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Experimental evaluation on the power characteristic of direct-photovoltaic charging for thermal storage equipment

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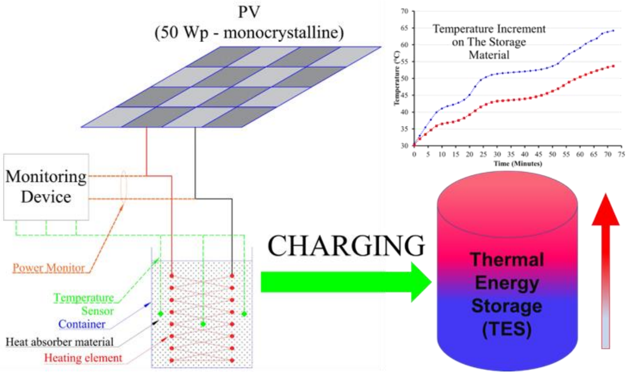

Highlights:

- Direct photovoltaic charge for thermal storage is preferable.
- Stabilized phase behavior is advantageous with isothermal phase transition.
- Higher resistive heating leads to a better power ratio up to 38.6%.

Abstract

Thermal storage is an essential equipment for storing excessive heat, especially for water heating systems. The present work proposes a preliminary study to maximize the operation of thermal storage using photovoltaics as the primary source for charging the heat storage material. The assessment indicates the concept is feasible, where the output power from photovoltaics can be directly converted to heat using a heating element. The power ratio is considerably high (up to 38.6%), resulting in the maximum temperature of the heat absorber material (water) increasing to 43.2 °C. The final assessment using suitable phase transition material shows that steady phase behavior is essential to maximizing the temperature profile of the material. It is achieved using stabilized-hexadecanoic acid, which shows a transient phase transition at a temperature of 54.2 °C, reducing the possibility of heat loss with an average temperature rate of 0.54 °C/min in the discharge stage. This finding proves the proposed concept is applicable, while further improvement can be done to adjust the suitable power output from photovoltaic and storage tank arrangement for the actual system. Despite that, the result is expected to accelerate the utilization of photovoltaics as reliable solar renewable technology.

Keywords: Direct heating; Heat storage; Phase stable; Photovoltaic; Water heater

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1. Introduction

The development of energy systems for the global community shows a positive trend as a direct approach to cutting the consumption of fossil fuels. Besides the transportation sector, the high consumption of fossil fuel from coal power plants can be replaced by alternative solid fuels from waste [1]. Optimization is also conducted to increase the efficiency of thermal systems for power generation [2]. Renewable technology has also developed enormously over the past two decades. The solar-based power can be harvested for electric power production using photovoltaic (PV) [3] and for heat generation using mirrors for concentrated plants [4]. Solar energy is also suitable for small-scale systems such as water heating [5]. The cumulative solar heating using an evacuated tube collector (ETC) is extremely high, indicating the need for heating demand remains high, especially for cold regions.

The conventional model of ETC uses water as storage material. The concept is advantageous since the water can be directly used for the demand [6]. However, using water is unfavorable in terms of its energy density, which means the storage size should be large to accommodate the heating demand [7]. Moreover, the ETC uses light absorption for heating generation and is placed on the roof, which requires extensive structural modification to accommodate its weight [8]. Modification is performed to improve the solar water technology (SWT) by replacing the water with different thermal energy storage (TES) material [9]. The usage of phase transition material (PTM) for the TES system [10]–[12] is advantageous as it has a better energy density than water. It makes the development in PTM accelerated notably as an ideal option to increase the energy density of SWT.

The TES system operates using the basic principle of heat transfer. It makes the fundamental aspect of heat exchange crucial for the operational aspect of the system [13]. The system can operate under active or passive configuration. The passive system generally requires less extensive equipment [14], but it has many technical limitations due to minimum temperature operation [15]. Contrary to that, the active operation is highly desirable for various applications, with a high possibility to operate above 500 °C as seen in typical solar thermal plants [16]–[18]. It makes the development for active operation increase rapidly [19], considering the positive outcome of the system to meet the requirement of energy system.

