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PERFORMANCE ANALYSIS OF EVACUATED TUBE COLLECTOR BASED SOLAR HEAT FOR INDUSTRIAL PROCESS (SHIP) SYSTEM IN MALAYSIAN CLIMATE

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Abstract

Industries commonly use natural gas boilers to fulfil the hot water and steam requirement of the factories. However, the emission of greenhouse gasses increases in the environment due to the vast usage of natural gas boilers. Therefore, Solar Heat for Industrial Process systems is being introduced around the globe to supply hot water and steam in the processing activities of factories. The performance and viability of Solar Heat for Industrial Process systems depend on several variables such as heating capacity, piping circuit, solar irradiation, cost of the project, shading effect, and storage method. This research aims to evaluate, analyse, and validate the Solar Heat for Industrial Process system performance and potential of greenhouse gas reduction. The performance analysis of the recently installed Solar Heat for Industrial Process system was carried out successfully for three months (October-December 2020) based on different analysis parameters. The monthly analysis shows that the Evacuated Tube Collectors produced 50.03%, 49.46%, 47.10% efficiency, and system efficiency recorded as 45.77%, 46.65%, 45.23%. The average losses rate per month is 2.98%. This rate met the requirement for final energy delivery terms to storage tank procedure. The Solar Heat for Industrial Process system also reduces a significant Carbon Dioxide emission with 20.7 Tons over the analysis period. This paper presents solar thermal performance analysis, particularly system efficiency and greenhouse gasses reduction. Results are highly acceptable and show the viability of Solar Heat for Industrial Process system in Malaysia climate is proven.

Keywords: Greenhouse gasses, Performance analysis, Renewable Energy, Solar heat for industrial process, Solar thermal.

1. Introduction

Solar Heat for Industrial Process (SHIP) systems are being implemented in the industries to reduce greenhouse gas (GHG) emissions. Solar energy is free from GHG emissions; therefore, it is an alternate source for thermal energy to preserve fossil fuel reserves. The primary element of a typical SHIP system is a solar thermal collector, and the area of each collector is between two to five meters square. It also consists of a control system, water circulation pump, hot & cold water storage tank, and finally, a heat exchanger [1-2].

Worldwide, there are two types of the solar thermal system being used. The first is a thermosiphon, in which the fluid circulates without the necessity of a pump, and the second is a pumped-based solar thermal system. 58% of the systems are thermosiphon, and 42% of the system are pump-based. The use of SHIP systems majorly depends on climate. The energy yield majorly depends on the climate and the solar thermal collector. The system yield also relies on its operation type, which can be pumped solar thermal systems or thermosiphon systems.

The capacity of the global solar thermal system raised around eight times over the last two decades. In 2000, the installed capacity was 62 Gigawatt thermal (GW_{th}) with 89 million m^2 of covered area, and in 2019, it was 479 GW_{th} with a covered area of 684 million m^2). The yearly solar thermal energy yields were founded as 51 terawatt hour (TWh) in 2000 and 389 TWh in 2019 [3].

Besides the SHIP system, the solar thermal collectors are also being used in several other applications like solar district heating, solar thermal cooling, food drying, space heating, swimming pool water heating for domestic hot water. Flat Plate Collector (FPC), Evacuated Tube Collector (ETC), and parabolic solar thermal collector are the more popular in the solar thermal applications [4-6]. Several studies have been done recently around the world on different domains of solar thermal systems.

These studies are categorised into three major domains, namely, 1) Feasibility studies on different climates; 2) Experimental setup for analysing the performance of different types of solar thermal collectors; 3) Experimental setup for an increase in performance by using different nanofluids. A few relevant studies are presented here, which are under the scope of this research. Different climates were considered during the literature review, including China, Canada, Hong Kong, Malaysia, Ireland, Poland, and Egypt. The test duration of analysis and flow rate varies based on studies to evaluate the performance of solar thermal systems. The aperture area from $1.14m^2$ to $5.58\ m^2$ is utilised to carry out the experimental studies.

A researcher group [7] from Hong Kong has done a performance analysis of the domestic solar hot water system based on ETC. They have done the experiments according to thermosyphon types, which includes open and closed set up. Based on their findings, ETC is more viable in the high-temperature process and terms of connection with a heat pump or absorption chillers.

The efficiency of ETC under several operating conditions was carried out in the climate of Canada [8]. The presented study is focused on the efficiency of various configurations of ETC. The experimental setup consists of five different sizes of evacuated tube collectors, and the efficiency was tested on different flow rates and panel angles. Thus, factors such as solar circuit pipes losses ($\dot{Q}_{loss}^{pipe}$), heat exchanger losses ($\dot{Q}_{loss}^{hex}$) and system losses ($\dot{Q}_{loss}^{sys}$) were not evaluated. The findings over a period of one and half year show that the maximum collector efficiency (η_{coll}) of ETC hit up to 34% under Canada climate.

