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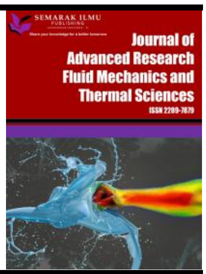

Experimental Investigation of Photovoltaic-Based Water Heating System

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ABSTRACT

Solar energy is an energy source whose availability is guaranteed, renewable energy which has enormous potential in the future. In addition to lowering environmental pollutants, solar energy can be used directly or indirectly for heating. A photovoltaic-based water heating system (PVWHS) is designed to utilize solar energy into electrical energy using photovoltaic cells, which are then connected to a DC heating element to heat the water in the tank. Testing this tool uses experimental methods to identify the optimal temperature of water, the energy needed to heat the water and thermal efficiency of the PVWHS. The test was carried-out using polycrystal photovoltaic cells and by varying the volume of the water tank, namely 10 liters, 15 liters and 25 liters. The results of this research show that a 10 liters water tank volume can increase the average water temperature by 10.7˚C. And a water tank volume of 15 liters can increase the average water temperature by 8.1˚C, and a water tank volume of 25 liters can increase the average water temperature by 5.6˚C. The efficiency of polycrystal photovoltaic cells was found to be an average efficiency of 7.34%. Meanwhile, the maximum heater efficiency was found to be 73.6% for all variations of water tanks. As for the maximum total efficiency value, the overall system efficiency is 5.35% for all water tank variations.

1. Introduction

A renewable energy source, solar energy is produced by the sun's light and heat emissions. Photovoltaic (PV) technology may produce energy, and solar collectors can heat water and air. Equipment that uses solar energy is becoming more and more popular since it is a sustainable and pollution-free energy source. The system's electrical and thermal efficiency have been increased recently, making it a viable choice for resource and energy management that is sustainable. The system with natural circulation outperformed the other two photovoltaic/thermal systems in terms of energy efficiency [1]. That integrating a cooling system can substantially improve the performance of photovoltaic panels while providing a sustainable solution for energy recovery [2,3]. Integrating zeotropic refrigerant blends in a direct expansion photovoltaic-thermal evaporator (DXPV-TE)-assisted compression heat pump water heater (CHPWH) system can significantly improve energy

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efficiency, reduce environmental impact, and provide economic benefits, thus making it a promising alternative to conventional refrigerants in solar energy applications [4]. Yildiz *et al.,* [5] also investigated how household behavior and seasonal variations affect the potential use of excess PV generation, finding that a typical working family may use 48% of the energy from excess PV for their daily domestic electric water heating systems (DEWH). PV using parabolic dish concentrator and fresnel lens has also been tested by Yi *et al.,* [6]. Depending on the kind and brand of solar module being utilized, PV/T water systems' electrical performance also differs [7]. Usually installed on the rear of a PV cell, the PV/T is a thermal collector. Increases in PV temperature will result in increased heat transfer to the thermal collector. In order to achieve high thermal efficiency, it maximizes heat transmission while cooling PV cells [8]. The technology of hybrid photovoltaic/thermal (PV/T) collectors and their uses in homes will be summarized by Veeramanikandan *et al.,* [9] more efficient than separate solar thermal and photovoltaic technologies will be the creation of advanced, high-performing hybrid PV/T collectors.

