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Photovoltaic-Thermal Systems for Producing Hot Water: A Thermal Study

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Abstract
Photovoltaic technology harnesses solar energy to generate electrical power. With high solar radiation intensity, battery overcharging is risky due to its limited capacity. The surplus electricity generated by solar modules can be converted into thermal energy. This study analyses the thermal behavior of water heating processes within a storage tank in the photovoltaic system. The experiment included a solar module, controller, battery, storage tank, water pump, heating element, and five thermocouples. The study was conducted outdoors over three days, and solar radiation intensity and water temperature were recorded in the tank. The collected data was used to evaluate the photovoltaic-thermal system, especially in the thermal aspect. Results showed that higher solar radiation intensity led to increased water temperatures. The study's highest recorded cumulative thermal energy and efficiency were 1502.74 kJ and 29.34%, respectively. The photovoltaic systems can serve as sources of both electrical and thermal energy.

INTRODUCTION

Solar energy is a naturally occurring renewable energy source. Indonesia has an abundant supply of solar energy, with data from the Directorate General of EBTKE indicating that the country's average solar energy insolation is 4.8 kW/m²/day (BPPT, 2019; Nehru et al., 2020). In 2025, Indonesia's electricity demand will reach approximately 120 GW (Sukmajati & Hafidz, 2015). According to Presidential Regulation No. 79/2014, the National Energy Policy mandates that renewable energy should contribute 23% to the primary energy mix by 2025 (BPPT, 2019). This policy underscores the importance of developing solar energy as a key energy source for Indonesia's future.

Solar energy applications are broadly categorized into solar thermal and photovoltaic (PV) systems. Solar thermal systems convert solar energy into heat for warming substances, while PV systems generate electricity for power supply. Typically, these systems operate independently. In solar thermal systems, external electrical energy is needed to circulate the working fluid through mechanical components. Meanwhile, PV system efficiency declines significantly as the module temperature rises. To eliminate the need for an external power source and to cool the PV module, it must be integrated with a solar heating collector using either air or water as the working fluid. This combined system is a solar photovoltaic-thermal (PV/T) collector (Sarhaddi et al., 2010).

A simple PV installation comprises four main components: solar modules, batteries, controllers, and lamps (Nadjib, 2014). Among these, the battery requires special attention due to its high cost. During daily operation, PV installations are prone to battery overheating, mainly when high solar radiation leads to rapid charging and a significant current flow from the PV module. One way to manage excess charging current is by utilizing electrical energy to generate hot water. This study explores the use of PV installations for both electrical and thermal energy production on a domestic scale. This approach is advantageous as it helps maintain PV module efficiency, prevents battery overheating, and extends battery lifespan. Additionally, it enables PV installations to provide hot water for household use.

The demand for hot water in households and industries continues to grow alongside technological and societal advancements. Hot water is essential for bathing, washing, healthcare, and heating in various industries. Solar energy provides a sustainable solution through solar thermal systems, specifically solar water heaters. Additionally, solar energy has long been used for electricity generation, with Indonesia reaching an installed capacity of 24.42 MW by 2018 (BPPT, 2019). Given the widespread use of PV installations, there is significant potential to harness this technology for hot water production using the photovoltaic-thermal (PV/T) concept.