A group of researchers [9] from the University Malaysia Pahang, Malaysia, performed the evaluation of ETC using water-based titanium oxide (tio) nanofluid. The experimental setup of the solar system consisted of a 16-tubes ETC module, a pump to circulate the water, a pyranometer to measure the irradiance, a temperature sensor, a heat exchanger, and finally, a power source for the pump and monitoring system. The test was conducted several times during sunny days only. Separate performance analysis was done with nanofluid and water, maximum efficiency founded as 73% and 58%, respectively.

A study was carried out for energy performance of an ETC using single-walled carbon nanotubes nanofluids by the Faculty of Engineering, University of Malaya, Malaysia [10]. The performance was tested by mixing different percentages of SWCNTs nanofluids. The study also compared water and SWCNTs nanofluid at different flow rates of 0.008, 0.017, and 0.025 kg/s. Application of ETC was proposed for domestic house application only. The tests were performed several times on sunny, cloudy, and rainy days as well. The efficiencies of the ETC based on different flow rates were found as 30.88%, 48.21%, and 54.37% for water.

Another study [11] was carried out on the same experimental system of the University of Malaya, Malaysia. This research focuses on performance analysis between two different working fluids: water and graphene nanoplatelets nanofluid. The thermal efficiency for water was found as 33, 51, and 54 (%) on three different flow rates of 0.5, 1, and 1.5 (LPM) respectively.

The techno-economic feasibility of using the Evacuated Tube Collector to assist heat pump was carried out in [12]. The test was performed from October to April during Sunny & Cloudy moments. An evacuated tube collector with a gross area of 9.75m^2 and aperture area of 5.58 m^2 was used, consisting of 60 glass tubes. The maximum solar irradiance values on sunny days were 1.17 kW/m^2 outside the greenhouse, and 0.770 kW/m^2 was noted inside the greenhouse under the climate of China. The ETC efficiency findings were 40-50% on sunny days and 35-40% on cloudy days. The payback period of the ETC, which operates in winter only, was found as four (4) years.

A feasibility study for Thermo-economic and Environmental Analysis of FPC and ETC was done [13] under Cold Climatic Conditions of Ireland. TRNSYS16 software was used to analyse the FPC and ETC performance and payback period. The test was carried out on three days of solar irradiance data with the collector area (2.04m^2) for FPC & ETC. It was analysed that the supply temperature (T_{supply}) and solar irradiance (G_t) are the notable parameters which affect the η_{coll}. According to the thermal and economic analysis, the system efficiency (η_{sys}) of ETC was found better than the FPC. The η_{coll} of ETC was found as 48%, 51% and 47% on 10th October, 22nd October, and 28th September respectively.

Recently, thermal performance was performed on ETC in Lublin, Poland [14]. The presented results consist of the energy performance of an experimental ETC system. The proposed collector consists of 24 tubes with 2.9m^2 of gross area. The analysis of thermal and exergy efficiencies was carried out for July and August only. G_t recorded as 80 kWh/m^2 for July and 112.8 kWh/m^2 for August. The mean value of energy generation by ETC was found as 4.28 MJ/(m^2·d). Furthermore, the monthly mean η_{coll} was 45.3% in July and 32.9% in the month of August.

Another recent study was carried out [15] under the Egyptian climate. The study covers a comparative study of the performance of a novel helical direct flow U-Tube Evacuated Tube Collector. The experimental setup was done on four (4) conventional U-tube ETC and four (4) modified helical U-tube collectors. The test was done on three different days with various flowrate and different modified helical U-tube collectors. The summary of the presented literature studies is shown in Table 1.

Table 1. Summary of literature studies on solar thermal analysis.

Ref. & Location	Test Period	Technique / Parameter	Eff (%)	Total Area	Total Tubes
[7] Hong Kong	13-16 Jan 2009 04-07 Jul 2009	Open / Close thermosyphon	35-62	3.12	28
[8] Canada	July 2008 – Jan 2010	Diff flow rate	Up to 34	-	32 & 16
[9] Malaysia	9.00am- 6.00pm 15 min of interval	Clear sky day	Up to 58	2.77	16
[10] Malaysia	Sunny & Cloudy, Several Days	Flow rate (kg/s) 0.008, 0.017, 0.025	30.88 48.21 54.37	1.14	12
[11] Malaysia	January to September	Flow rate (lpm) 0.5, 01 1.5	33 51 54	1.14	12
[12] China	Oct - Apr	Sunny & Cloudy moments	40-50 35-40	5.58	60
[13] Ireland	3 Days	FPC vs. ETC 10 Oct 22 Oct 28 Sep	48.00 51.00 47.00	-	-
[14] Poland	Two Months	July August	45.30 32.90	3.60	24
[15] Egypt	2019 04 Sep 08 Sep 11 Sep	Flow rate (lpm) 10 20 30	31.6 35.8 38.6	Less then 1.14	08

In summary, the stated studies presented in this section on the ETC are based on the solar thermal systems implemented around the globe. However, there is no single industrial standard performance analysis performed under Malaysia climate. Only experimental studies were carried out, which is insufficient evidence for industries to embark on solar thermal systems. Therefore, it is necessary to develop a real industrial solar thermal project, and its performance analysis should be carried out in the Malaysian environment.