The PV-based water heating system (PVWHS) is a cutting-edge method that combines PV technology with hot water heating, using solar energy to heat water and produce electricity. A number of studies looked into the use of PV modules coupled with electrical heating elements for hot water in homes. In order to match the PV panel's current-voltage characteristics to the load, Newman and Newman [10] patented a PV water heater with resistive elements connected to a resistor controller. Butler patented a PV water heater that connected a resistive heating element that could be inserted through an impedance matching power maximizer box. Numerous uses were made possible by this innovative design, such as the incorporation of an insertable resistive heating element into open liquid containers, air heating systems, and hot water tanks that were already in place. In a number of realistic situations, the approach enables the effective use of PV energy for heating [11]. A typical Portuguese home's energy and financial performance in comparison to solar self-consumption. When coupled with electrified domestic hot water systems, there is a considerable possibility for increasing photovoltaic size in order to accept higher solar percentages while reducing costs through energy management [12]. Studies have been conducted on the effectiveness of solar water heating systems that use PV cells and directly connect PV arrays to DC resistive heating elements [13]. Optimized wavy cooling fins in a hybrid solar chimney-collector system demonstrate significant potential for passively improving the cooling and efficiency of solar PV panels [14]. The use of thermal resistor heaters using photovoltaic energy, resulting in thermal efficiency through water boiling experiments, which showed a maximum heating efficiency of up to 72% [15]. Buckley *et al.,* [16] also conducted study comparing four solar water heating alternatives and analyzing their thermal energy yield. The SWH system studied in this study provided the most appealing investment opportunity for homes to minimize their power use for hot water generation. SWH systems have shorter payback times and produce more thermal energy over a 25-year period [16,17]. A 3.6 kWp PV system placed on a residential property with a 315 L storage hot water heater is examined. With careful supervision, electric storage water heaters can save more than 80% of their purchased grid electricity [18]. Ahsan *et al.,* [19] in their research incorporated PV on a distillation system that uses DC water heaters connected to solar panels can improve the thermal performance of the distillation process. This resulted in higher water production rates compared to traditional solar distillation. In recent years, photovoltaic (PV) modules have become significantly less expensive. Solar PV has therefore become a viable choice for water heating. The PV array is directly connected to the heating element in a direct-coupled PV water heater (DPVWH) system. Optimizing the resistance value of the heating element is therefore a crucial step in the design of a DPVWH system. Hachchadi *et al.,* [20] sought to optimize the resistance value of the heating element for a range of climate conditions. Since a direct-coupled PV solar water heater system is simple, long-lasting, and inexpensive to operate, it is advised for remote and chilly areas. The performance of evacuated tube, flat-plate, and photovoltaic solar water heating systems is examined in this study. With a levelized cost of heat (LCOH) ranging from 0.14 to 0.23 $/kWh, the results of a simulation of the three systems energy, economic, and environmental performances indicate that it is more efficient from a techno-economic perspective. A life cycle analysis reveals that photovoltaic water heaters have a higher environmental impact than their solar thermal counterparts, despite being carbon neutral when compared to fuel-fired water heaters. In particular, it emits 4.3 tCO_2, or three times as much CO_2, over its lifetime [21]. Draou *et al.,* [22] planned to use actual high resolution PV surplus energy data to perform a techno-economic comparison and in-depth analysis of a divert-driven PVWHS and a standard solar thermal water heater (STWH). As a baseline, an electric water heater was used to compare the two systems. Phase change materials (PCM) and electric heating from photovoltaic installations are combined in thermal energy storage systems, which are a practical method of storing and utilizing solar energy for a variety of uses. The system operates by using PV panels to generate electricity, which is then used to heat PCMs. The PCMs, which have a high latent heat of fusion, absorb and store the heat until it is needed [23]. An integrated photovoltaic grid-tied system with a home hot water storage tank system is optimized with a power diverter. The optimized system reduces energy losses, increases energy efficiency, and does away with the need for backup power sources. All things considered, the improved PV water heater system is a possible step toward more economical and environmentally friendly domestic hot water energy solutions for small-scale uses [24].

Based on this, more information concerning solar water heaters employing PV cells is required. The goal of this study is to evaluate the performance of PV combined with a water heater. PV cells may also convert solar radiation into electrical energy, which can subsequently be used to heat water via direct current heating elements. This study investigated the performance to heat water of the PV water heating system with various volume of 10 liters, 15 liters, and 25 liters of water tank. The PV cell-based water heating system, PV cell efficiency, heater efficiency and total efficiency will be presented.

