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Performance Analysis of Roof-Integrated Water-Type PVT Heating System

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Abstract

The Photovoltaic-thermal (PVT) collector is a single device that combines a photovoltaic module and a solar thermal collector, producing thermal energy and generating electricity simultaneously. PVT collectors produce more energy per unit surface area than side-by-side PV modules and solar thermal collectors. They can be classified into air-type and water-type collectors according to the thermal medium used for collecting heat in the collector. The water-type PVT collector tends to show better thermal performance than the air-type PVT collector. The thermal energy from water-type PVT collectors can be used in buildings for hot water and heating. It is important to understand the overall energy performance of building heating systems that work in conjunction with PVT collectors to demonstrate the potential of their building applications.

The aim of this study is to analyze the performance of heating system combined with PVT collectors that are integrated on a building roof. For this study, a 1.5kW$_p$ roof-integrated water-type PVT system was installed onto an experimental house and was incorporated into its heating system. The experimental results showed that the total heat gain from the collector is 9.7 kWh, while the average thermal and electrical efficiency levels of the system are 30% and 17%, respectively. It was also found that the heating energy for the house can be reduced by 47%, as the heat gained from roof-integrated PVT system pre-heated the water used for heating system.

Keywords: *Water-type PVT, roof-integrated PVT, building heating system, thermal efficiency, electrical efficiency, heating energy performance*

1. Introduction

The photovoltaic/thermal (PVT) concept offers an opportunity to increase the overall efficiency of solar devices by utilizing heat exhausted from the PV module of a BIPV system. It is well known that PVT systems enhance PV efficiency by PV cooling, which can be achieved by circulating a colder fluid, water or air, along the underside of the PV module. PV/T collectors can be categorized according to the type of working fluid used, *i.e.*, whether it is the water type, air type or combined (water/air) type of PVT collector. The water-type PVT collector has better thermal performance than the air-type PVT collector. The thermal energy from the water-type PVT collector can be used in buildings for domestic hot water and for space heating purposes.

A considerable amount of research has been conducted regarding the water-PVT collector, which is similar in terms of its manufacturing to a conventional solar thermal collector. Most studies involving performance estimations examined various absorber plate types, such as the sheet-and-tube, fully-wetted and box channel types.

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Zondag *et. al* [8] analyzed several different types of PVT collectors (sheet and tube, channel, free flow and dual absorber), as shown in Figure 1. Various types of water PVT collectors have been suggested, such as a channel-type PVT collector [8], a PVT collector with polymer absorbers [3], thermosyphon PVT collectors [23],[26] and [10] and a PVT collector with a sheet-and-tube absorber [6]. Glazed and unglazed PVT collectors were compared by Tripanagnostopoulos *et. al* [28] and Chow *et. al* [24-25]. Bergene and Løvvik [21] thoroughly analyzed the electrical and thermal efficiency levels of a water-type PVT system and the energy conversion characteristics depending on different factors.

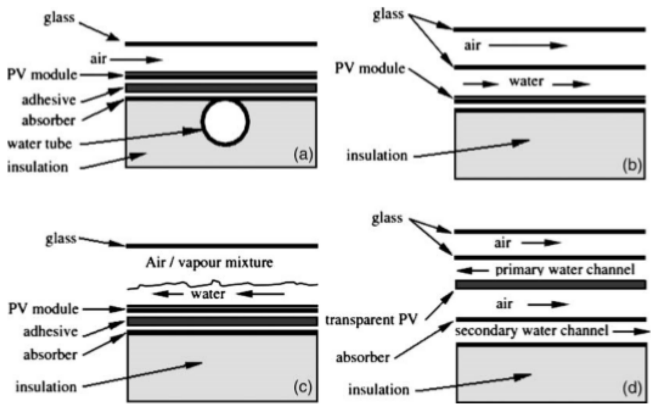

Figure 1. Types of PVT Collectors: Sheet-and-Tube (a), Channel (b), Free-Flow (c) and Dual-Absorber (d) Designs [8]