2. SHIP System

2.1. Description of system

The Solar Heat for Industrial Process (SHIP) system is installed at the latitude of 01°28'57" and longitude of 103°54'25" in one of the process industries, Pasir Gudang, Johor, Malaysia. The solar thermal panel was installed on the rooftop of the boiler section of the factory. Pasir Gudang is about 8 meters above sea level, and the rooftop is 8.35 meters above the ground. The total height of the panels is approximately 16.35 meters. ETC's are widely used as stationary solar collectors. In the developed SHIP system, ETC's are tilted with an optimum angle of 10˚ based on manufacturer recommendation, and the standard calculation method used [9] to maximise the harnessing of solar radiation.

ETC's are designed to use a vacuum shield that reduces absorber heat losses, boosting solar radiation to improve energy efficiency. The vacuum shield around the heat pipe prevents heat loss through convection and conductivity to allow the collectors to work at higher temperatures than the Flat Plate Collectors (FPC) [16]. The ETC life depends on its manufacturer, few brands can last below than 20 years but majorly the lifespan is 20-25 years. The standard economic ROI period of ETC is 20 years, as mentioned by Fayaz et al. [17]. These are the primary reasons to select the ETC for the developed SHIP system.

The three arrays were installed on the roof, at 8-meter high from the ground with no shading effect, and its area is 38.95 x 15.05 m^2. Total Seventy-Five (75) ETC panel was mounted, and each array consists of 25 ETC panels. The CPC-1518 is used, manufactured by [18]. Each ETC panel consists of 18 evacuated tubes with a gross area of 3.41 m^2 and an aperture area of 3.0 m^2. Thus, the total gross area of 75 ETC panels is 255.75 m^2, and the aperture area is 225 m^2. The ETC array installed in the SHIP system is shown in Fig. 1, and technical specifications are presented in Table 2.

Fig. 1. Evacuated tube collectors (ETC) at SHIP system.

Table 2. Technical specifications of evacuated tube collector (ETC).

Item	Unit	Amount
Series	-	CPC1518
Tubes	-	18
Annual Yield	kWh/m^2a	651
Dimensions	m	2.08x1.64x0.1
Gross surface area	m^2	3.4
Aperture area	m^2	3.0
Collector contents	liter	2.4
Weight	kg	54
Max. working overpressure	bar	10
Max. stagnation temperature	°C	345
Connection clamping ring	mm	15

The schematic diagram of the SHIP system is shown in Fig. 2. Coldwater is being injected into the cold-water tank, which has a 20 m^3 storage capacity. Pump 02 is pumping the water from the cold-water tank to the heat exchanger. Whereas Pump 01 is pumping water from heat exchanger to solar array and pushing towards heat exchanger again. The flow rate of both pumps is being controlled at 6.5 m^3/hour. The final hot water is supplied from the heat exchanger to the hot water tank, with the same storage capacity as the cold-water tank.

A pump 03 is used to supply the water from hot water tank for factory process. Only pump 01 and pump 02 are controllable through the PLC system. Both pumps trigger once the solar irradiance instant value remains equal or more than 100 Wh/m^2 and turn off once the temperature difference of the Solar inlet and outlet is less than 3°C. The heat meters are installed on two different loops. First at ETC array loop (Heat Meter 01) and second meter (Heat Meter 02) before final delivery to the hot water tank.

These heat meters have built-in flow and temperature sensors and able to generate instant energy value in kWh. An ultrasonic level sensor is installed on top of the hot water tank to monitor the water level. Five different temperature sensors are used in different locations. Finally, a pyranometer is installed on the rooftop near to ETC array to monitor the solar irradiance.

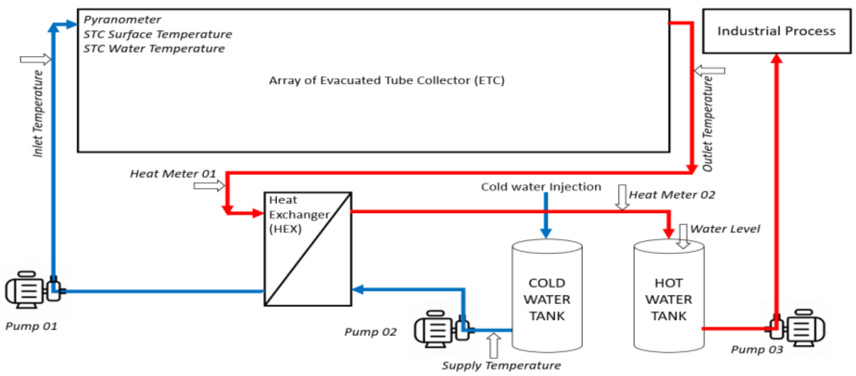


Fig. 2. Schematic diagram of SHIP system.

