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Effect of Solar Utility Temperature to Costing and Design Parameters of Integrated Solar Thermal System

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The objective of this research is to evaluate the trade-off between solar utility temperature and solar collector efficiency, in the context of Malaysia, and also evaluating the proposed system efficiency and economic feasibility. Since Malaysia receives an abundance amount of solar radiation throughout the year, generating thermal energy from solar thermal energy system is highly attractive. In the illustrative case study, flat plate collector (FPC) and compound parabolic collector (CPC) were used for evaluation of integration with different temperature process. For each process, configuration with and without HEX were evaluated. Generally, solar collector cost for configuration with HEX is more than configuration without HEX, solar collector cost will be lower when solar utility temperature is lower, and effect of solar utility temperature variation affect more on FPC than on CPC. The results show that annual saving is 174,952 MYR/y. The payback period for all processes vary from 4.7 to 7.6 y.

1. Introduction

The generation of energy by consumption of fossil fuel resources has led to global warming and climate change. Eventually, the overall temperature of the atmosphere will be increased, negatively affecting the environment and mankind himself. Renewable energy technologies have an enormous potential in the world. Among all renewable energy, solar energy has the potential to sufficiently satisfy the energy demands of the entire world only if technologies for complete solar energy harvesting are available (Blaschke et al., 2013). Low pollution, low maintenance effort and high reliability also made solar energy a promising source of energy to be used in the future (Saidur and Mekhilef, 2010).

Malaysia is located in the equatorial region and has a tropical rainforest climate where the weather is hot and humid all year. That means Malaysia receives higher solar radiation than most of the other country in the world, monthly solar radiation received in Malaysia is about 400 – 600 MJ/m^2 (Mekhilef et al., 2012). Generating thermal energy from solar thermal energy system in Malaysia is highly attractive. Among the solar energy harnessing technologies, solar thermal energy system, with its niche area in supplying the low grade thermal heat (80 to 100 °C), has a great potential to reduce the fossil fuel dependency and carbon footprint in industry sector. In the context of Malaysia, the industrial sector of Malaysia contributes to the 26.2 % of the total final energy demand in 2013, which was approximate 2,160 PJ (Malaysia Energy Commission, 2014). Among the total final energy used in industry, 67 % is contributed by thermal energy. Given the fact that 30 % of the total industrial process heat demand requires temperature below 100 °C, solar energy has a significant industrial market in Malaysia (Sohif and Hafidz, 2015).

While a significant amount of research work has been commenced on the subject of solar equipment (Kalogirou, 2004), a relatively small amount of research has been conducted into the optimal integration of solar technologies with industrial sites (Schnitzer et al., 2007). For example, Nemet et al. (2012) developed a

procedure based on the combination of time slice of solar thermal supply profile and thermal heat load profile for integrating solar thermal energy, this study only considered combination of solar energy supply and energy demand by process in time slice but not the temperature of solar energy supply and temperature required by process. Walmsley et al. (2015) investigated three general methods for integrating solar thermal system into a Heat Recovery Loop (HRL) by using a New Zealand dairy factory case study. This study fixed a supply temperature for solar collector for all the process and done composite curve graph to show maximum and average solar heating target. Allouhi et al. (2017) investigate the utilization of a centralized solar water heating system in a milk processing industry located in Casablanca. This study mainly focused on the effect of solar collector area, tilt angle, and storage tank volume to the economic feasibility.
Based on the literature review, several research gaps could be identified. Firstly, there is lacking study to consider temperature range of solar collectors for the specific process requirement. The temperature range of the process must be fulfilled to ensure the quality of the finished product, for this reason, selection of design temperature range of solar collectors is essential in integration of solar thermal system for process heating. Secondly, there is lack of study on the application of solar thermal energy system in the context of Malaysia. Depending on the local meteorological data, it may affect the energy saving potential of different solar integration strategy. Lastly, there is lack of study about the effect of solar utility temperature to the design parameters and economic feasibility. With different solar utility temperature, it will affect the solar collector efficiency, and affect the design parameters and costing of entire system.
The objective of this article is to evaluate the trade-off between solar utility temperature and solar collector efficiency, in the context of Malaysia, and also evaluating the proposed system efficiency and economic feasibility.

2. Method

The method is shown in Figure 1. The method is divided into two general parts. The first part is identification of the potential streams for the solar thermal integration and the second part is the evaluation of the integration configuration.