2. PV-Based Water Heating System

PV is a type of semiconductor device that uses solar radiation to generate electricity. PV cells are an environmentally friendly, noiseless, and portable conversion technology. PV cells can also be employed in domestic and industrial settings. The fundamental worry of PV cells is their long-term performance. Another type of solar energy gadget is the thermal collector, which uses the sun radiant heat. A water heater is a device that functions to heat water which is usually used for bathing needs, and heat sources generally use sources from gas, solar, or those using electricity. A series of PV cells can power solar direct current (DC) heating elements. With the right protection from the sun, DC voltage can be either low or high. An existing cooking pot, hot tub, or gas, propane, or electric hot water tank can be equipped with an immersion heating element. under order to optimize the power given to the heater under all solar conditions, the PV cell's output is connected to the DC heating element either directly or through the use of a solar charge controller.

The efficiency of PV water heating system is calculated to investigate its performance. The heat flow rate received by the water in the tank can be calculated by the equation:

$$q_{water} = \frac{m_{water}c_{water}(T_{out}-T_{in})}{\Delta t} \quad (1)$$

m_{water} is mass of water in the tank (kg), c_{water} is specific heat of water (J/kg°C), T_{out} and T_{in} is water temperature of outlet and inlet tank (°C), and Δt is water heating time (s).

The heat provided by the heater can be calculated as following

$$q_h = V_h \cdot I_h \quad (2)$$

where V_h is heater voltage (V), and I_h is current heater (A). The heater efficiency is calculated by the equation:

$$\eta_h = \frac{q_{water}}{q_h} \times 100\% \quad (3)$$

where q_{water} is rate of heat flow received by water (W), and q_h is heat flow rate from heater (W). The PV efficiency can be calculated as following

$$\eta_{pv} = \frac{P_{out}}{P_{in}} \times 100\% \quad (4)$$

where P_{out} is PV output power (W), and P_{in} is PV input power. The equation that follows can be used to determine the PV-based water heating system's overall efficiency:

$$\eta_{total} = \eta_{pv} \times \eta_h \quad (5)$$

where η_{pv} is PV cell efficiency and η_h is heater efficiency.

3. Experimental Study

In this research, the solar water heating experiment does not depend on the weather because it uses a halogen bulb as a light source. Lighting from halogen bulbs simulates as natural solar radiation. Light is converted into electrical energy using PV cells which are connected in parallel and then connected to a DC heating element or PTC heater to heat water stored in a storage tank. Experimental study was carried-out by operating the PV water heating system with various volume of 10 liters, 15 liters, and 25 liters of water tank. Solar radiation, PV voltage and current, and tank water temperature are among the recorded data.

Figure 1 shows the PV water heating system design includes a PV, heater circuit, and water tank. Considerations that need to be considered in designing a water heater are economical, strong, high productivity, ease of manufacturing process and easy to operate. The experimental set-up is shown in Figure 2.