Previous studies have extensively explored photovoltaic-thermal (PV/T) systems. Jakhar et al. (2017) developed and analyzed a hybrid system integrating a photovoltaic thermal solar system with a groundwater heat exchanger (Jakhar et al., 2017). Hasan et al. (2018) designed, built, and tested a thermal photovoltaic (PVT) solar collector utilizing water jet impingement (Hasan et al., 2018). Fu et al. (2019) compared a PV/T system using a direct-coupled photovoltaic pump with a traditional DC pump and natural circulation (Fu et al., 2019). Hossain et al. (2019) examined a PV/T system incorporating parallel serpentine pipe flow (Hossain et al., 2019). Abdullah et al. (2020) introduced a novel double-oscillating copper pipe absorber designed for a water-based PVT system (Abdullah et al., 2020). Li et al. (2020) focused on simultaneous electrical and thermal energy generation through PV/T system development (Li et al., 2020). Xu et al. (2020) conducted experimental research on PV/T combined with phase change materials (PCM) (Xu et al., 2020). Fadli et al. (2021) investigated the impact of Titanium Dioxide (TiO_2) nanofluids at a 0.5 wt% concentration mixed with water in a PV/T collector system (Fadli et al., 2021). Anand et al. (2021) explored the application of PV/T technology for desalination, utilizing both electricity and thermal energy from photovoltaic thermal collectors to lower costs, reduce primary energy consumption, and enhance overall system efficiency (Anand et al., 2021).

Previous research on PV/T systems has primarily focused on generating hot water by circulating a working fluid beneath the PV module. However, studies examining hot water production by directing electricity from the PV module to a water storage tank by using electric heating elements remain unexplored. Therefore, this research is essential to address this gap in PV/T system development. The study emphasizes the thermal aspects of the PV/T system as a hot water producer. Its objective is to analyze the thermal behavior of a PV/T system integrated with a hot water storage tank. In the long run, this development aims to create a dual-function PV system capable of simultaneously generating electricity and hot water.

RESEARCH METHODS

Materials

This experiment uses water as the heat transfer fluid (HTF). The thermal energy absorbed by the water gradually raises its temperature over time. The water circulates continuously from the storage tank to the heater and then returns to the tank.

Experimental Setup

This experiment integrates a PV system with a hot water generation system, utilizing the electrical energy produced by the PV system for water heating. The primary equipment includes solar modules, batteries, battery charge controllers (BCC), pumps, electric heaters, and water storage tanks. The solar module, battery, and charge controller generate and store electrical energy, while the remaining components facilitate thermal energy production. Measurement instruments used in the experiment include a solarimeter, flow meters, thermocouples, and a data acquisition system. The solarimeter records solar irradiation, the flow meter controls the water flow rate, and thermocouples are used to measure and record temperature data. Figure 1 illustrates the experimental setup.

