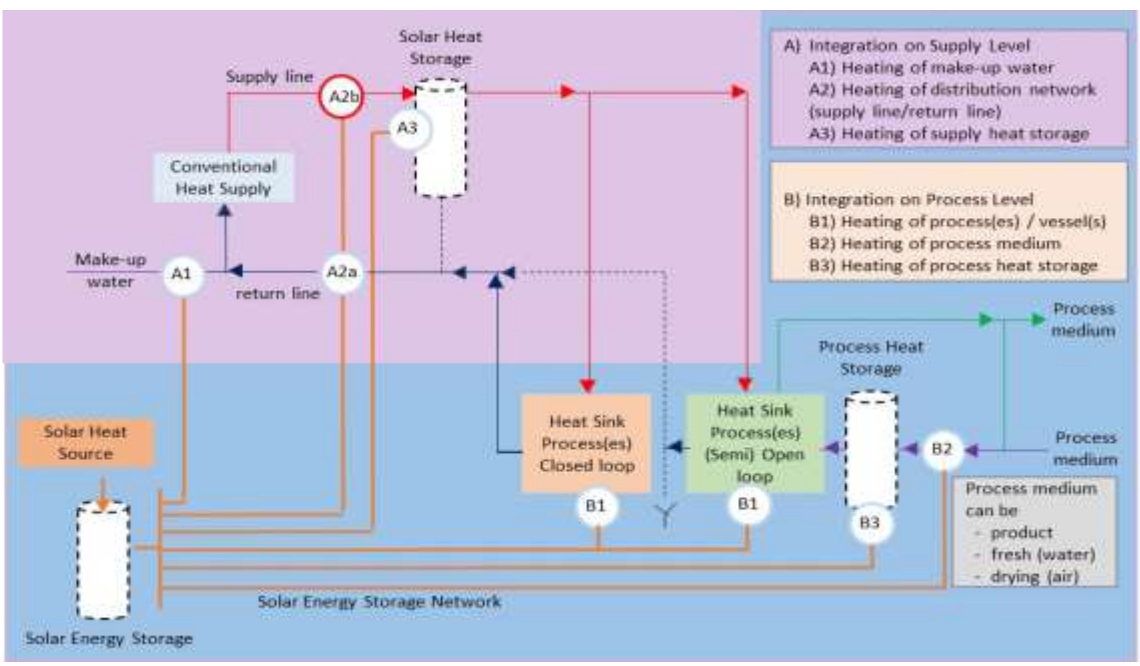

Figure 15. Solar heat integration point for Zehnder Group AG plant (INTEC, 2015)

CONCLUSION

Malaysia has a big potential to implement solar heat for industrial process. This is due to the fact that Malaysia is located at the equatorial region that receives numerous sunlight throughout the year. Furthermore, a significant share of the final energy demand in Malaysia i.e. 26.2 % in 2013 was used by industries. From this figure, 67 % of the energy use in industries is for heating. An enormous impact on the fuel savings and CO_2 emission reduction can be generalized if some of the shares of the heating demand in industries are supplied by solar energy. From the reviews, low and medium temperature solar process heat are suitable for industrial sectors in Malaysia due to most of its industrial energy demand are from chemical and food industries where most of the processes involve low and medium temperature. Three types of solar collectors can be used for low and medium temperature of process heat namely 1) flate plate collector, 2) evacuated-tube collector and 3) non-tracking and one axis parabolic trough collectors. Solar thermal can be possibility integrated into the industrial process heat using three mechanisms: 1) in the conventional heat supply system (preheating water and steam generation) or directly coupled to individual process, 2) directly to the existing heating system and 3) directly to process heat.

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