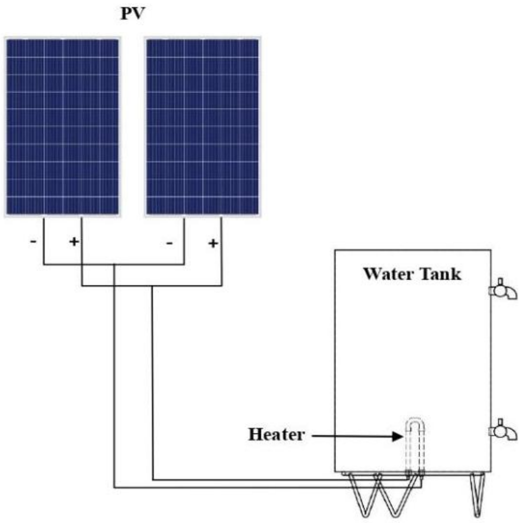

Fig. 1. Scheme of PV-based water heating system

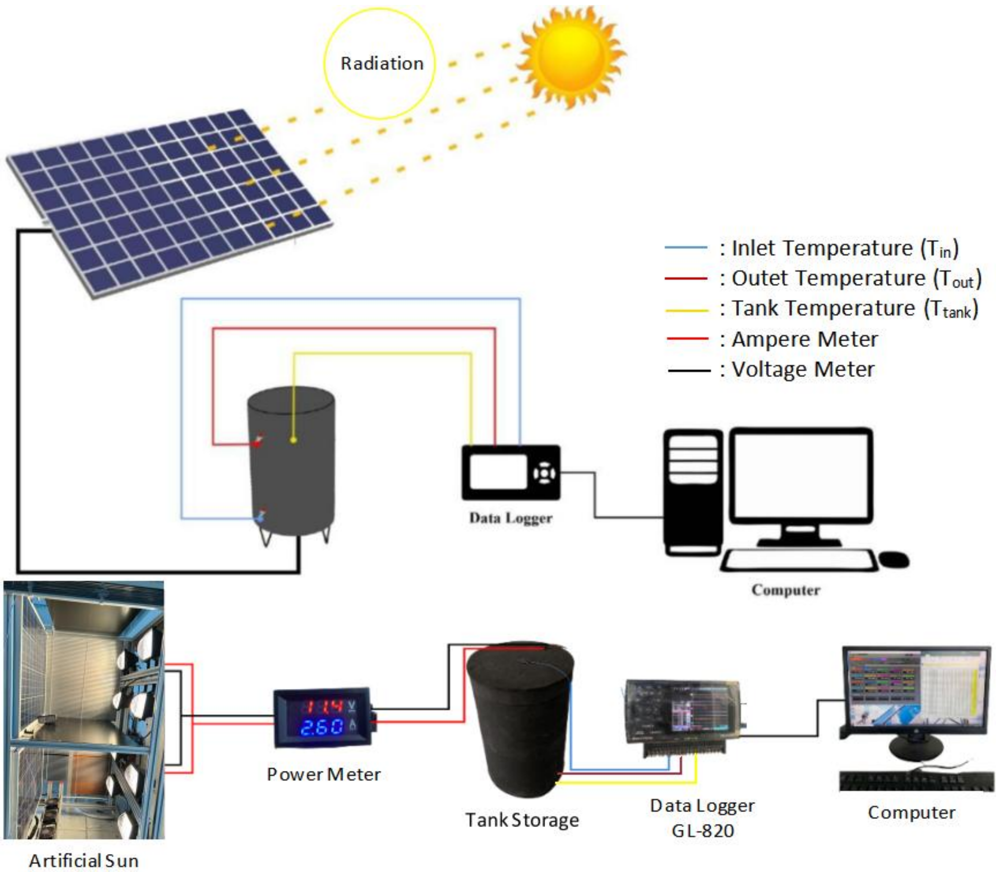

Fig. 2. Experimental set-up

The PV cells used are 2 polycrystalline cells with a capacity of 85 WP for each cell. The lamps used as energy sources are 500 watts and 230 volts halogen lamps as many as 8 pieces. Heater using a heating element plate are 30 watts and 12 volts DC. The tools used as experiments in the research included three variations in water tank volume, namely 10 liters, 15 liters, and 25 liters. Experimental testing for each variation of water tank volume was tested from 9.00 am to 16.00 pm. The recorded data includes radiation intensity, water temperatures, PV cell voltage and current. A voltmeter is used to measure the voltage and current generated by a photovoltaic cell, a data logger Graphtec

GL-820 with a thermocouple is used to measure the temperature of the water in the storage tank, and a solar power meter is used to measure the intensity of light produced by a halogen bulb.

4. Results and Discussion

The experimental approach was used to carry-out this study. The changes are achieved by changing the water tank's capacity, which is 10 liters, 15 liters, and 25 liters. To ascertain the ideal water temperature in the storage tank, the energy required to heat the water, and the thermal efficiency of PV-based water heaters, tests were conducted.