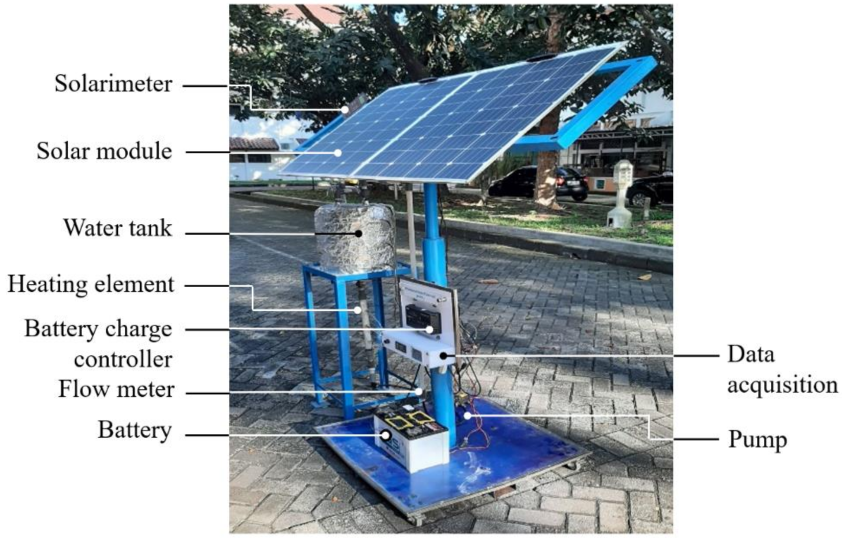


Figure 1. Experimental apparatus

The experiment utilized two thin-film solar modules, each with a power rating of 50 Wp (watt-peak). The modules were installed facing north at a 20° tilt angle. They were connected in parallel, maintaining a voltage of 12 V while doubling the current. The output cable from the solar module junction box was linked to the battery charge controller (BCC), which was then connected to the battery. A 100 Ah automotive battery was used for energy storage. The pump and electric heater were subsequently connected to the battery. The piping system was assembled using ¾" PVC pipes running from the outlet to the tank inlet. The water storage tank had a capacity of 20 litres, and a 35 W electric heater was installed in a pipe at the tank's inlet. The water temperature was measured using five K-type thermocouples, with sensors placed at the tank's inlet and outlet and three positioned inside the tank. A flow meter was installed in the inlet piping system to monitor water flow. Solar radiation intensity was recorded using a solarimeter.

Data collection was conducted outdoors from 09:00 to 14:00 WIB over three days. The recorded parameters included solar radiation intensity and the temperature of the heat transfer fluid (HTF) at a flow rate of 1 litre per minute. Data acquisition was performed using a system connected to a laptop, where the recorded data was processed using Cool Term software. Analysis was carried out by examining the measured solar radiation intensity and the evolution of HTF temperature. Subsequently, calculations were made for instantaneous heat storage, cumulative heat stored in the thermal energy storage (TES) tank, and the thermal efficiency of the PV/T system. The results were then presented in graphical form.

Instantaneous heat stored (Q) is the thermal energy of HTF stored momentarily in the TES tank. This thermal energy is sensible heat type and expressed as in the equation (1) (Nallusamy et al., 2007).

$$Q = \dot{m}_{HTF} \mathrm{c}_{p,HTF} (T_{in} - T_{out}) \qquad (1)$$

with $\dot{m}_{HTF}$ represents the mass flow rate of the heat transfer fluid (HTF) in kg/s, $\mathrm{c}_{p,HTF}$ denotes the specific heat capacity of the HTF in kJ/kg·K, T_{in} and T_{out} correspond to the HTF temperatures at the tank's inlet and outlet, respectively, measured in degrees Celsius (°C).

Cumulative heat stored Q_{cum} is the amount of heat stored in the HTF from the beginning to the end of the charging process. This parameter is found by summing up the instantaneous heat stored in each data collection and accumulating it until the end of the data collection. Cumulative heat stored is calculated based on the equation (2) (Agarwal & Sarviya, 2016).

$$Q_{cum} = \int_0^{t_1} Q_{ch1}\, dt + \int_{t_1}^{t_2} Q_{ch2}\, dt + \cdots + \int_{t_{n-1}}^{t_n} Q_{chn}\, dt \qquad (2)$$

with Q_{chn} is the instantaneous thermal energy occurring in the TES tank at each data collection time, and t_n and t_{n-1} describe the time between instantaneous thermal energy calculations.

The thermal efficiency of a PV/T system is defined as the ratio of useful energy utilized for heating water to the total energy received by the solar module (Al-Waeli et al., 2017).Thermal efficiency is calculated using Equation (3).

$$\eta = \frac{\dot{m}_{HTF} c_{p,HTF}(T_{in}-T_{out})}{A_m . I_R} \quad (3)$$

with A_m is the surface area of solar module (=0.756 m^2) and I_R is the solar irradiation (watt/m^2).

RESULTS AND DISCUSSION

Solar Irradiance

Figure 2 illustrates the variation in solar radiation intensity recorded throughout the experiment. Each data collection time is five hours. The graph created is a recording of radiation intensity every five minutes.