2.2. Measurement and monitoring system.

The Industrial IoT (IIoT) system was installed for remote monitoring through a cloud-based application. The data recording is done by a Programmable Logic Controller (PLC) through different sensors and actuators with 5 minutes intervals and pushed to the cloud through an IIoT data gateway. The breakdown of the equipment is shown in Table 3.

Table 3. Details of measurement and monitoring system equipment.

Item	Qty	Brand	Type/Model
Pyranometer	1	RIKA	RK200-03
Surface Temperature Sensor	1	Optris	Infrared CS LT
Water Level Sensor	1	Senix	CHEM 35
Energy Meter	2	DIEHL	SHARKY 775
Water Temperature Sensor	1	LKY	PT100
Water Temperature Sensor	3	JUMO	PT500
PLC System	1	Siemens	S7-1200
Industrial IoT Gateway	1	Siemens	IOT2000

Three-panel enclosures are used in different locations. First is the central panel enclosure, located near the heat exchanger and connected to heat meter 01, pump 01 & pump 02. It includes, power supply, PLC, touch HMI, IIoT gateway, ethernet switch, relays & magnetic contactors for circulation pumps. Second is the rooftop sub panel (includes power supply, PLC IO module) connected to pyranometer, wind speed sensor, direction sensor, surface temperature sensor & water level sensor. Finally, third is the hot water tank sub panel (includes power supply, PLC IO module) connected to heat meter 02, hot water temperature sensors, and cold-water temperature sensor.

3. Theoretical Considerations

There are three types of studies carried out by researchers around the globe regarding solar thermal: 1) Performance analysis, 2) Economic analysis, and 3) Performance & Economic Analysis. The presented study falls into the first type. Additionally, this setup is considered an industrial grade which can be related to experimental setup instead of feasibility or nanofluid study only.

SHIP system was commissioned for operation in late September 2020. However, the analysis was carried out for three (3) months; October, November, and December 2020. There were five (5) days from 27th Nov to 1st Dec 2020 when the data went missing due to an on-site internet connection. Thus, the performance analysis was only managed to be initialised for eighty-seven (87) days.

The SHIP system refers to the complete arrangement of many components that collect, store, and deliver useful heat to the process. It includes the ETC, hot & cold pipes, hot & cold water storage tank, circulation pumps, heat exchanger, and control system. The performance of the system depends on each component. The performance analysis of the SHIP system is based on the following mathematical model, which is derived from [14, 19-22] and explained in Eq. (1) to Eq. (7).

The useful energy ($\dot{Q}_u$) from the ETC calculated as:

$$\dot{Q}_u = \dot{m}_w \cdot c_{pw} \cdot \left(T_{c,o} - T_{c,i}\right) \tag{1}$$

Where $\dot{m}_w$ is mass flow rate, c_{pw} is water specific heat, $T_{c,o}$ is collector outlet temperature, and $T_{c,i}$ is the collector inlet temperature.

The delivered energy ($\dot{Q}_{sc}$) supplied to storage tank calculated as:

$$\dot{Q}_{sc} = \dot{m}_w \cdot c_{pw} \cdot \left(T_{s,i} - T_{s,o}\right) \tag{2}$$

Based on that, the collector efficiency figured as:

$$\eta_{coll} = \frac{\dot{Q}_u}{A_c \cdot G_t} \times 100\% \tag{3}$$

In Eq. (3), the A_c is collector area and G_t is the total solar irradiance.

Similarly, the system efficiency figured as:

$$\eta_{sys} = \frac{\dot{Q}_{sc}}{A_c \cdot G_t} \times 100\% \tag{4}$$

The system losses consist of ETC loss ($\dot{Q}_{loss}^{coll}$), piping loss ($\dot{Q}_{loss}^{pipe}$) & heat exchanger loss ($\dot{Q}_{loss}^{hex}$):

$$\dot{Q}_{loss}^{sys} = \dot{Q}_{loss}^{coll} + \dot{Q}_{loss}^{pipe} + \dot{Q}_{loss}^{hex} \tag{5}$$

The solar irradiation per day (SID) is defined as:

$$SID\left(\frac{kW.h}{m^2.d}\right) = \frac{\sum_{i=1}^{n}(G_t.t_p)}{3600000} \tag{6}$$

where n is number of measurement periods for a given day, G_t is a mean value of total solar irradiance in W/m^2, and t_p is the duration of the measurement period in seconds.