In another study [10-11], the experimental and theoretical performance capabilities of a water-type flat-plate PVT collector were examined. Fujisawa and Tani [22] evaluated the effective energy of a PVT collector depending on the presence of a glass cover. In addition, various designs of water-type PVT systems have since been proposed, and the theoretical and experimental performances of these PVT systems have been evaluated. In addition, research has been actively carried out on PVT systems linked to conventional heating and cooling facilities. Moreover, economic feasibility studies have been presented, including calculations of the payback period and determinations of the effectiveness of different PVT systems. Another paper focusing on a building energy system with PVT collectors examined the heating performance of the system as well as the performance of the PVT collector when it was linked to the heating system. A study of PV/T systems with TRNSYS was published by Kalogirou [18-19], dealing with the modeling and simulation of a hybrid PV/T collector, linked to a thermal storage tank. They analyzed the solar fraction during heating and cooling seasons. In addition, they studied simulation models of a PVT collector according to the operation mode, thermosyphon and pump in circulation. One study [2] analyzed the heating energy performance of a PVT collector with a corrugated polycarbonate and rectangular channel absorber. Fraisse *et. al.*, [5] pointed out that the low operating-temperature-requirement (35 ^{o}C) of the Direct Solar Floor (DSF) system is highly suitable for use in conjunction with a PVT water system. Using the TRNSYS simulation program, they studied such an application for a glazed collector system. Another study [17] described a space and tap-water-heating system with a roof-sized PVT array combined with a ground-coupled heat pump. The system performance, when applied to a one-family Dutch dwelling, was evaluated through the TRNSYS simulation program.

More recently, an extensive analysis of a PVT heat pump system with a variable-speed pump was performed in China. An experimental investigation of an unglazed PVT evaporator system prototype with R-22 as the refrigerant was conducted. A winter-day test showed a peak COP of 10.4 and an average value of 5.4 with a condenser water supply temperature of 20 ^{o}C [13-14]. Moreover, mathematical models based on a distributed parameter approach were developed [15-16]. Simulation results showed that at a fixed compressor speed and refrigerant flow level, and with a condenser water supply of 30 ^{o}C, PVT evaporator arrays showed an overall efficiency level in the range of 0.64 ~ 0.87, thermal efficiency of 0.53 ~ 0.64, and a PV efficiency range of 0.124 ~ 0.135. Pei *et. al* [6] conducted a comparative study of the merits of a glass cover. The result of their analysis indicated that a single glass cover is able to raise the photothermic exergy efficiency, though it has an adverse effect on the photovoltaic exergy efficiency. Chow *et. al.*, [23] studied a BiPV/w system applicable to a multistory apartment building for water pre-heating purposes. Later, they [27] installed modular box-structure PVT/w collectors onto the SW-facing façade of an experimental chamber. Their experimental results demonstrated that the space cooling load was reduced by 50% under a peak summer condition. Erdil *et. al* [4] carried out experimental measurements of an open-loop PVT/w domestic water pre-heating system. Another study [7] analyzed the performance of PVT collectors in domestic heating and cooling systems. The thermal efficiency of this PVT collector system was found to be approximately 9% lower than that of a conventional solar thermal collector.

In the present paper, the experimental performance of a heating system combined with a roof integrated PVT (BIPVT) collector is analyzed. For this paper, a water-type unglazed PVT collector of 1.5kW$_p$ PV was installed onto an experimental house and was incorporated into a heating system.

2. Unglazed water-type PVT Collector

2.1. Design and Experimental Method

For this study, a prototype of an unglazed water-type PVT collector with a rectangular channel absorber was developed, and both the thermal and electrical performance capabilities of the prototype PVT collector were measured in outdoor conditions.

The configuration of the unglazed PVT collector with the rectangular channel absorber is shown in Figure 2. The PVT collector consisted of a PV module and rectangular-channel heat-exchange units made of aluminum plates. The aluminum absorber plate and the rectangular channel were attached onto the backside of the PV module with thermal conduction adhesive. The PVT collector had no additional glass cover, and it was thermally protected with 50 mm of thermal insulation. The PV module used for the PVT collector was a 240W$_p$ mono-crystalline silicon PV module; its electrical efficiency was 16.7% under a STC. The specifications of the PV module are shown in Table 1. Figure 3 shows with the unglazed PVT collector with rectangular channel absorber created for this study.

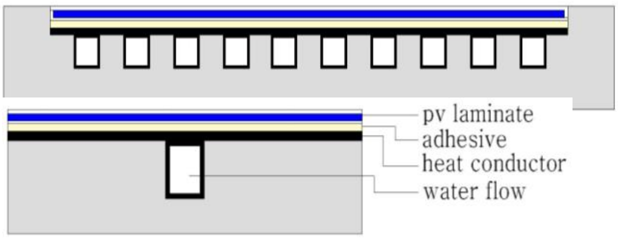

Figure 2. Sectional View of the Unglazed Water-Type PVT Collector with the Rectangular Channel Absorber