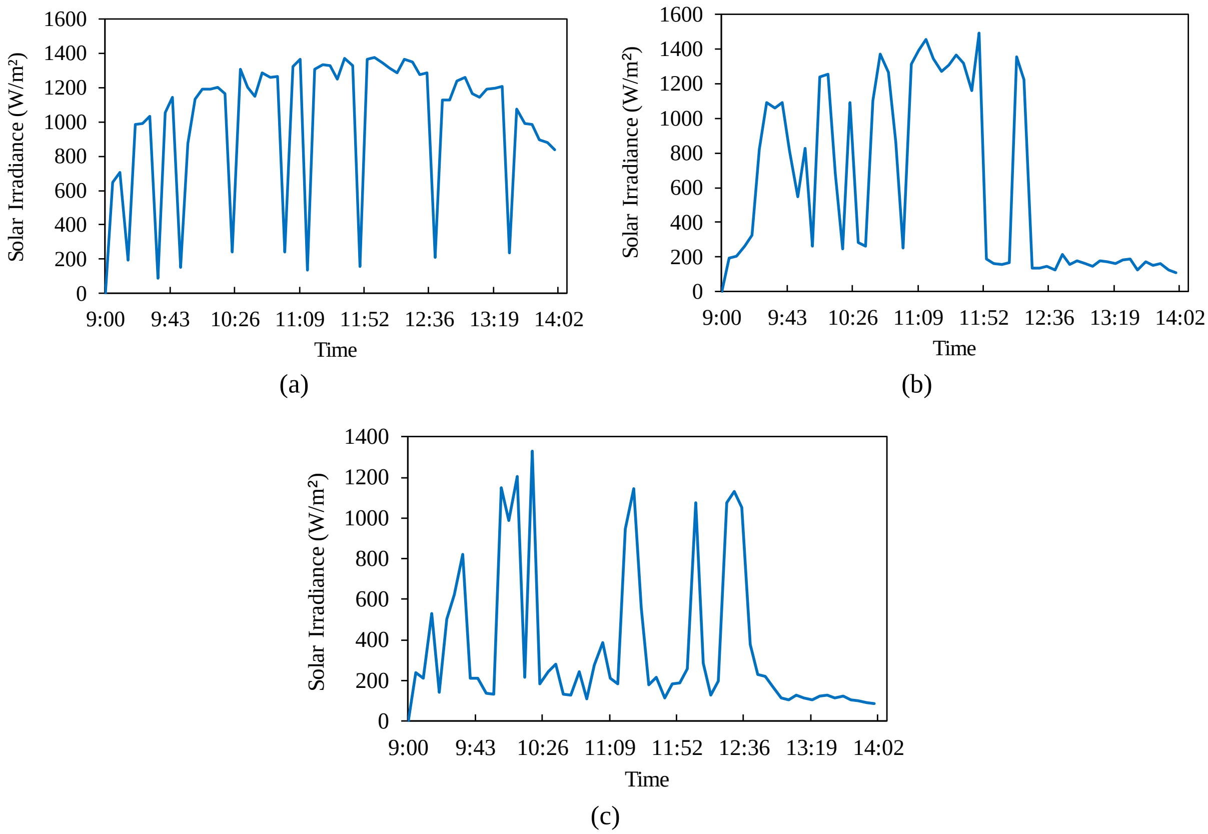
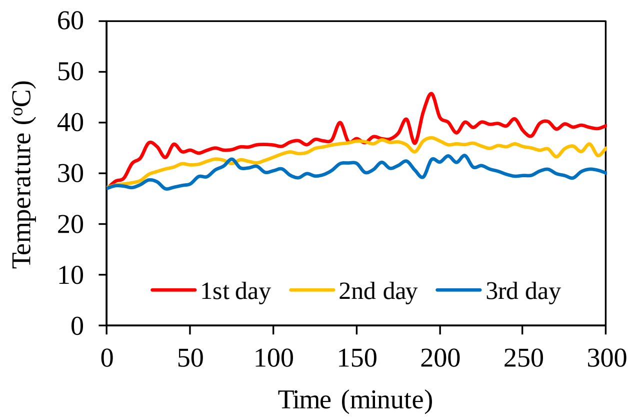


Figure 2. Solar irradiance during experiment: (a) first day, (b) second day, (c) third day