The variation of useful energy ($\dot{Q}_u$) based on Solar Irradiance (G_t) including tilt angle (β) & orientation (γ) can be calculated as:

$$\dot{Q}_u(\beta,\gamma) = \sum \frac{\eta_{coll} \cdot A_c \cdot G_t(\beta,\gamma)}{1000} \tag{7}$$

4. Results and Discussions

4.1. Variations of temperature

The system is closed-loop, and there is a process of return water being injected into the cold tank. In effect, it is analysed that the supply temperature varies from 31.88°C to 39.82°C at different times of the day. However, this effect does not link with sunny or cloudy/rainy days because it depends on the process return water from the different operations of the plant.

Figure 3 shows that on a sunny day, collector inlet temperature was ranged from 34.21°C to 42.36°C, and the collector outlet temperature was between 37.86°C to 45.97°C. The peak temperature of the collector output was noted at 01:00 PM as a value of 58.23°C, which offers the highest temperature difference (*ΔT)* of the day as 14.81°C. The ΔT was recorded from 3.61°C to 14.81°C. Thus, the solar irradiance hit up to 964.09 kWh.

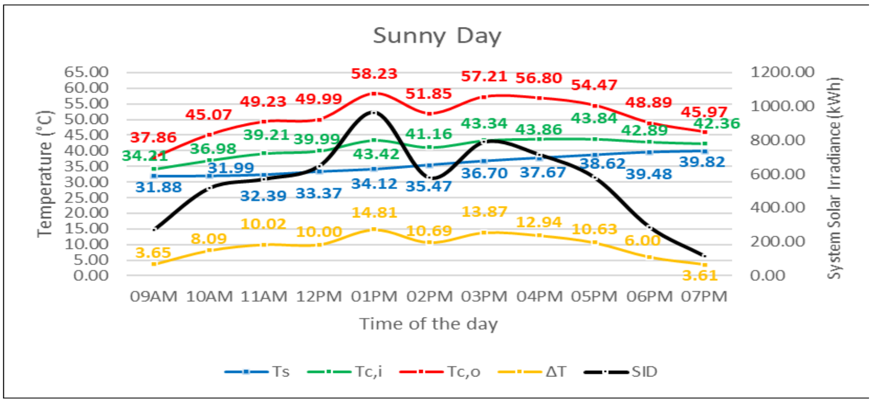


Fig. 3. Variation in temperature on a sunny day.

On the cloudy/rainy day (as shown in Fig. 4), the solar irradiance was less, and its range was between 82.34 kWh to 282.90 kWh. The collector inlet temperature was between 35.42°C to 37.86°C, and the collector outlet temperature was ranging from 38.68°C to 43.43°C. The peak temperature of the collector output was noted at 02:00 PM, which offers the highest ΔT of the day as 5.57°C.

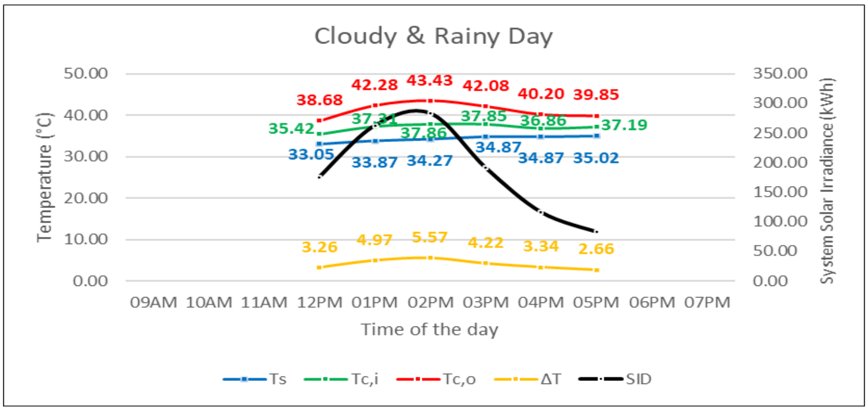
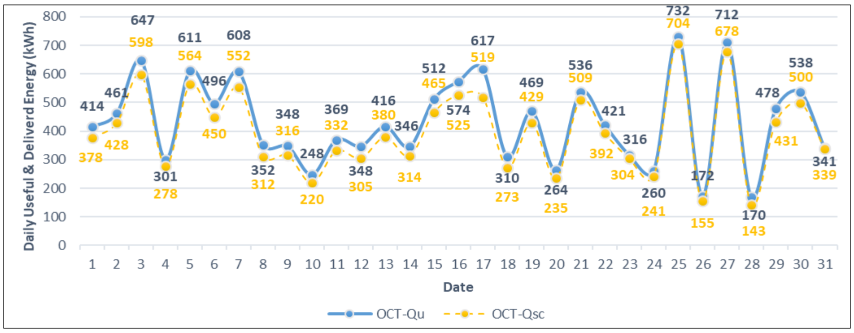


Fig. 4. Variation in temperature on a cloudy day.