The PTM is located in a specialized container, while the heat transfer process is done using external fluid [20]. The proposed model is generally used for the typical SWT system with PTM material, including the advanced model that uses a fin for better heat exchange [21]. The system requires an external pump to ensure the heat transfer from the external sources. It makes the net energy balance for the system less attractive. A better configuration can be designed using direct conversion from PV. A. Hamada et al. PV-thermal (PVT) for charging the PTM, resulting in an improvement in overall efficiency up to 74.1% [22]. The same concept is also proposed for further optimization. A. Basuhaib et al. studied the effect of operation for a PVT system, indicating the flow rate influences the maximum output with the highest water temperature at the outlet 45.8 °C [23]. The combined PVT is also suitable for cooling the PV layer and increases its efficiency. However, the system requires several modifications to locate the piping system and PTM material which possibly increases the cost of production.

The ideal model for the modification is considered using direct conversion of the electricity generated by PV for heating the PTM or water. For the SWT system, the literature here [24] focused on the usage of a charge controller, indicating the maximum power can be achieved for an advanced charge controller. For the site location, O. Hachchadi et al. performed a detailed evaluation of a large operation PV heater, where site location is considered as the crucial aspect to achieving the maximum solar fraction of the system [25]. M. Draou and A. Brakez proposed an optimized model for the application of a diverter-PV heater, resulting in a suitable achievement due to a significant decrement in the average auxiliary energy consumption up to 46% [26]. The excess electric production from PV was analyzed in this work [27], considering the integration of excess PV production for water heating, showing a better possibility to improve self-consumption by more than 50%. Direct PV conversion for heating purposes is also suitable for solar-still to produce distilled water [28]. The previous work demonstrates the interesting topic for development in PV heating systems, particularly for the possibility of integrating with SWT systems.

Improvement in the direct-PV heating for PTM system potentially improves the usability of solar-based energy. The key problem for the typical operation of a PV system is related to the electric battery [29]. It is the most vulnerable component, which has a shorter lifetime due to continuous operation [30]. Acceleration in the energy transfer leads to a substantial decrement in the long-term performance, reducing the lifetime of the battery [31]. Researchers focus on the modification of the material for the battery as well as operational management, aiming for the extended lifetime of the battery. Thus, using PTM system as alternative storage for PV systems is suitable to maximize the usability of PV and support the development of electric batteries to achieve a reliable solar-based energy system.

The direct-PV heating is considered a suitable method for performing direct charge of TES, utilizing the basic principle of a passive charge system [32]–[34]. It makes the component for TES simplified, making it more cost-effective and less energy-consuming for the operation. Nevertheless, the concept is rarely addressed by using direct-PV heating. Further evaluation is demanded to observe the possibility of integrating the TES system with direct-PV heating. The present work aims to analyze the charge characteristic of using direct-PV heating for TES material.

The result from this work can be adopted for the suitable development of TES system using PV as the thermal charger, potentially improving the usability of PV as a renewable energy source.

2. Methods

The assessment is performed through an experimental process. The first goal was to analyze the characteristics of PV output using different heating loads. The schematic of and view of the experimental process is shown in **Figure 1**. The electricity output of the PV was connected directly to the heater (**Figure 1a**), while the power output and temperature of the heat-absorbed material were recorded continuously. There were two PV panels installed on the rooftop to minimize the shading effect and deviation of the measurement (**Figure 1 b**). The monitoring device was installed in-lab to ensure the readability of the measurement and recording process

