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Prospect of Solar Thermal Integration for Multiple Processes in Oleochemical and Poultry Industries

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The implementation of solar thermal technology in the industries has huge potential in a tropical region due to abundant solar radiation. Getting limitless source of sunlight throughout the year is not a guarantee for solar thermal to be implemented in industries as many factors from the demand and supply sides need to be considered. These include process heat demand profiles, solar intensity, weather patterns, types and capacity of the solar thermal system, site suitability, and availability. This paper presents the establishment of a process heat demand profile to examine the potential of solar thermal integration in oleochemical and poultry industries in Malaysia. A systematic method for matching the solar energy supply under variable climatic conditions with an appropriate heat demand profile leads to improved design and created an optimal operating strategy. Two illustrative case studies are demonstrated to highlight the potential of solar thermal integration at the process and product sides in oleochemical and poultry industries, which provide significant progress towards fossil fuel and emissions reduction. The results revealed that the increase of process demand needs to be accommodated with bigger thermal storage tanks and larger solar collector area to achieve and maintain high solar fraction. The increase of investment cost was offset by larger energy savings and concluding all the simulated scenarios had their payback period within 13 to 18 y.

1. Introduction

The global demand for energy is increasing sharply due to increased population, greater industrial outputs, and radical changes in the patterns of consumption. The global energy demand is expected to increase by 30 % by 2040 (Islam et al., 2019). The higher consumption of fossil fuels leads to higher greenhouse gas emissions that contribute to global warming. The huge energy consumption in industrial processes and the serious environmental problems caused by the combustion of fossil fuels have encouraged companies to reduce the dependence on fossil fuels in industrial processes (Oh et al., 2018). These situations increase the demand for more sustainable and renewable energy solutions and cost-effective measures for sustained global growth. Currently, the industries are trying to shift traditional energy supplies to renewable energy-based industrial systems to increase the profitability of the market, and to reduce the costs of fuel and the associated environmental pollution.

Various new technologies have been introduced in industries. Solar energy receives the most attention among all types of renewable energy, as the most promising alternative to be implemented in industrial processes. Solar energy is free, clean, and does not cause environmental pollution and emissions. The implementation of renewable energy to industrial processes particularly solar energy is indeed highly important. Solar energy is the radiant light and heat from the sun that is harnessed using a range of ever-changing technologies such as solar photovoltaics, solar thermal energy, and concentrating solar power (CSP). Solar thermal energy uses the sun's energy to heat up a fluid to a higher temperature, then the heated fluid moves and heats water creating steam. The vapour is converted into mechanical energy and generates electricity.

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1.1 Solar thermal integration in industries

There is a significant amount of research on solar equipment (Kalogirou, 2004). The selection of appropriate type of solar collector and the optimum size of solar thermal collector to meet the designed temperature is essential. Suitable selection of solar thermal technologies can be implemented by identifying the energy profile in the industry. The temperature range profile of tropical climate processes such as those in Malaysia 's industry is unfortunately not available in the literature. There are comparatively fewer studies on the optimal integration of solar technologies with industrial sites. Solar thermal process was integrated by Atkins et al. (2010) for a milk powder factory where the authors focused on solar collector performance based on solar radiation, collector fluid temperature, and mass flow rates. Quijera et al. (2014) studied the viability of a tuna canning factory for the integration of solar thermal systems and heat pumps into the energy structure based on mathematical models and Pinch Analysis. Baniassadi et al. (2015) applied the heat integration concept for an organic distillation plant to identify the solar fraction targets for several collector areas and also established a tool for the economic analysis of solar heat integration. Sing et al. (2018) proposed a method to optimise solar heat integration for different process conditions to minimise the levelised cost. The authors demonstrated a combined method from the literature using a case study and found that the integration with hot water for the clean-in-place stream produced the lowest cost of heat. Sing et al. (2020) presented a method for the optimisation of solar thermal integration using a case study based on the meteorological data in Malaysia. The authors reported that the solar thermal integration for hot water gave the lowest levelised cost of heat with RM 0.63/kWh (0.13 EUR/kWh). The study did not consider the integration for multiple process heat demand.

To address these issues, this paper presents the establishment of a process heat demand profile to explore the capacity of solar thermal integration through a systematic method. This method is used for matching the solar energy supply under variable climatic conditions in Malaysia to enhance the design and optimise the operating strategy. This method is also applied to the selected industry as a case study to illustrate the potential of solar thermal integration on the process and product sides in oleochemical and poultry industries that show substantial progress towards reducing fossil fuels and emissions.