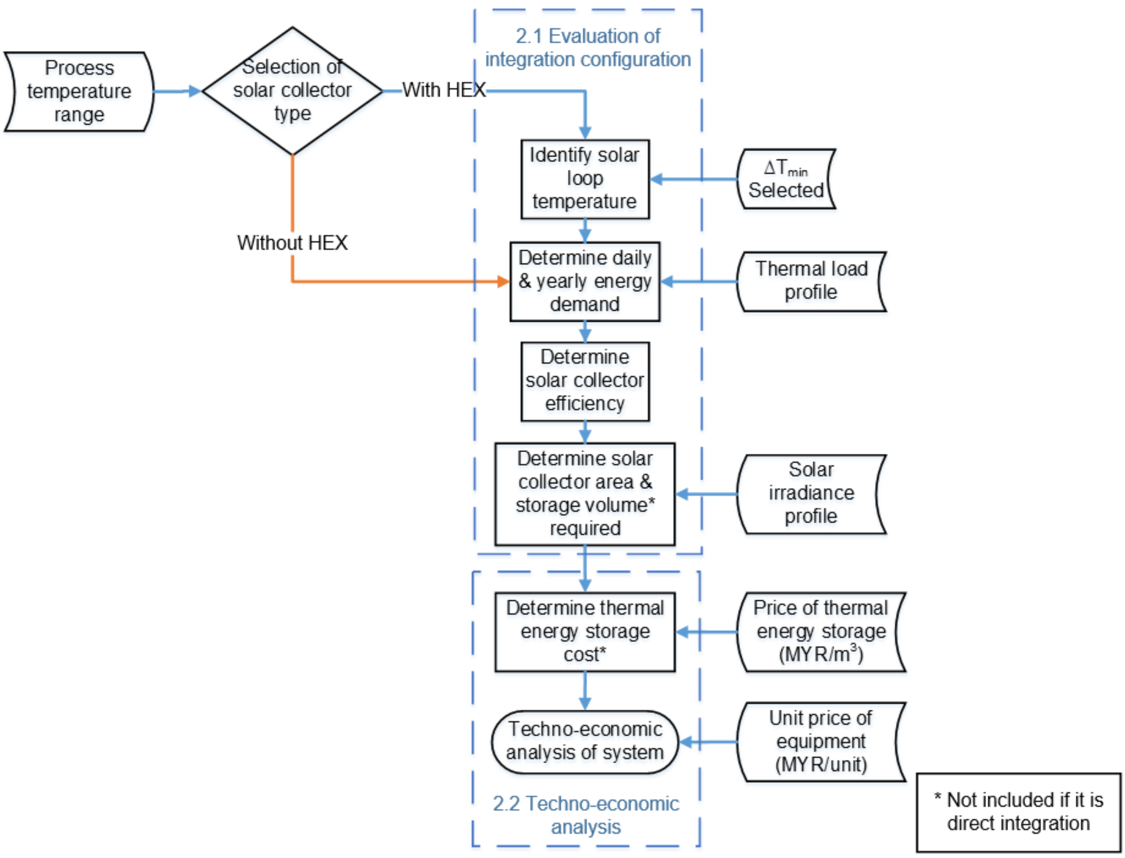

Figure 1: Flow chart of proposed method

2.1 Evaluation of integration configuration

Firstly, suitable solar collector is selected based on the required temperature range of the process. Three different general configurations are evaluated in this research and are shown in Figure 2.