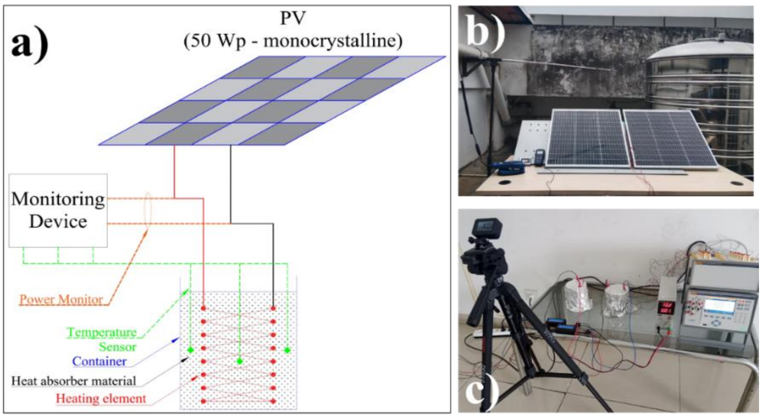

Figure 1. Experimental procedure: a) schematic of the measurement, b) PV installed at rooftop, c) In-lab monitoring device

The initial assessment was performed using two heating elements at different resistances: 2.6 Ω (low load/L1) and 3.2 Ω (high load/L2). The determination of the given loads was taken according to the maximum power of the PV (50 Wp). Moreover, the variation was intended to observe the power characteristic of the PV under the operation of a direct heating system. The nature operation was observed without a charge controller which potentially changes the output of the PV. It was also considered for design simplification since direct conversion can be achieved without extensive equipment as commonly found in the PV-based electric system. Thus, the maximum power and basic operation of the PV as a heat source can be observed more in detail according to this scenario.

The initial assessment used water as storage material. The volume of the water was 300 ml considering the maximum power of the PV in this work. The temperature was recorded simultaneously while the process was performed twice times. The final evaluation was performed using a suitable heating load according to the power profile from the initial measurement. In addition, the heat absorber material for the final test was hexadecanoic acid (HA) and stabilized HA (with LDPE), which is categorized as PTM. The proposed materials were used due to its high melting enthalpy and suitable phase behavior for active PTM. The detailed properties of the material can be found in this work [35].

3. Results and Discussion

Figure 2 presents the characteristics of weather conditions during the experimental phase of this work. In general, the relative humidity is relatively high due to geographical conditions. The same condition is also applied for the average temperature above 30 °C. In addition, the wind speed is extremely low during this work. The basic data is taken to support the analysis of the performance curve for each designed case.

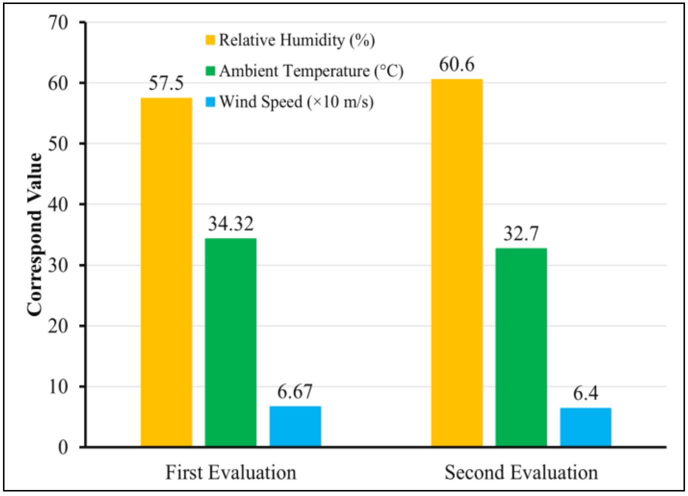

Figure 2. Weather condition during experiment test

The voltage and current curve from the first phase experimental stage is shown in **Figure 3**. The voltage has an identical pattern between the low and high loads. It indicates both PV experiences the same light conversion based on the environmental condition. The voltage output for low loads is generally lower than for high loads, with a maximum voltage is only 3.8 volts. In contrast, a high load is able to generate a better voltage with the highest value of 5 volts. Taking into detail the current profile, there is no substantial difference between the low and high load PV. The highest deviation is only 0.25 amperes.