Table 1. PV Module Specifications

Cell type	Mono-crystalline silicon
Maximum power	240W
Maximum voltage	29.93V
Maximum current	8.15A
Shot current	8.56A
Open voltage	37.55V
Size	1656*997*50mm

Figure 3. Macrograph of the Unglazed PVT Collector with a Rectangular Channel Absorber

The PVT collector with rectangular absorber was tested under outdoor conditions based on ASHRAE Standard 93-2010 [1] and the PVT performance measurement guidelines of ECN [12]. The PVT collector was tested at a solar radiation level that exceeded 790 W/㎡ and at a water flow rate of 0.02 kg/s ㎡. The electrical and thermal performance measurements were carried out under a quasi-stationary condition in an outdoor environment at the same time. Several experimental devices were installed to measure the data related to the thermal and electrical performance results of the PVT collector (see Figure 4).

The PVT collector was also tested under steady-state conditions to determine its electrical and thermal performance levels at various inlets operating temperatures. The inlet and outlet water temperature of the collector were monitored and measured using a RTD-type thermocouple with measurement error of ±0.1% at 0 ^{o}C. The inlet water temperature of the collector was controlled by set temperature equipment and the inlet temperature remained constant, while the outlet temperature was varied. Additionally, the ambient temperature was measured by a T-type thermocouple with measurement error of ±0.2 ^{o}C. An anti-freezing liquid was supplied to the PVT collector at a uniform flow rate from a pump. The mass flow rate at the inlet pipe of the PVT collector was measured by an electronic flow meter. The normal quantity of solar radiation on the PVT collector surface was measured using an Epply pyranometer installed parallel to the collector plane. Electrical loading resistors and a power meter were used to measure the electrical performance of the PVT collector. All data related to the thermal and electrical performance of the PVT collector were monitored and recorded at 10 s intervals through a data acquisition system.

Figure 4. (left) View of the Experimental Setup of the PVT Collector and the (Middle and Right) Measuring Equipment

2.2. Results and Discussion

With the results of the outdoor test of the PVT collector, the thermal and electrical performances were analyzed.

The thermal efficiency is determined as a function of the solar radiation (G), the mean fluid temperature (T_m) and the ambient temperature (T_a). The steady state efficiency is calculated by the following equation:

$$\eta_{th} = \dot{m}\ Cp\ (T_o - T_i)/(A_{pvt}\ G) \quad (1)$$

η_{th}	thermal efficiency [-]
A_{pvt}	collector area [m^2]
T_o	collector outlet water temperature [^{o}C]
T_i	collector inlet water temperature [^{o}C]
$\dot{m}$	mass flow rate [kg/s]
Cp	specific heat [J/kg K]
G	irradiance on the collector surface [W/m^2]

The thermal efficiency of the PVT collector was conventionally calculated as a function of the ratio of ΔT/G, where $\Delta T = T_m - T_a$. Here, T_m and T_a are the mean fluid temperature and the ambient temperature of the PVT collector, respectively, and G represents the solar radiation on the collector surface. Hence, ΔT denotes the measurement of the temperature difference between the collector and its surroundings relative to the solar radiation. The thermal efficiency, η_{th}, is expressed as

$$\eta_{th} = \eta_o - \alpha_1(\Delta T/G) \quad (2)$$

where η_o is the thermal efficiency at a zero-reduced temperature, and α_1 is the heat-loss coefficient.

From the measurement results of the PVT collector, it was found that the thermal performance can be expressed as shown in Figure 5. The thermal efficiency levels of the PVT collector can be expressed with the relational expression $\eta_{th} = 0.73 - 16.4(\Delta T/G)$. Thus, thermal efficiency (η_0) of the collector at a zero-reduced temperature is 70%, which indicates relatively high performance; however, the heat-loss coefficient (α_1), which can reduce thermal efficiency, is -16.4 W/㎡ K. The average thermal efficiency of the PVT collector is approximately 51% under outdoor test conditions and with the given X axis coefficients (ΔT/G).