4.2. Variation of Energy

The solar irradiance at the location of the SHIP system was recorded almost the same as mentioned by [23] for Senai, Johor, Malaysia. Whereas the daily values of the useful energy & delivered energy for the month of OCT 2020, NOV 2020 & DEC 2020 are shown in Fig. 5, calculated based on Eq. (1) & Eq. (2). The daily useful energy of the SHIP system was noted as 170 – 732 kWh, 76 – 699 kWh, and 123 – 645 kWh for the month of OCT 2020, NOV 2020, and DEC 2020, respectively. Whereas daily delivered energy varies from 65 kWh to 704 kWh over three months; the monthly range was 143 – 704 kWh for OCT, 65 – 653 kWh for NOV, and 107 – 611kWh for DEC.

The total energy generated by the system was 34,514.00 kWh, and delivered energy was recorded as 32,379.00 throughout analysis (three months). The 6.19% losses incurred during the delivery of energy equals to 2135 kWh. The minimum losses were found as 4.05% in DEC 2020, and comparatively maximum losses were 8.33% in OCT 2020, whereas the losses were 5.79% in NOV 2020. From the total one hundred and seventy-four (87 for useful energy & 87 for delivered energy) samples, values of over three months, the daily mean value is calculated as 396.71 kWh (useful energy) and 372.17 kWh (delivered energy). These results show satisfactory performance as compared to related studies.



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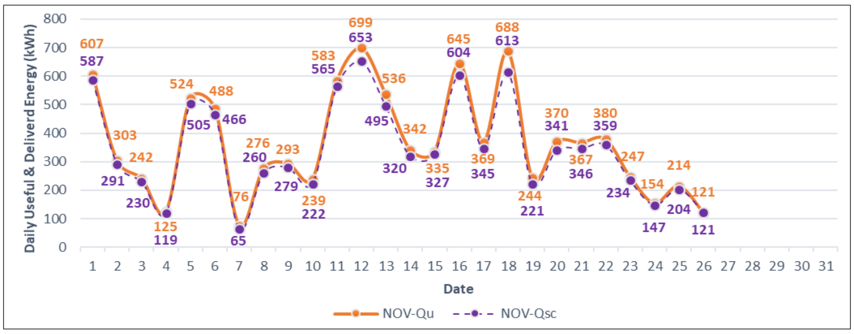

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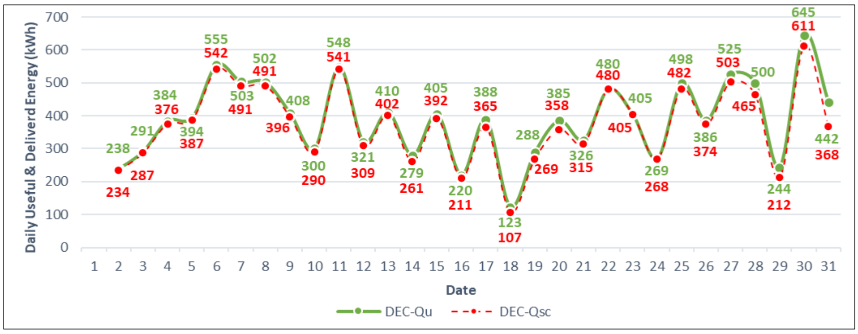
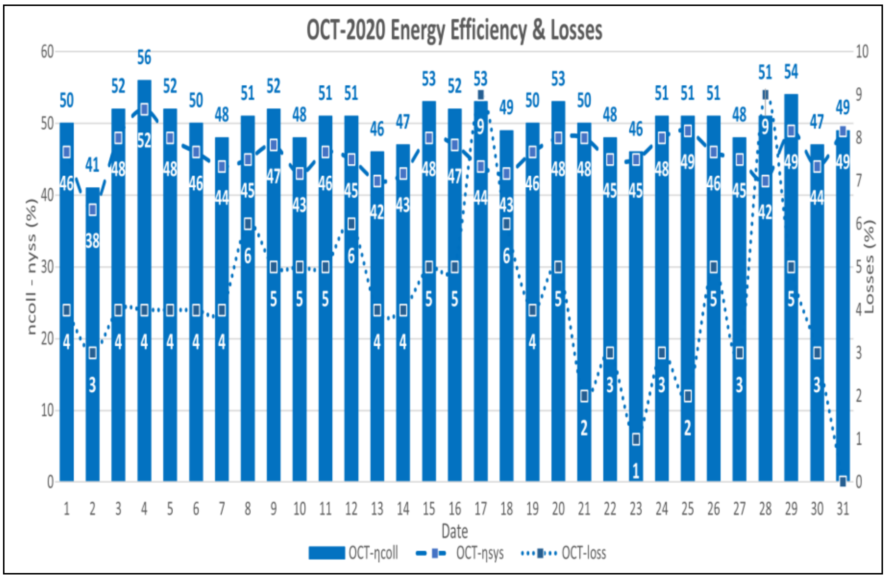


(c)

Fig. 5. Variation in the energy of the SHIP system
(a) October 2020 (b) November 2020 (c) December 2020.