4.1 PV Cell Efficiency

Based on the data obtained, it can be seen that the efficiency of the PV produced over time, where the efficiency of the photovoltaic cell obtained comes from the amount of output power produced by the PV cell divided by the amount of input power from the PV cell itself. Figure 3 shows the efficiency characteristics of PV cells over time at varying water tank volumes of 10 liters, 15 liters, and 25 liters. Based on the Figure 3 for the 10 liters water tank variation, the efficiency produced from PV cells achieved an average efficiency of 7.17%. In the 15 liters water tank variation, the efficiency produced from PV cells achieved an average efficiency of 7.49%. Meanwhile, in the 25 liters water tank variation, the efficiency produced from PV cells achieved an average efficiency of 7.36%. One of the factors that affect the size and efficiency of photovoltaic cells is the intensity of solar radiation that affects the efficiency of photovoltaic cell performance. The greater the intensity of solar irradiation, the higher the performance of photovoltaic cells.

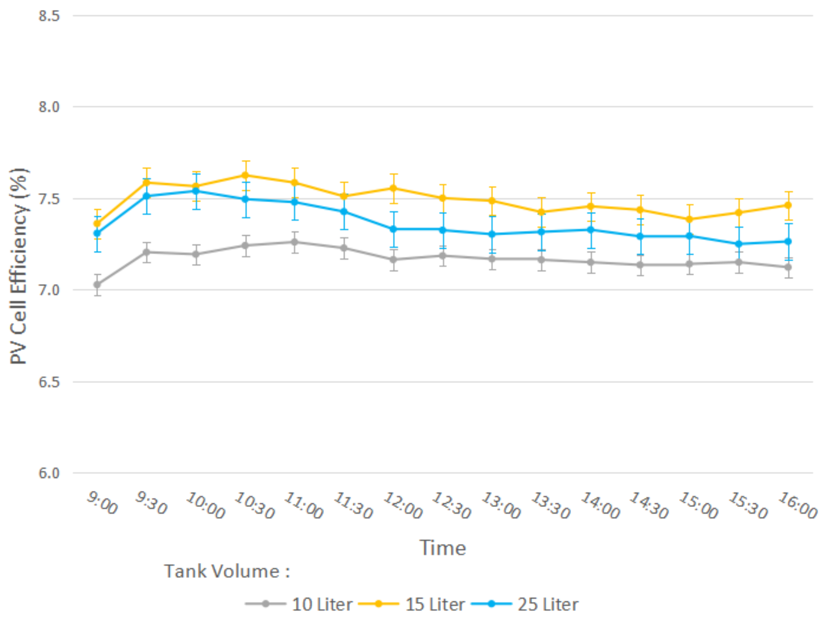

Fig. 3. PV cells efficiency

4.2 Heat Energy of Water

Figure 4 shows the heat characteristics of water over time in varying water tank volumes of 10 liters, 15 liters, and 25 liters. Based on this figure, the accumulated heat energy of water produced from 09.00 am to 16.00 pm increases for all variations of water tanks. For the 10 liters water tank variation, the water heat energy produced reaches 552 Joule in average. For the 15 liters water variation, the water heat energy produced reaches 519 Joule in average. Meanwhile, For the 25 liters water tank variation, the water heat energy produced reaches 598 Joule in average. Based on the data generated, it can be concluded that the higher the temperature of the water in the water tank, the greater the heat of the water in the tank. Other influencing factors are water mass and water temperature differences.