1.2 Heat demand profile for oleochemical and poultry industries

Malaysia is a Southeast Asian country with a promising development for solar energy due to its climate, which has a high level of irradiance. The abundant source of sunlight is suitable for the oil palm plantation industry, which becomes an important commodity for the country. Malaysia currently accounts for 28 % of world palm oil production and 33 % of world palm oil exports (MPOC, 2017). There are several key processes to obtain various end products, including milling, palm kernel crushing, refining, and oleochemical production. These processes require heat supply to produce food and non-food products. Prior to implementing solar thermal technology, it is vital to overview the current type of energy source used and the heat demand profile. The heat demand for refineries and oleochemical industries is higher, in the range of 80 – 260 °C for the refining process and up to 300 °C for the oleochemical industry (Shahidi, 2015). The poultry industry also utilises a huge amount of energy for the heating process. For example, the scalding process for the removal of chicken leather requires a scalding tank with a temperature between 60 and 70 °C. Figure 1 shows the temperature range in the palm oil and poultry sectors. Solar technology can be selected based on the heat demand profile and the existing energy source.

2. Potential of solar thermal integration in industries

The heat demand profile of an industry is essential to select the appropriate type of solar collector and the optimum size of solar thermal collector to meet the designed temperature. The heat demand can be fulfilled by using solar thermal energy with the aid of thermal storage or integration with the existing heat supply. The general methodology of this study is shown in Figure 2. The method consists of four main stages. The first stage is the determination of solar energy supply variability to match the heat demand profile. The expected outcomes from Stage 1 are the data on energy demand and the simulation data for the solar thermal system. The second stage is the synthesis and design of the solar thermal system. It includes synthesising the best solar collector and its installation area, and also identifying the optimum size for thermal storage based on the process load and the solar irradiance profile. The proposed methodologies will be performed using Solar Heat for Industrial Processes (SHIP) design and analysis tool developed by AEE - Institute for Sustainable Technologies (AEE INTEC, 2020). The tool is used to design and analyse solar heat in the industrial process that requires various considerations. The tool can also be used to determine the yearly analysis of the proposed design based on the climate and hourly process demand. The simulation will consist of different scenarios by manipulating the process heat load using different collector field areas and thermal storage volumes to achieve a higher solar fraction. The third stage is the techno-economic analysis, followed by the measurement and verification process of the designed system in the fourth stage.

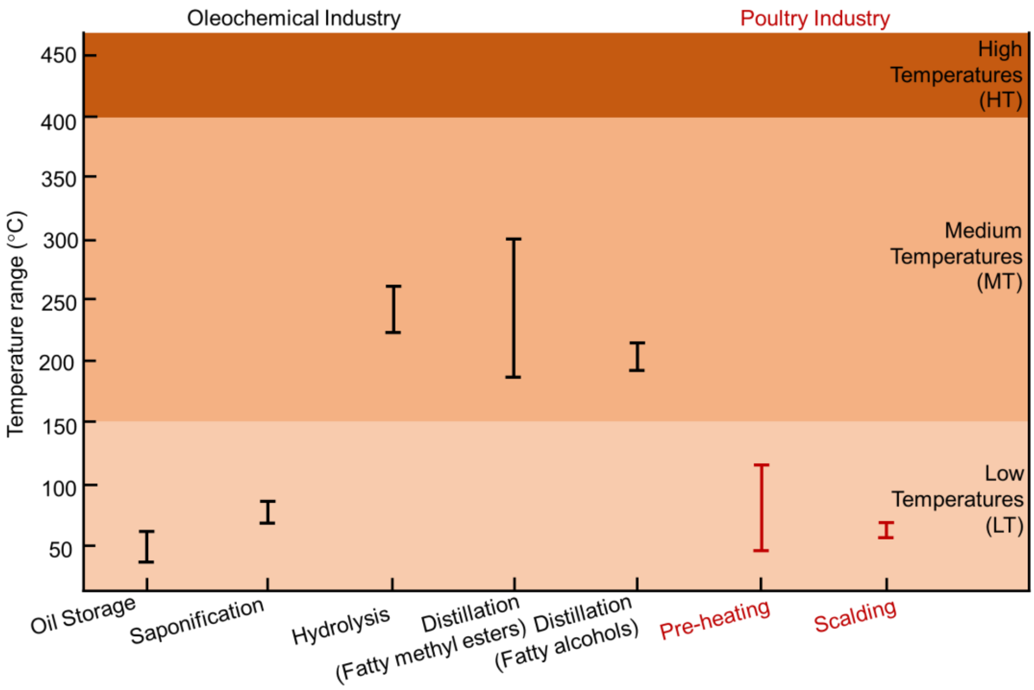

Figure 1: The heat demand for main processes in palm oil and poultry sectors by temperature ranges