4.3. Variation of Efficiency

The daily values of the collector efficiency, system efficiency, and system losses for the month of OCT 2020, NOV 2020 & DEC 2020 are shown in Fig. 6. The efficiencies of the solar collectors were noted as 41-56%, 44-56%, and 38-52% for the month of OCT 2020, NOV 2020, and DEC 2020, respectively (evaluated according to Eq. (3) & Eq. (4)). Whereas system efficiencies vary from 33% to 53% over three months, while the monthly range was 38-52% for OCT, 41-53% for NOV, and 33-52% for DEC.



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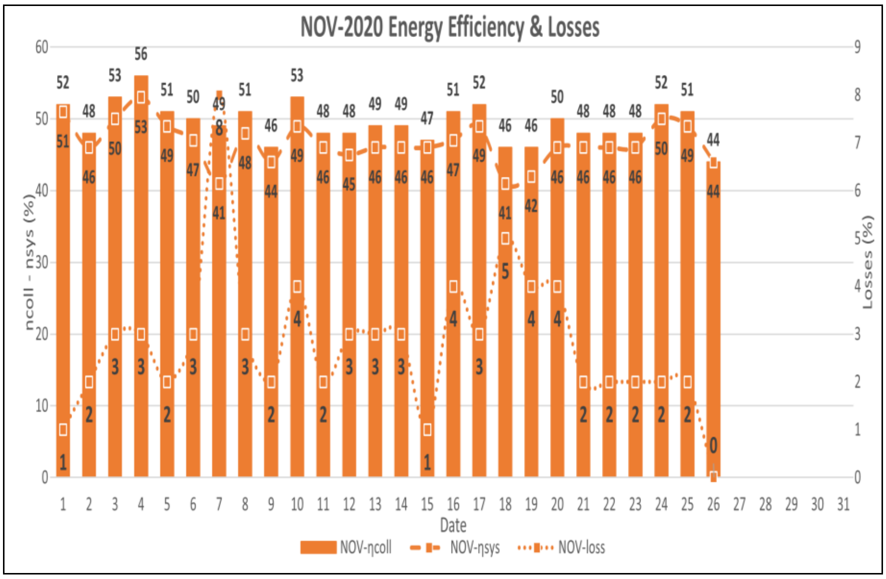

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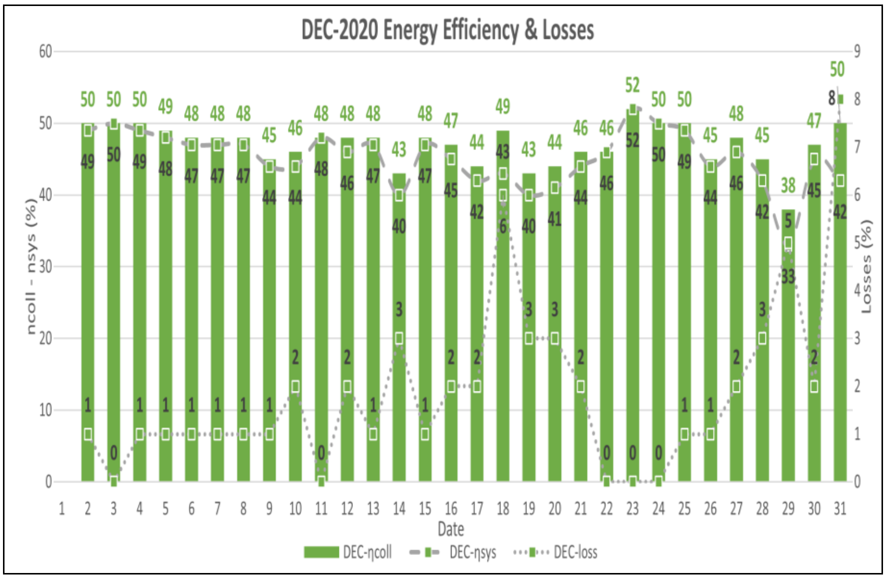

(c)

Fig. 6. Energy efficiencies and losses of the SHIP system (a) October 2020 (b) November 2020 (c) December 2020.

The mean values of daily efficiencies show great results and are highly acceptable compared to other studies around the world (as shown in Table 1). Collector and system efficiencies founded are (50.03%, 49.46%, 47.10%) and (45.77%, 46.65%, 45.23%) respectively. The two conditional parameters (solar irradiance & Delta T) are used as circulation pump ON/OFF settings. The October losses were monitored high due to circulation pump setting during the probation period of the SHIP system. After resolving the issue, the next two months losses are acceptable in terms of final energy delivery to the storage tank. Table 4 shows the monthly mean values of both efficiencies and losses over the analysis period.

Table 4. Monthly mean efficiencies and losses over the analysis period.

Month	Collector efficiency	System Efficiency	Total Losses
October	50.03%	45.77%	4.26%
November	49.46%	46.65%	2.81%
December	47.10%	45.23%	1.87%

The analysis realized that both efficiencies (collector & system) depend on several factors. These factors include Solar Irradiance, Supply Temperature, PUMP Start & Stop condition, flow rate, and specific water heat.