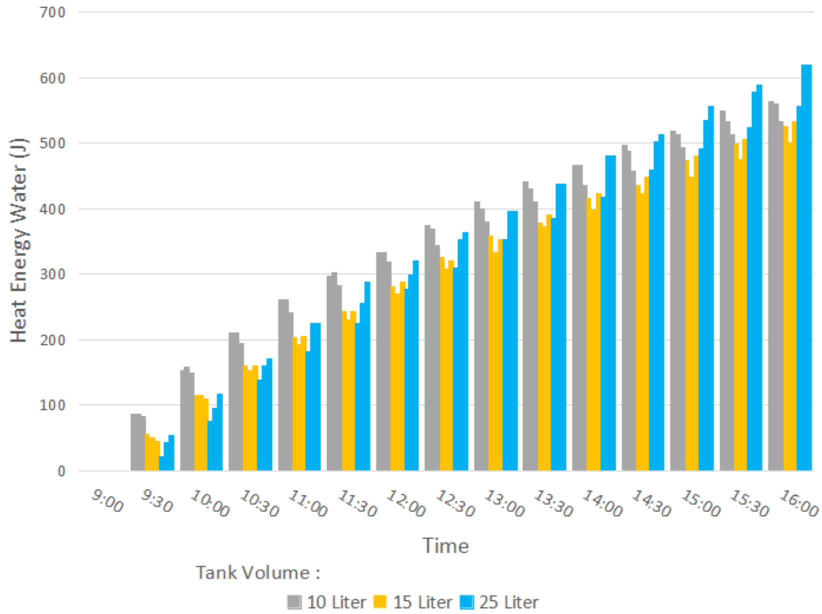

Fig. 4. Heat energy of water

4.3 Heater Efficiency

Figure 5 shows the characteristics of heater efficiency over time for varying water tank volumes of 10 liters, 15 liters, and 25 liters. Based on the Figure 5, the resulting heater efficiency increases for all variations of water tanks. For variations in the volume of the 10 liters water tank, the average heater efficiency obtained from the overall data is 44.40%. With variations in the volume of the 15 liters water tank, the average heater efficiency obtained from the overall data was 38.96%. Meanwhile, for variations in the volume of the 25 liters water tank, the maximum average heater efficiency obtained from the overall data was 73.6%. This is due to the power generated from the photovoltaic cell is stable while the power required by the heater is sufficient to heat the water in the tank because the power required by the heater is not too large. Another factor is that the heat of the water in the tank is increasing, while the heater power used is fixed so that it takes a long time to heat the water. The heat required to heat the water is fixed and the heater power is also fixed, the greater the time required to heat the water. This is because the greater the heat required to heat the water, the longer it takes to reach the desired temperature.