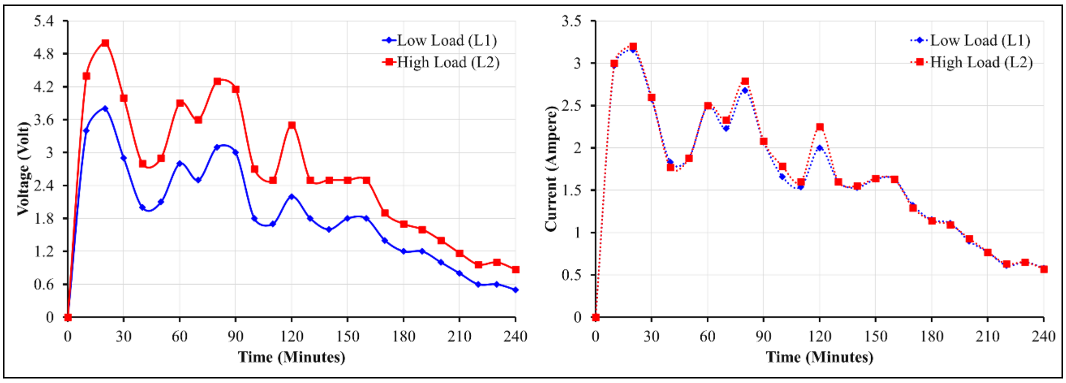

Figure 3. Voltage and current curve based on the load on the first phase experimental stage

The second stage evaluation shows the identic profile (**Figure 4**). The low load PV tends to produce a lower voltage compared to high-load PV. The average voltage for low-load PV is only 2.4 Volts while high-load PV has a higher voltage output of about 59.6%. It proves the dynamic behavior of PV output as a direct conversion for the electric load. In addition, there is a minor exception for the current curve where the low load PV is slightly higher than the high load PV. Despite the variation, it has an average ampere of around 1.78 ampere while high-load PV is able to produce a higher current output with an average of 2.27 ampere.

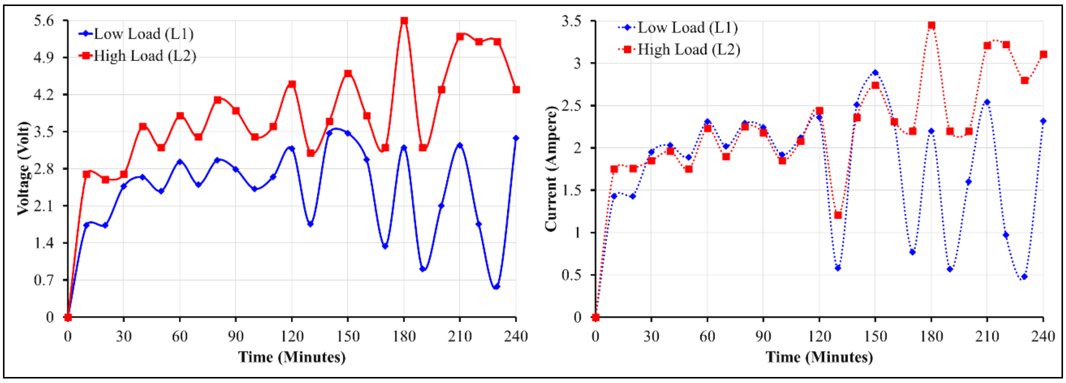

Figure 4. Voltage and current curve based on the load on the second phase experimental stage

The fluctuating power profile shows the natural operation of the PV when coupled with direct load. The final assessment was performed without a charge controller. It is intended to maximize the power output from the PV since the charge controller normally operates by limiting the voltage from the PV. Also, the proposed system uses resistive heating which requires no additional controller since the supplied power can be converted directly into heat. Thus, it reduces the number of components for the system and can maximize the power generated from the PV to the load.

The changes in the current and voltage output cause fluctuation in the effective power ratio. As displayed in **Figure 5**, the low load PV has the lowest effective power ratio. The power ratio is obtained by comparing the theoretical maximum power from the PV and the power obtained from the measurement. It shows a clear indicator to understand the effectiveness of the power generated from PV. The highest power ratio is only 24.6%, much lower compared to high-load PV which can produce an effective power ratio of around 32%. It signifies the power output of PV is highly dependent on the load, especially for the direct conversion method. The largest deviation is obtained from the second stage experiment, which is around 18.6% between the low and high load PV.