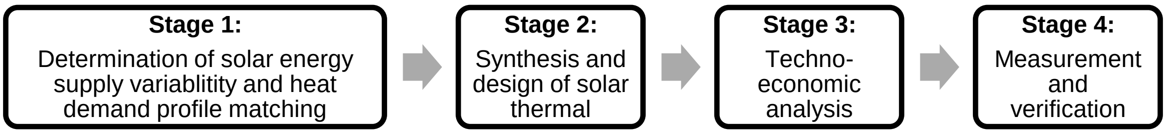

Figure 2: General methodology for solar thermal integration

The estimation of thermal energy requirement (i.e., heat demand), $Q_{process}$, in kJ/t of product can be performed by using Eq(1), based on the work by Suresh and Rao (2017):

$$Q_{process}\ (kW) = [M \times C_p \times (T_{avg} - T_{in})] \quad (1)$$

where C_p is the specific heat of water or air (kJ/kg/K) and T_{in} is the fluid inlet temperature. The steps for estimating the thermal energy requirement in any industry are as follows:

Step 1: Identify the number of processes required for thermal heating.

Step 2: Calculate the average operating temperature for each process, T_{avg} (°C).

Step 3: Calculate the hot water/hot air requirement for each process, M, as L/t of product.

The energy demand specifically to maintain the storage tank temperature can be calculated using Eq(2):

$$Q_{storage} = \frac{[A \times (\frac{1}{R}) \times \Delta T \times SF]}{3412} \quad (2)$$

where the surface area (A) is calculated for the round tank (ft^2), R is the value of the insulation, and the value of 0.5 is used if the steel tanks are uninsulated. The temperature difference (ΔT) is the difference between the process setpoint temperature and the lowest ambient temperature. SF is the safety factor and its recommended value is 1.2. The value 3,412 is used for the conversion of BTU to kW. The type of solar collector necessary for the intended process application can be identified through its required operating process temperature range. The selection of the most appropriate solar collector is determined experimentally by plotting and analysing the solar collector's efficiency curve. The efficiency of each solar will be evaluated using Eq(3) (AEE INTEC, 2020).

$$n_{coll} = (c_o - c_1)\left(\frac{T_{m,coll} - T_a}{G} - c_2\right)\left[\frac{(T_{m,coll} - T_a)^2}{G}\right] \quad (3)$$

The average collector internal fluid temperature ($T_{m,coll}$) is assumed to be the average of the collector inlet and outlet temperature, and T_a is the ambient air temperature. c_o is the maximum efficiency, c_1 is the linear heat loss coefficient W/(K·m²), and c_2 is the quadratic heat loss coefficient W/(K·m²). The average daily solar radiation data, G (W·m²) for any site can be obtained from the PV-GIS website. The website provides hourly radiation data after specifying the mounting type, slope, and azimuth (PV-GIS 2017). The values of c_0, c_1, and c_2 depend on the solar collector, and its values are obtained from the datasheet of the manufactured solar collectors. The solar collector output per area (E_{coll}) is calculated hourly using Eq(4). If the amount of solar radiation (G) is too low, the solar collector efficiency becomes a negative value, and the solar collector output per area (E_{coll}) for that hour is assumed to be zero.

$$E_{coll} = n_{coll} \times \mathrm{G} \quad (4)$$

The required solar collector field size (A_{coll}) for the process heating is calculated using Eq(5):

$$A_{coll} = \frac{\text{Daily Energy Demand}}{Total\ E_{coll}\ in\ a\ day} \quad (5)$$