4.4. Environmental Impact of SHIP System

The CO_2 reduction of the SHIP system directly depends on generated energy. The facts responsible for energy generation are already described in section 3, e.g., Evacuated Tube Collector, piping system, water storage tanks, circulation pumps, heat exchanger, and control system. The clean energy delivered by the SHIP system shows a great impact on the environment. It is calculated that the SHIP system has reduced 20,722.39 kg of CO_2 over three months (OCT 2020-DEC 2020). The GHG reduction factor of Carbon dioxide (CO_2) for Natural Gas (NG) Boiler (0.64) was derived from [24]. The reduction calculation of GHG emissions of SHIP system is calculated by the Eq. (8). Table 5 describes the detailed breakdown of the monthly calculation of CO_2.

$$GHG\ Emission\ Saved = \text{Energy (kWh) x GHG Factor (kg/kWh)} \quad (8)$$

Table 5. Breakdown of monthly calculation of CO_2.

Month	OCT	NOV	DEC	TOTAL
Energy Generation (kWh)	12,269.69 kWh	8,918.79 kWh	11,190.26 kWh	32,378.74 kWh
CO_2 Reduction (kg)	7,852.60	5,708.03	7,161.76	20,722.39

5. Conclusions

This research is being carried out based on the Solar Heat for Industrial Process (SHIP) System that has been installed in one of the process industries in Johor, Malaysia. Evacuated Tube Collectors (ETC) are deployed at the rooftop of the boiler section in a factory. Each ETC panel consists of 18 evacuated tubes that cover a 3 m^2 aperture area. In total, 75 ETC panels covering a gross area of 255.75 m^2 and aperture area of 225 m^2 are used. In addition, an industrial IoT (IIoT) based Solar Thermal Monitoring System (STMS) is installed for data monitoring and control of water circulations pumps.

The performance analysis of the SHIP system was carried out successfully within three months of the probation period. Ten (10) different parameters were included in the analysis; Useful Energy ($\dot{Q}_u$), Delivered Energy ($\dot{Q}_{sc}$), Supply Temperature (T_{supply}), Collector Inlet temperature ($T_{c,i}$), Collector Outlet Temperature ($T_{c,o}$), Temperature Difference (ΔT), Collector Efficiency (η_{coll}), System Efficiency (η_{sys}), System Losses ($\dot{Q}_{loss}^{sys}$), and Greenhouse Gases (GHG) reduction.

The monthly efficiency of Useful Energy ($\dot{Q}_u$) and Delivered Energy ($\dot{Q}_{sc}$), are found as (50.03%, 49.46%, 47.10%) and (45.77%, 46.65%, 45.23%) respectively. System Losses ($\dot{Q}_{loss}^{sys}$) found an averagely 2.98%, which are also acceptable in terms of final energy delivery to the storage tank. Thus, the SHIP system reduces notable GHG emissions (20.7 Tons of CO_2) during the analysis period. Furthermore, the Solar Thermal Performance result analysis shows an acceptable efficiency percentage. Also, the GHG reduction performance was satisfactory and justified in accordance with the viability of the SHIP system within Malaysia climate.

Nomenclatures

A_c	Collector Area, m^2
CO_2	Carbon dioxide
c_{pw}	Water specific heat, Joules
G_t	Total Solar Irradiance, Wh/m^2
$\dot{m}_w$	Mass flow rate, pounds/hour or Kg/sec

T_{set}	Set Temperature, ℃
T_{supply}	Supply Temperature, ℃
$T_{c,i}$	Collector Inlet Temperature, ℃
$T_{c,o}$	Collector Outlet Temperature, ℃
$\dot{Q}_{loss}^{coll}$	Solar Collector Losses, %
$\dot{Q}_{loss}^{pipe}$	Solar Circuit Pipes Losses, %
$\dot{Q}_{loss}^{hex}$	Heat Exchanger Losses, %
$\dot{Q}_{loss}^{sys}$	System Losses, %
$\dot{Q}_{u}$	Useful Energy, kWh
$\dot{Q}_{sc}$	Delivered Energy, kWh
Greek Symbols	
β	Solar Thermal tilt angle, deg
η_{coll}	Collector Efficiency, %
η_{sys}	System Efficiency, %
γ	Solar Thermal Panel orientation, deg
Abbreviation	
FPC	Flat Plate Collector
ETC	Evacuated Tube Collector
GHG	Greenhouse Gases
IIoT	Industrial Internet of Things
LPM	Litres Per Minute
PLC	Programmable Logic Controller
PV/T	Photovoltaic/Thermal
SAH	Solar Air Heater
SHW	Solar Hot Water
SHIP	Solar Heat for Industrial Process
SID	Solar Irradiance per Day
STES	Solar Thermal Energy System
STMS	Solar Thermal Monitoring System
STC	Solar Thermal Collector

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