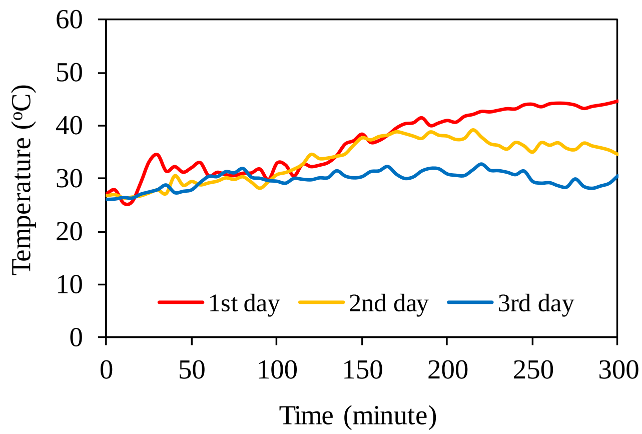
The three graphs in Figure 2 illustrate the fluctuations in solar radiation intensity throughout the experiment. On the first day, the highest recorded intensity was 1376.7 W/m² at 11:59. In comparison; the lowest was 89.7 W/m² at 09:75. On the second day, the peak intensity reached 1492.1 W/m² at 11:50, with the lowest value recorded at 109.5 W/m² at 14:00. On the third day, the maximum intensity was 1330.2 W/m² at 10:20. In contrast, the minimum was 86.2 W/m² at 14:00. These variations indicate that solar radiation intensity fluctuates due to changing atmospheric conditions, such as clouds, water vapor, dust, and aerosols (Sen, 2008). The average solar radiation intensity for the first, second, and third days was 1006.6 W/m², 610.1 W/m², and 364 W/m², respectively.

Evolution of HTF Temperature

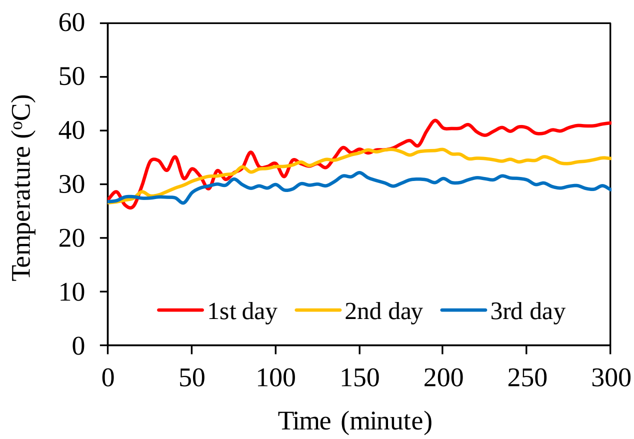
The variation in HTF temperature reflects the water temperature conditions during the charging process. Figure 3 presents the HTF temperature changes at the tank's inlet and outlet, along with the average temperature inside the tank.



(a)



(b)



(c)

Figure 3. HTF temperature evolution: (a) tank inlet side, (b) tank outlet side, (c) in the tank

Water passing through an electric heating element obtains thermal energy by convection heat transfer mode. The hot water produced then enters the tank. The installed thermocouples allow for measuring the water temperature at the tank's inlet and outlet and determining the average temperature of the hot water inside the tank.

The three graphs in Figure 3 have the same characteristics: the temperature increase fluctuates throughout charging. The fluctuating intensity of solar radiation causes the power produced by the solar module to change so that the electrical energy received by the electric heater also fluctuates. This phenomenon causes the heat transfer to water to change over time. Figure 3 also shows that the gain in water temperature depends on the irradiance.