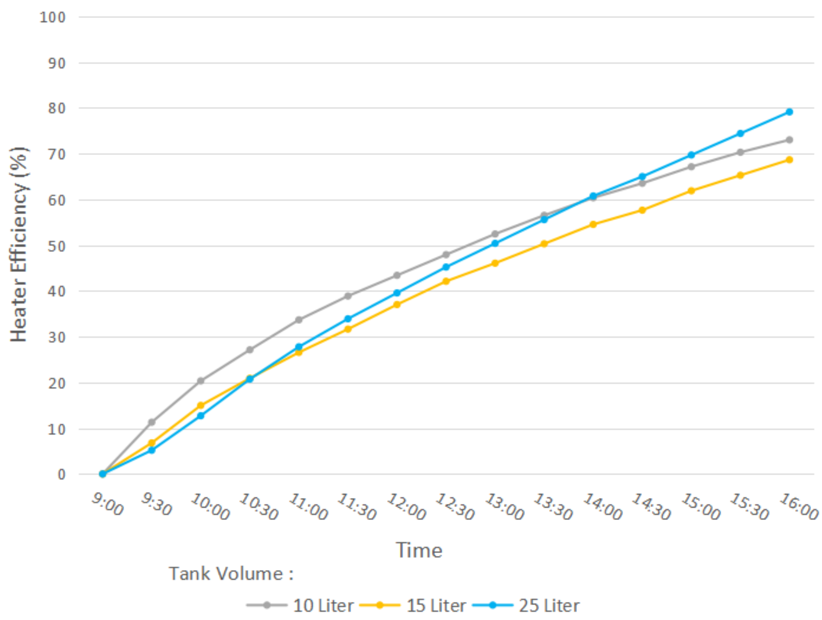

Fig. 5. Heater efficiency

4.4 Total Efficiency

The features of overall efficiency over time for different water tank capacities of 10 liters, 15 liters, and 25 liters are displayed in Figure 6. For all modifications in water tank volume, the total efficiency attained over time is increasing. Up to 16.00 pm, the average total efficiency over time derived from all data was 3.18% for variations in the volume of the 10 liters water tank. With variations in the volume of the 15 liters water tank, the average of total efficiency over time from all the data was 2.91% up to 16.00 pm. Meanwhile, for variations in the volume of the 25 liters water tank, the average of maximum total efficiency over time obtained from all data was 5.35% up to 16.00 pm. The total efficiency value produced is influenced by the type of photovoltaic cell used because the type of photovoltaic cell used can affect the overall efficiency of the solar panel. In addition, the intensity of solar radiation received by solar panels, as well as the type of heater used also affect the total efficiency of photovoltaic cells.

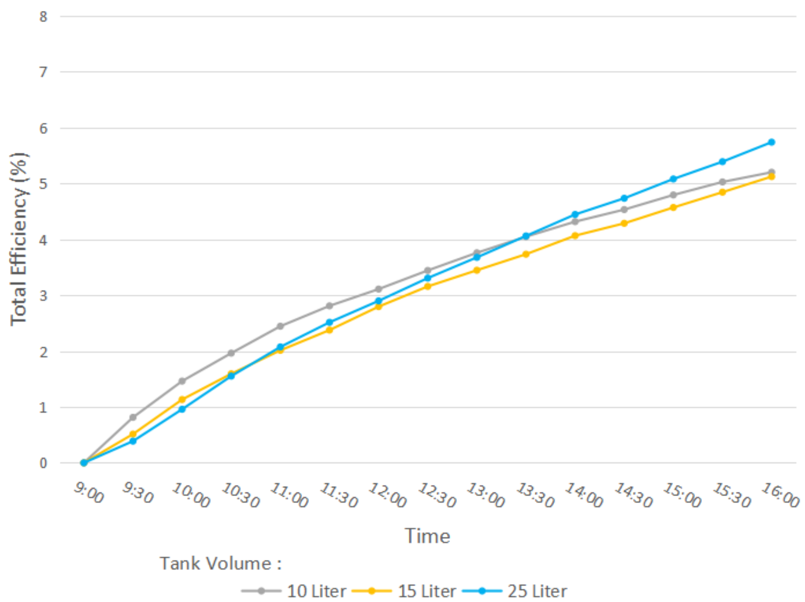

Fig. 6. Total efficiency

4.5 Optimal Water Temperature

Figure 7 shows that the temperature of the water produced for a 10 liters water tank volume increases from 09:00 am to 16:00 pm. For the first data, the resulting water temperature reached 38.6°C, where the initial temperature was 27.6°C. Likewise, in the second data the resulting water temperature reached 38.4°C, where the initial temperature was 27.5°C. Meanwhile, for the third data, the resulting water temperature reached 37.6°C, where the initial temperature was 27.2°C. So, the increasing temperature in average obtained from variations in the volume of a 10 liters water tank is 10.8°C. In the water tank volume of 15 liters, for the first data, the resulting water temperature reached 35.2°C, where the initial temperature was 27°C. Likewise, in the second data, the resulting water temperature reached 35°C, where the initial temperature was 27.2°C. Meanwhile, for the third data, the resulting water temperature reached 35.6°C, where the initial temperature was 27.3°C. So, the increasing temperature in average obtained from variations in the volume of a 15 liters water tank is 8.1°C. Similar to variations in the volume of 10 and 15 liters water tanks, the water temperature of the 25 liters water tank also increases from 09:00 am to 16:00 pm. For the first data, the resulting water temperature reached 32.9°C, where the initial temperature was 27.7°C. Meanwhile, in the second data and the third data, the resulting water temperature is the same, namely 33.7°C, where the initial temperature was 27.9°C. So, the increasing temperature in average obtained from variations in the volume of a 25 liters water tank is 5.6°C. Based on this data, it can be concluded that what affects the change or increase in water temperature in the storage tank is the mass of water in the tank. In addition, the type of heater used also affects the effectiveness of the photovoltaic cell.