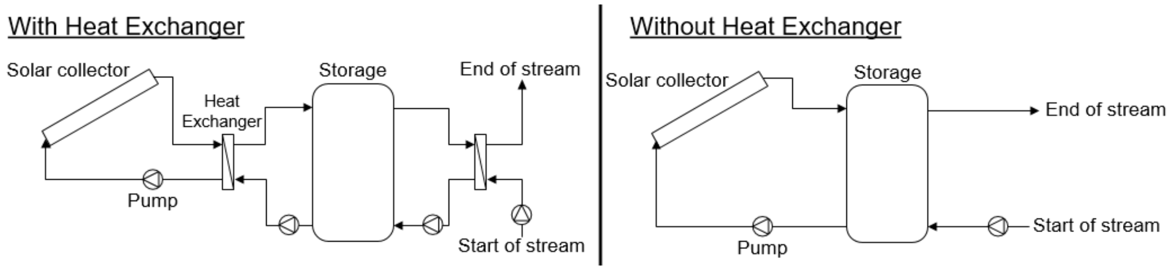

Figure 2: Evaluated integration configurations

The configuration with two heat exchangers is recommended when the process medium, storage medium, and the solar heat transfer fluid are all different, similar configuration has been used in brewery industry in Germany (Lauterbach et.al, 2014), and proposed in milk processing industry in Casablanca, Morocco (Allouhi et al., 2017). On the other hand, the configuration without heat exchanger is recommended when all the medium is same, but suitable storage medium is necessary as the medium should meet the criteria to be a suitable solar heat transfer fluid, storage medium, and process medium at the same time. Single sensible heat storage is used in this evaluation as it is currently the most commonly used storage type in solar thermal system (Pelay et al., 2017), and single tank system is about 35 % cheaper than two tank systems (Gil et al., 2010).
For the next step, inlet and outlet temperatures of the solar collector is calculated by adding the process temperature with the multiplication of selected ΔT_{min} and the number of heat exchanger in the system. After that, daily and yearly energy demand are calculated based on operating heat duty and thermal heat load profile of the selected stream. The heat load profile consists of operating hour per day, operating days per week, and the operating weeks per year. The energy demand is the product of operating heat duty and operating time.
The solar collector efficiency is calculated from Eq(1) (Atkins et al., 2010).

$$n_{coll} = a_0 - \frac{a_1}{G}\left(T_{m,coll} - T_a\right) - \frac{a_2}{G}\left(T_{m,coll} - T_a\right)^2 \tag{1}$$

The average collector internal fluid temperature ($T_{m,coll}$) is assumed to be the average of the collector inlet and outlet temperatures. G is the amount of solar radiation, and T_a is ambient air temperature. Optical efficiency (a_0), linear heat loss coefficient (a_1), and quadratic heat loss coefficient (a_2) depend on the solar collector type and should be determined experimentally.
From the solar radiation (G) profile and ambient air temperature (T_a) profile, solar collector output per area is calculated hourly using Eq(2). It is worth noting that if the amount of solar radiation (G) is too low, the solar collector efficiency becomes a negative number and the solar collector output per area (E_{coll}) for that particular hour is assumed to be zero.

$$E_{coll} = n_{coll} G \tag{2}$$

Required solar collector field size (A_{coll}) for the process heating is calculated using Eq(3).

$$A_{coll} = \frac{\text{daily energy demand}}{\text{Total } E_{coll} \text{ in one day}} \tag{3}$$

If the integration configuration involves thermal energy storage, Eq(4) is used to determine volume of thermal energy storage required,

$$V_{storage} = \frac{Q_{storage} \times 3600}{c_p \rho (T_{max} - T_{avg})} \tag{4}$$

Where $Q_{storage}$ is the storage capacity required and mainly depends on heat load profile of the process. c_p is the heat capacity of the storage medium, ρ is the density of the storage medium. T_{max} and T_{avg} is maximum and average storage temperature.

2.2 Techno-economic analysis

Based on the known solar collector field size from Eq(3), capital cost of solar collector is calculated by multiplying the collector field size and corresponding solar collector price per area. The solar collector price varies with different solar collector type. Once the storage volume required is known from Eq(4), capital cost of storage is determined by multiplying the storage volume with storage price per volume. The storage price varies with different storage type. The capital cost for heat exchanger and pump is calculated based on the cost estimation equations from Smith (2005).

3. Case study and discussion

3.1 Information of case study and selection of solar collector

The information of processes in this case study are presented in Table 1, based on required temperature range of process, compound parabolic collector (CPC) is selected for processes no 1 and 2 as it can support temperature range of less than 120 °C (IEA-ETSAP and IRENA, 2015). On the other hand, flat plate solar collector (FPC) is selected for processes no 3 and 4 as its design temperature range of less than 80 °C) (IEA-ETSAP and IRENA, 2015). For each type of solar collector case study, every factor is fixed except of different temperature range, this is for the study on effect of solar utility temperature to other design parameters.

Table 1: Processes for case study

Process No	Supply temperature T_s [°C]	Target temperature T_t [°C]	CP [kW/°C]	Heat duty, Q [kW]
1	80	110	15	450
2	60	90	15	450
3	40	70	15	450
4	20	50	15	450

3.2 Evaluation of integration configuration

A ΔT_{min} of 5 °C is assumed for this case study, as the result, inlet and outlet temperature of solar collector is increased by 10 °C since there are two heat exchangers in the evaluated configuration with HEX.

Operation profile for all processes in this case study are 12 h/d, 6 d/w, 52 w/y. From the operation profile, daily and yearly energy demand for all processes are 5,400 kWh/d and 1,684,800 kWh/y. Since different solar collectors are used for both stream, their optical efficiency (a_0), linear heat loss coefficients (a_1), and quadratic heat loss coefficients (a_2) are also different and it is shown in Table 2.