The experimental results indicate that the highest inlet water temperature on the first day reached 45.77°C at 195 minutes, while on the second and third days, it peaked at 36.96°C and 33.59°C at 195 and 215 minutes, respectively. The maximum outlet water temperature was recorded at 44.57°C at 300 minutes on the first day, 39.12°C at 215 minutes on the second day, and 32.34°C at 220 minutes on the third day. The highest HTF water temperature inside the tank occurred at 195 minutes on the first day, reaching 43.13°C, followed by 37.54°C at 195 minutes on the second day and 32.66°C at 215 minutes on the third day. The average HTF water temperature inside the tank over the three days was 36.44°C, 33.23°C, and 29.64°C, respectively.

Instantaneous Heat Stored

Instantaneous heat stored represents the amount of thermal energy accumulated in the water within the tank at any given moment. This parameter is calculated based on the difference in water temperature on the tank's output and input sides, as shown in Figures 3(a) and 3(b). Figure 4 shows the instantaneous heat stored during charging.

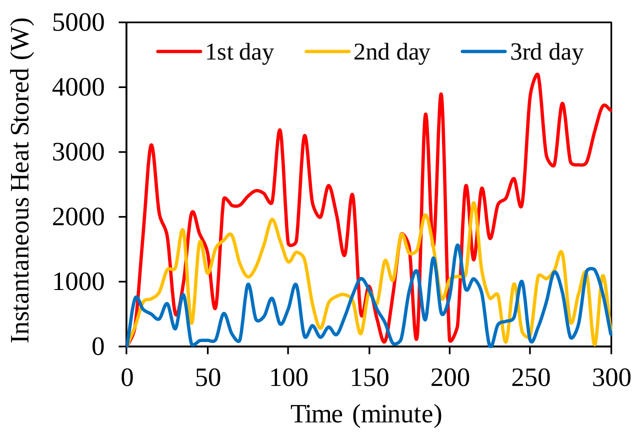


Figure 4. Instantaneous heat stored for three days experiments

The research findings indicate that the stored instantaneous thermal energy initially increases gradually due to the slow rise in water temperature at the beginning of the charging process. On the first day, the highest instantaneous thermal energy stored was recorded at 255 minutes, reaching 4182.98 kJ/s. On the second day, the peak value was 1723.25 kJ/s at 170 minutes, while on the third day, it reached 1559.73 kJ/s at 205 minutes. The decrease in instantaneous thermal energy stored was influenced by low solar radiation intensity due to cloudy weather. Conversely, higher solar radiation intensity led to an increase in thermal energy stored in the TES tank. Fluctuations in solar radiation during the experiment resulted in unstable input and output water temperatures, causing variations in temporary heat storage. A higher intensity of solar radiation generates more incredible electrical energy, allowing the electric heater to operate optimally and raise the temperature of the water entering the tank. According to Equation (2), a higher inlet water temperature leads to more excellent instantaneous heat storage. These results align with the findings of Nallusamy et al. (2007), which suggest that increased solar irradiation enhances the hot water temperature produced by a solar water heater (Nallusamy et al., 2007).

Cumulative Heat Stored

Cumulative thermal energy is obtained by multiplying the instantaneous stored thermal energy in the TES tank with time and then adding it cumulatively. This energy represents the total accumulation of thermal energy stored in the TES tank. Figure 5 illustrates cumulative heat storage throughout the experiment.