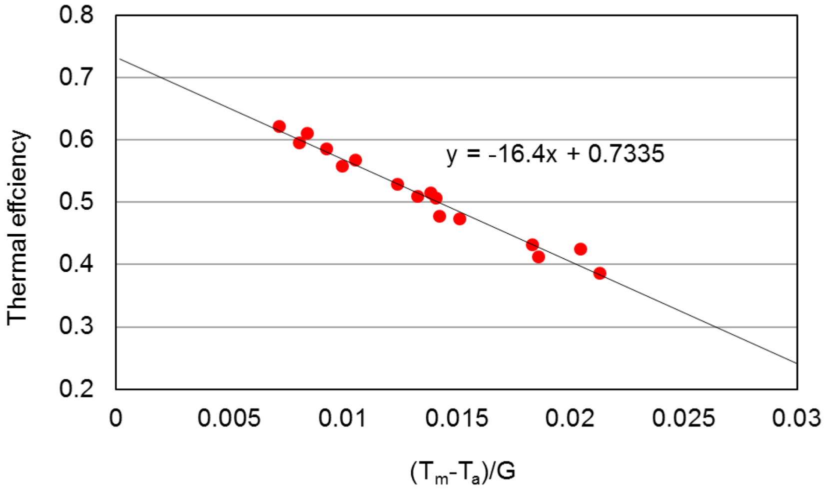

Figure 5. Thermal Efficiency (at the Standard Test Condition) of the PVT Collector

The electrical efficiency depends mainly on the incoming solar radiation and the PV module temperature. It is calculated with the following equation:

$$\eta_{el} = I_m V_m / A_{pvt} G \quad (3)$$

Here, I_m and V_m are respectively the current and the voltage of the PV module operating at a maximum power. The electrical efficiency levels of the PVT collector in the outdoor condition are shown in Figure 6. The performance of PVT collectors can be expressed with the following relational expression: η_{el} = 0.16-0.04 (Δ T/G). Thus, the electrical efficiency (η_o) at a zero-reduced temperature is 16.29 % and the electricity loss coefficient is -0.04.

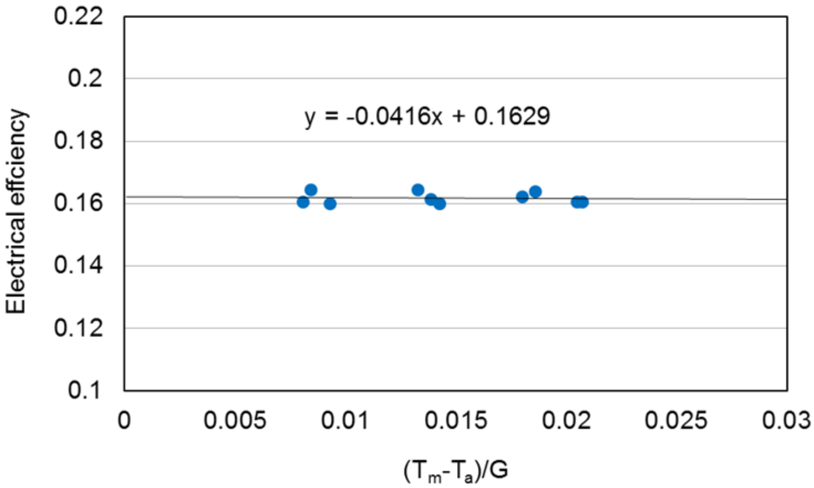

Figure 6. Electrical Efficiency (at the Standard Test Condition) of the PVT Collector

3. Roof-Integrated PVT Heating System

3.1. Heating System with PVT Collector

For the heating system combined with the PVT collector, an experimental house was built, including a test room and a service room (see Figures 7 and 8). The slope of the roof is 30˚, and it was orientated toward the south. The PVT collectors were placed on the roof as building-integrated PVT components (BIPVT). The power generation capacity was 1.5kW$_p$, and the collecting area was 8.64 ㎡. The system consisted of one array composed of six serially connected modules with a maximum current of 8.15A and a maximum voltage of 179.58 V.

In order to use the thermal energy from the PVT collectors for heating in the unit, the roof-integrated PVT system was installed onto an experimental unit and was incorporated into a heating system. The heating system for the house with the PVT collector was configured with 500-liter thermal storage tank, an auxiliary boiler, an inverter and a fan-coil unit (FCU) to release the heat. RTD thermocouples were used to measure their temperatures, and two flow meters were installed to measure the collector supply and heating supply. A data acquisition instrument was also connected to record all of the data related to the thermal and electrical outputs of the BIPVT collector and to record the outdoor conditions. A schematic diagram of the heating system with the PVT collector is shown in Figure 9. In order to evaluate the heating performance of the heating system with the PVT collector, the experiment was performed under the conditions described below during October of 2012.

The pump, controlled by a differential temperature-controller (DTC), circulated the heat-transfer fluid from the PVT collector through the heat exchanger in the thermal storage tank and back to the PVT collectors. When the temperature of the PVT collectors exceeded that of the tank bottom by 4 ^{o}C, the differential temperature controller switched the circulating pump on. When the temperature of the PVT collectors dropped to 2 ^{o}C above the thermal storage tank temperature, the differential temperature controller stopped the pump. The water flow rate of the PVT collector was maintained at 10 LPM (liter/min). For the heating performance experiment, the heating load of a 100m^2 building was assumed to be 17 kW. The assumed value of the heating load was then consumed by the FCU from 1:00 p.m. to 7:00 a.m. The supply flow rate of the FCU was 5 LPM.