The volume of thermal energy storage ($V_{storage}$) can be determined using Eq(6):

$$V_{storage} = \frac{\mathrm{Q}_{storage} \times 3600}{\rho \times c_p \times (T_{max} - T_{ave})} \quad (6)$$

where $Q_{storage}$ is the storage capacity required, c_p is the heat capacity of the storage medium, ρ is the density of the storage medium, T_{max} is the maximum storage temperature, and T_{ave} is the average storage temperature. The simulation is performed to determine annual energy gains. Economic analysis will be conducted for the parameters of annual final energy savings, payback years, and levelised cost of heat (LCoH) for categorised scenarios. Finally, performance verification can be performed to verify the performance of the solar thermal system with respect to the design specification, energy demand, and energy supply. The verification process can be performed to calculate the solar fraction to analyse the actual energy provided by the solar thermal system. The equation for the solar fraction is shown in Eq(7).

$$\text{Solar Fraction} = \frac{\text{Amount of Energy Provided by Solar Thermal System}}{\text{Total Input Energy Required}} \quad (7)$$

2.1 Case study on the oleochemical industry

The first case study involves a processing plant that utilises crude palm oil (CPO) as the feedstock, refined bleached deodorised palm oil (RBDPO) as its major product, and palm fatty acid distillate (PFAD) as its by-product. The integration and configuration of the solar thermal system for this case study focus on the supply level, which involves several storage tanks of oleochemical by-products. The solar thermal system is proposed to be integrated at the PFAD product tank farm to maintain its temperature at 65 to 70 °C. The temperature range of this process suits this purpose. The solar thermal system will be integrated with waste heat recovered streams to produce hot water at the range of 100 to 110 °C. The hot water will act as a heating medium for the PFAD tank farm and it will be stored in the thermal storage tank.

2.2 Case study on the poultry industry

In the second case study, a solar thermal systems is proposed as a backup for heat generation from electric boilers to supply the heat in the scalding tank. The components that involve in the solar thermal system are including solar collector systems, hot water storage, and auto-regulated heat exchangers. The system consists of two main streams which are solar stream and hot water stream. Both streams are closed loop. The solar thermal system cycle is starts by heating water as the working fluid. The water heats up from 30 to 120 °C and flows through pipes to the plate heat exchanger. The heat exchanger is used to transfer heat from the stream of solar collectors to the flow of cold water. The storage tank serves as a medium for storing heat for use when the solar thermal system is unsuitable for heat generation due to certain climatic conditions such as low irradiation and night time. The fixed point water temperature inside the storage tank is at 70 °C.

3. Results and discussion

3.1 Solar thermal integration in the oleochemical industry

Table 1 shows the evaluation of the energy demand for the tank farm and the calculated daily process demand. It is important to consider the pattern of heat requirement in the process and the distribution of solar radiation over the course of hours in the area. Figure 3 shows the scenarios simulated through SHIP design and analysis tool. By varying the number of tanks into three categories, which are one tank (75 kW), three tanks (224 kW), and seven tanks (523 kW), the effect of energy load on the solar thermal system efficiency can be analysed. Two more sub-scenarios were simulated for each category. The first simulation was based on a fixed thermal storage tank (20 m^3) and the second simulation was based on a fixed solar collector area of 50 × 30 m^2. Table 2 shows that the annual final energy savings increased by using a larger thermal storage tank and more mounted collectors. The payback period for all six scenarios is over 13 y, and Scenario 2 recorded the highest payback period. This is because Scenario 2 has high stagnation compared to other scenarios.

Table 1: Evaluation of the main variables and the energy demand for the tank farm

Variables	Unit	Value
Inlet Temperature, T_{out}	°C	70
Ambient Temperature, T_a	°C	30
Area	m^2 per tank	247
Maintain Heat	kW per tank	74.74
Total (7 tanks)	kW	523.4
Daily Energy Demand	kWh/d	12,552
Yearly Energy Demand	kWh/y	4,568,928