The high fluctuation for low-load PV reduces the maximum power output. Based on the measurement, the low load PV only converts 8.4% and 11.75% of the useful energy from the PV. In contrast, the high load PV produces much higher energy that converts around 11.8% and 17.9%. It indicates that stable conversion is ideally achieved to produce a higher power output. The heating load depends on the supplied voltage from PV, which means choosing a suitable heating load is essential to ensure the optimum power conversion. The result is important to understand the characteristics of PV output for the direct heating process.

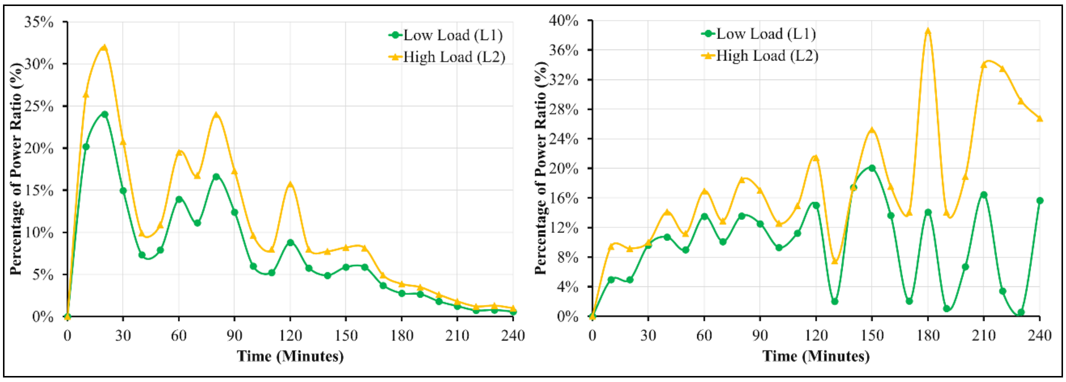

Figure 5. The effective power ration between low and high load PV

The proposed method shows a good result according to the targeted function as a direct conversion to heat water. As seen in **Figure 6**, the water temperature increases as the heating process continue from the PV. The maximum temperature for the low load PV (TW-LL) is 42.8 °C and 43.2 °C from this experiment. The maximum temperature increment is obtained at 12.5 °C and 9 °C for the first and second phases. The water tank is designed without external insulation. It makes the temperature fluctuate along with the experiment. Moreover, the decrement in the temperature corresponds to the power profile for the low load which has a higher fluctuation due to inconsistent conversion.

The water temperature for high load PV (TW-HL) is relatively lower than low load PV. However, it shows a steady temperature increment without causing significant fluctuation to achieve the maximum temperature at 41.3 °C and 42.7 °C. It has a suitable rating charge around 0.34 °C/minutes and 0.35 °C/minutes. Both results confirm the stable heating process is achieved for the high load PV. The water temperature falls after reaching the maximum temperature. It is caused by the significant decrement in the output from PV. However, high load PV is able to increases the temperature again after this condition. It confirms the suitable charge behavior from the high-load PV.

The high load PV is preferable. Hence, final evaluation was taken using a higher load (8 Ω) and using PTM as the TES material. The load is obtained by considering the average of power effective as seen in **Figure 5**. The resulting charging profile from PV for HA and SHAL is plotted in **Figure 7**. The HA has a higher temperature rate (0.26 °C/min) than SHAL (0.21 °C/min). Moreover, the higher temperature is obtained by PA due to different heat transfer characteristics since SHAL is combined with polymer. However, it indicates the unstable solid-liquid transformation (green square), causing the temperature to fluctuate in this region. Moreover, temperature tends to decrease with value of 2.1 °C. In contrast, stable solid-liquid transition makes the transition of SHAL becomes flattened, which means the isothermal transition can be obtained. It is the main benefit for embedding the PTM with polymer which act as shape stabilizer [36].