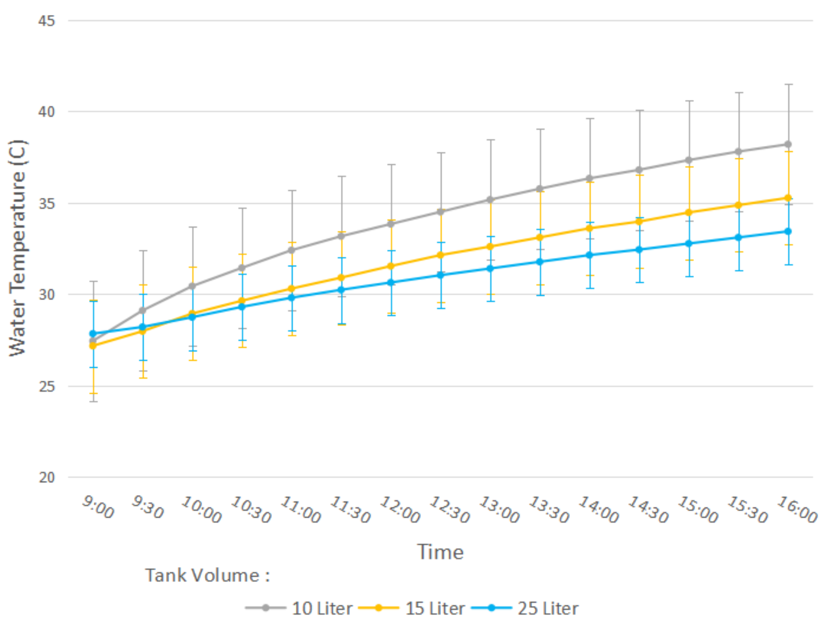

Fig. 7. Optimal water temperature

5. Conclusions

The PVWHS design consists of a storage tank, 2 polycrystalline PV cells with a capacity of 85 WP for each cell, lamps used as energy sources are 500 watts and 230 volts halogen lamps and uses a PTC water heater as a water heater with a capacity of 12 volts and 30 watts. The storage tank is made of stainless steel with a tank volume of 25 liters. This system is safe to use to meet daily hot water needs and also has high productivity, is more economical, and is very easy to operate.

With a 10 liters water tank, the PVWHS can raise the average water temperature by 10.8˚C, bringing the ideal water temperature down to 38.2˚C from its starting point of 27.4˚C. Additionally, it can raise the average water temperature by 8.1˚C at a 15 liters water tank, making the optimal water temperature 35.2˚C instead of the initial 27.1˚C. At a 25 liters water tank, it can raise the average water temperature by 5.6˚C, making the optimal water temperature 33.4˚C instead of the initial 27.8˚C.

PV cell efficiency, heater efficiency, and overall efficiency are all provided by the PVWHS. It was discovered that the efficiency of polycrystal photovoltaic cells was 7.34% for all variations of water tanks. The highest heater efficiency was discovered to be 73.6% for all variations of water tank. Regarding the highest overall efficiency, 5.35% was the average for all water tank variations.

Compared to the system utilizing traditional water heater with energy sources from fossil fuels, the use of solar water heating system based on photovoltaics is an environmentally friendly technology that is more economical, especially if solar energy sources are available and also reduces carbon emissions. This system will also enhance performance when integrated with conventional solar water heating systems based on collector plates in a hybrid configuration.

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