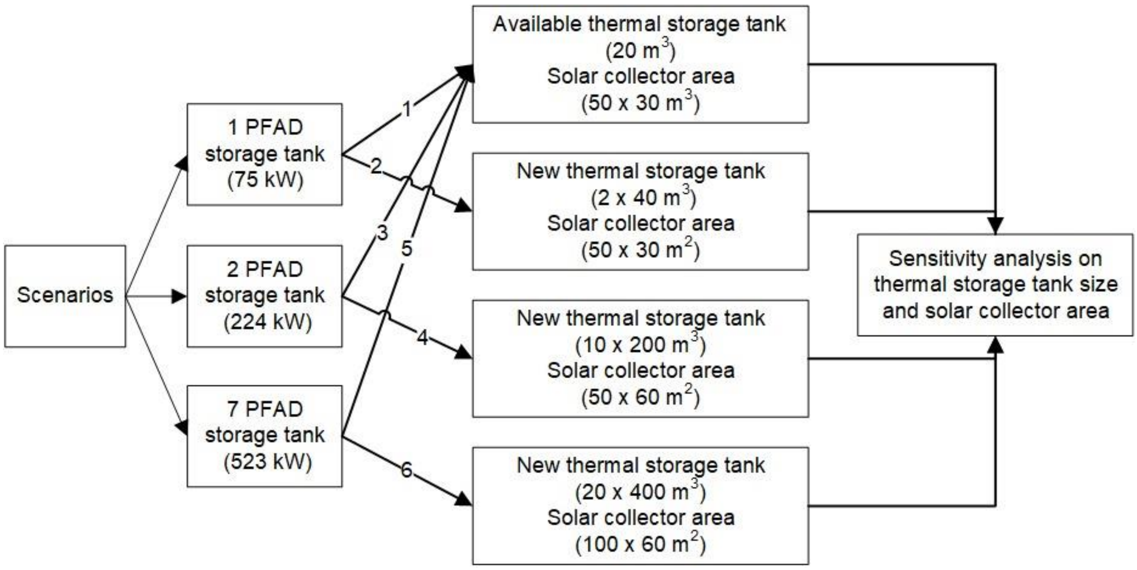

Figure 3: Algorithms for the scenarios simulation approach in the SHIP design and analysis tool

Table 2: Economical values of the PFAD storage tank

Scenarios	1	2	3	4	5	6
Investment costs [MYR]	881,337	2,647,925	2,566,381	5,295,851	2,566,381	11,073,142
Annual final energy savings [MYR/y]	51,658	86,427	114,163	254,611	147,274	563,791
Simple payback [y]	14.9	24.5	18.0	16.6	13.9	15.7
LCOH [MYR/MWh]	144	236	173	160	134	151
NPV [MYR]	-234,957	-1,473,805	-976,177	-1,731,268	-483,573	-3,152,441

3.2 Solar thermal integration in poultry industry

The poultry industry requires heat energy with a temperature between 60 and 70 °C in a scalding tank for the removal of chicken leather. The real-time heat supply by the solar collector and low temperature required by the process were analysed. The solar thermal system is integrated at the scalding process to support the electric boiler by heating. Details of the calculated energy demand are shown in Table 3. The energy supply for the process is the energy provided by the solar thermal and electric boiler. Energy demand is the energy required or losses caused by various factors. The calculation of solar fraction was verified to analyse the actual energy provided by the solar thermal system. The average solar fraction is approximately 88 %. The solar fraction has significant potential to be increased, such as by adding an additional hot water storage tank, increasing the current storage, isolating the hot water store, and reusing the water from the scalding cycle to preheat the fresh water entering the store.

Table 3: Evaluation of the main variables and the energy demand for the scalding tank

Variables	Unit	Value
Solar heat delivery annually	kWh	99,598
Collector aperture area	m^2	118.95
Daily energy demand	kWh/d	329
Yearly energy demand	kWh/y	102,648

4. Conclusions

Solar thermal heat can provide an attractive alternative energy source to many industries in tropical countries. Its application largely depends on the space available for solar collectors and the heat demand of its intended process. SHIP design and analysis tool was used to evaluate the trade-off between increasing the heat demand in case studies for oleochemical and poultry industries, and varying the available area to install solar collectors and identifying whether the energy supply is sufficient to accommodate the process demand. The results showed that the available thermal storage tank was only able to support the demand for one PFAD storage tank and an increase in the demand would lower the efficiency of the solar thermal system. The highest annual energy savings were recorded for Scenario 6, approximately 86 % based on collector's gross area, but the scenario also had the highest process load and investment cost. In short, the higher the process demand, the larger the thermal storage unit needed, and also a higher number of solar collectors. For all the scenarios tested, the payback period is over 13 y, although the final energy savings are relatively high. The energy demand and solar fraction for the poultry case study were calculated, 88 % of energy could be saved by using the solar thermal system. Further research is needed to identify the effects of process demand, process temperature range, and different collector types on the economic vialibity of an industrial integrated solar thermal system.

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