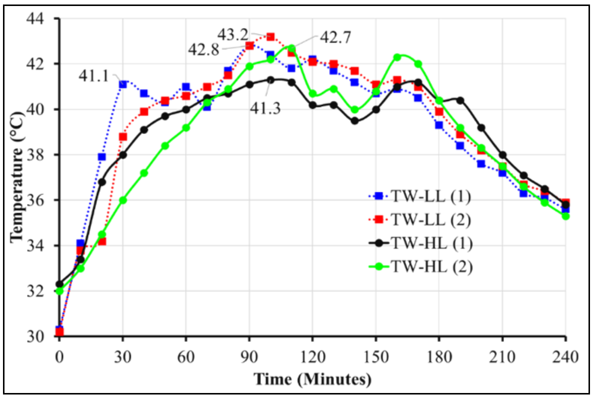

Figure 6. The temperature of water during the experiment process

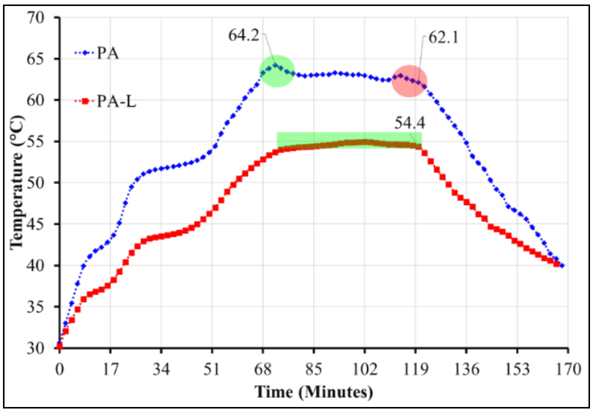

Figure 7. Charge temperature profile from direct-PV heating between two PTMs

The stored heat is liberated naturally as a function of discharge process. The HA has rapid temperature drops with maximum rate of 0.79 °C/min, while SHAL only 0.54 °C/min. The finding shows the suitability of direct-PV heating as an effective method to charge TES system, while using stable-PTM is favorable to obtain steady phase transformation. Moreover, the steady transformation reduces temperature gradient with environment, minimizing the potential for heat loss during the operation.

4. Conclusion

The preliminary work for evaluating PV as method to charge TES system is done by connecting the output to the heating element. It indicates a suitability to obtain combined TES system that can be integrated with SWT. The finding demonstrates a higher power can be achieved by using a higher heating resistant, with the highest power ratio up to 38.6%. The temperature of the heat absorber material increases along with the supplied electricity, with maximum temperature of water is 43.2 °C. In addition, phase stabilization for PTM implies a suitability to perform steady phase change, reducing the temperature fluctuation with a lower discharge rate 0.54 °C/min. This study demonstrates high fluctuation on the power output of PV, which can be further evaluated to ensure stability without using additional equipment such as charge controller. Moreover, the stored heat can be used for heating application, including solar heating system. It makes the proposed model ideal to maximize the utilization of PV as reliable solar power generation. The obtained results from this work are essential to further develop the PV-based TES system. The simplification of the charge method is favorable to simplifying the designation of the TES system. Further research is advisable, by employing different heating rates, including the possibility of autonomous charge scenario. Moreover, the combination of active heat liberation is also possible to achieve by employing various configurations of the TES's tank. It also can be combined by employing different PTM to improve the temperature operation of the system.

Authors' Declaration

Authors' contributions and responsibilities - Reza Abdu Rahman: Writing – original draft, Investigation, Data curation, Conceptualization. Sulistyo: Writing – review & editing, Validation, Supervision, Writing – review & editing, Validation, Supervision. M.S.K. Tony Suryo Utomo: Formal analysis. Dimas Ragil: Visualization, Methodology. Budhi Muliawan Suyitno: Supervision, Methodology.

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Competing interests - The authors declare no competing interest.

Additional information – No additional information from the authors.

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