The solar irradiation profile used in this case study was obtained from Photovoltaic Geographical Information System (PVGIS) and location was set to Malaysia, and ambient temperature used was 28 °C. From the solar irradiation profile, solar collector efficiency and solar collector output are calculated. The evaluation results for the processes are presented in Table 3 and Table 4.

Generally, solar collector field size required for configuration with HEX is more than configuration without HEX because the present of HEX will make average solar collector temperature higher, this cause solar collector efficiency becoming lower, as a result, more area required to supply same amount of energy demand. From a similar reason, the lower the solar utility temperature, the solar collector field size required is lower. This is because of the higher solar collector efficiency and it is causing higher solar collector output.

3.3 Techno-economic analysis

Calculation of storage is based on only 1 day of thermal energy required to be stored and the unit price is based on price of sensible heat storage from IEA-ETSAP and IRENA (2013), which is 593 MYR/m^3. The solar collector prices are according to prices in China from IEA-ETSAP and IRENA (2015), which are 1,500 MYR/m^2 for FPC and 2,160 MYR/m^2 for CPC. For the calculation of HEX, heat transfer coefficient, U is assumed same in all processes, the only difference is heat duty of the stream. Same conditions such as flow rate and type of fluid inside the pipe are assumed in the calculation of the pump, the only different between the configurations is number of pump in the system. Saving is a result from multiplication of yearly energy demand of the stream and the price of LPG of 0.10 MYR/kWh, the price of LPG is the average of all category price based on Gas Malaysia (2018). Techno-economic analysis results for this case study is presented in Table 5 and Table 6.

Since the collector field size required will become lower when solar utility temperature is lower, collector cost will become lower also. It is worth to notice that the effect of solar utility temperature variation affects more on FPC than on CPC. In the case with HEX, collector cost for process no 1 is more than process no 2 by 96,812 MYR, process no 3 is more than process no 4 by 378,183 MYR, the different is 281,370 MYR.

Table 2: Coefficients of solar collectors

	Optical efficiency, a_0	Linear heat loss coefficients, a_1	Quadratic heat loss coefficients, a_2
Processes no 1 and 2 (CPC)	0.687	0.613	0.003
Processes no 3 and 4 (FPC)	0.706	3.555	0.013

Table 3: Evaluation results for configuration with HEX

Process no	1	2	3	4
Average collector temperature [°C]	105	85	65	45
Solar collector efficiency	0.61	0.63	0.52	0.63
Total E_{coll} in one day [kWh/m^{2}d]	2.46	2.69	1.82	2.66
Solar collector field size required [m^2]	2,194	2,008	2,963	2,029

Table 4: Evaluation results for configuration without HEX

Process no	1	2	3	4
Average collector temperature [°C]	95	75	55	35
Solar collector efficiency	0.62	0.64	0.57	0.67
Total E_{coll} in one day [kWh/m^{2}d]	2.57	2.80	2.25	3.11
Solar collector field size required [m^2]	2,099	1,930	2,398	1,738

Table 5: Techno-economic analysis results for configuration with HEX

Process no	1	2	3	4
Solar collector capital cost [MYR]	1,141,042	1,044,230	1,200,268	822,085
Heat exchanger cost [MYR]	7,043	7,043	7,043	7,043
Pump cost [MYR]	35,124	35,124	35,124	35,124
Storage cost [MYR]	95,077	95,077	95,077	95,077
Total system cost [MYR]	1,278,287	1,181,474	1,337,513	959,330
Saving [MYR/y]	174,952	174,952	174,952	174,952
Payback period [y]	7.3	6.8	7.6	5.5

Table 6: Techno-economic analysis results for configuration without HEX

Process no	1	2	3	4
Solar collector capital cost [MYR]	1,091,315	1,003,615	971,350	704,213
Pump cost [MYR]	17,562	17,562	17,562	17,562
Storage cost [MYR]	95,077	95,077	95,077	95,077
Total system cost [MYR]	1,203,955	1,116,254	1,083,989	816,852
Saving [MYR/y]	174,952	174,952	174,952	174,952
Payback period [y]	6.9	6.4	6.2	4.7

4. Conclusions

A process system engineering tool were used to evaluating the trade-off between solar utility temperature and system efficiency plus economic feasibility of an integrated solar thermal system, considering different process temperature range, different integration configuration, and in the context of Malaysia. As the result, the proposed tool shows various effect of solar utility temperature to the system efficiency and economic feasibility. The tool was then used to evaluate an illustrative case study. The results show that annual saving is 174,952 MYR. The payback period for all processes vary from 4.7 to 7.6 y. In future research, more case study with different temperature range and heat duty, and different solar collector type can be further investigated.

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