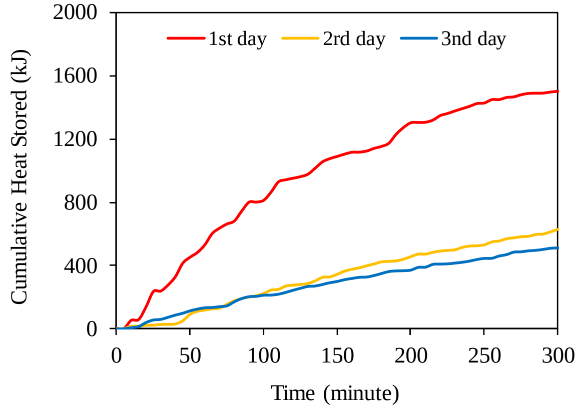


Figure 5. Cumulative heat stored for three days experiments

Figure 5 illustrates the impact of solar radiation intensity on the cumulative energy stored in the TES tank. When solar radiation intensity is high, cumulative energy storage increases significantly, whereas lower solar radiation intensity results in a slower accumulation of stored energy. As shown in Figure 4, the high instantaneous heat stored on the first day was due to intense solar irradiation. Although on the first day, there was a fluctuation in solar irradiation, the level of fluctuation tended to be stable throughout the day. This condition caused hot water production to be undisturbed, so the difference in water temperature at the inlet and outlet of the tank tended to be significant. This phenomenon is different from the experiments on the second and third days, where solar irradiation fluctuated wildly so that the difference in temperature at the inlet and outlet of the tank was low. Since cumulative heat storage is the sum of instantaneous heat storage, a higher instantaneous heat value leads to more excellent cumulative heat storage. The highest cumulative energy recorded was 1502.74 kJ on the first day, 629.29 kJ on the second day, and 511.48 kJ on the third day. These findings confirm that higher solar radiation intensity produces more incredible cumulative energy (Nallusamy et al., 2007). Additionally, increased solar radiation enhances hot water production, resulting in higher thermal stratification within the tank (Nadjib et al., 2023). The presence of thermal stratification improves the system's overall thermal efficiency.

Thermal Efficiency

This parameter represents the comparison between the energy absorbed by the solar module and the thermal energy accumulated in the TES tank. The thermal efficiency of the PV/T system is presented in Figure 6.

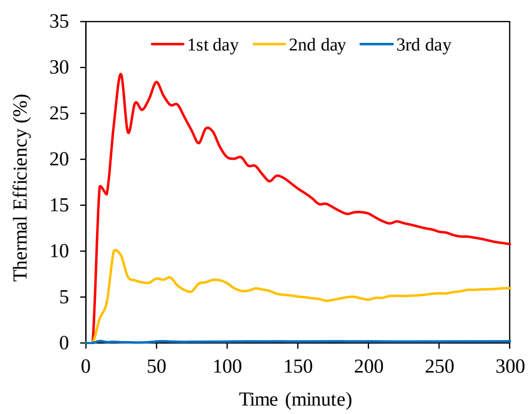


Figure 6. Thermal efficiency for three days experiments

Figure 6 illustrates that the thermal efficiency of the PV/T system rises at the beginning of the charging process. This phenomenon is because the thermal energy stored at the start of charging is still high but decreases as the charging process progresses. The highest thermal efficiency on the first day occurred at 25 minutes at 29.34%, then experienced a gradual decrease in efficiency along with the length of the charging process. The highest thermal efficiency value on the second day was recorded at 9.95% at 20 minutes; on the third day, it was 0.23% at 10 minutes. The thermal efficiency value for the third day is minimal compared to the first and second days. This condition is influenced by the low solar radiation intensity observed on the third day. The low intensity of solar radiation, coupled with its high fluctuation level, causes low electrical energy production, thus inhibiting the performance of the electric heating element. This situation results in low thermal energy stored in the tank; according to Equation (3), low beneficial thermal energy results in low thermal efficiency of the PV/T system.

CONCLUSION

Experimental studies have been conducted on PV/T systems for thermal energy production through water heating. The intensity of solar radiation significantly affects the thermal performance of a PV/T system. At an average solar radiation intensity of 1006.6 W/m² and a charging duration of 300 minutes, the average water temperature in the TES tank, cumulative heat stored, and thermal efficiency were recorded as 36.44°C, 1502.74 kJ, and 29.34%, respectively. These findings confirm that PV systems can generate thermal energy for water heating, although on a small scale. The developed PV/T system offers additional benefits, such as extending battery lifespan by reducing overcharging conditions and producing hot water for daily household use. Similar research can be conducted in the future by simultaneously evaluating electrical and thermal performance for large water tank volumes.

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