Figure 7. View of the Roof-Integrated PVT (BIPVT) on the Experimental House

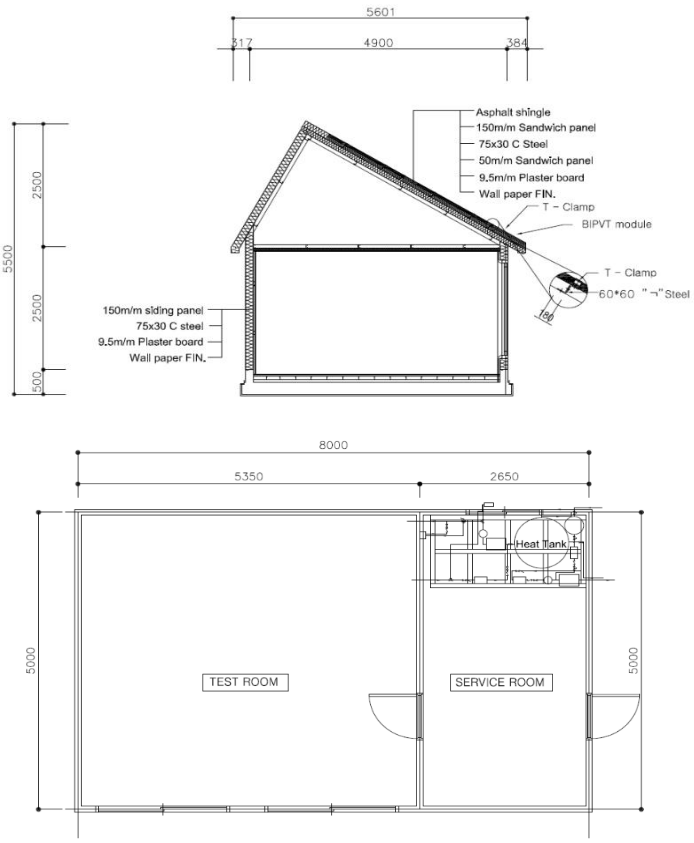

Figure 8. Sectional and Plan View of the Experimental House

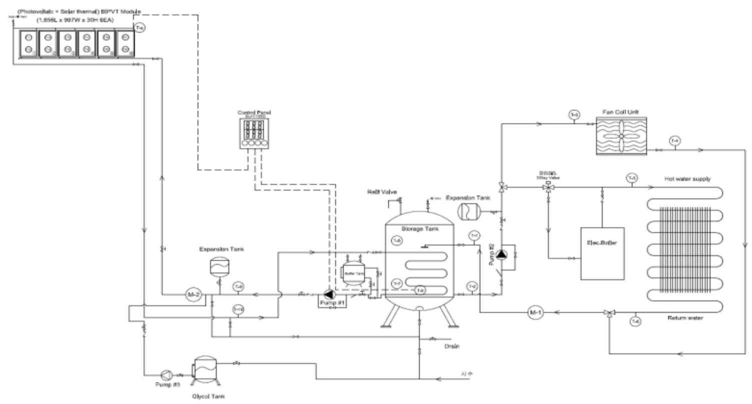

Figure 9. Schematic Diagram of the BIPVT Heating System

3.2. Results and Discussion

The thermal performance of the BIPVT heating system during a clear day is shown in Figure 10, indicating that the temperature of the thermal storage tank rose to 40 ^{o}C from 18 ^{o}C through the heat gain from the BIPVT collectors. The temperature of the thermal storage tank and the BIPVT collector continuously rose from 9 a.m. to 3 p.m. in spite of the reduced solar radiation starting at 12 p.m. Moreover, the temperature of the FCU inlet as the heating supply rose increased by more than 40 ^{o}C from 2 p.m. to 3 p.m. From 4 p.m. to 7 a.m. on the next day, the water temperature of the FCU inlet and the thermal storage tank decreased slowly as it was used for the heating load. These results indicate that when the hot water temperature for the heating supply is approximately 40 °C, from 2 p.m. to 3 p.m., the heating energy can be solely supplied by the heat gain from the BIPVT collector system. From the experimental results, it was also found that the average temperature difference between the BIPVT collector inlet and outlet was 3.3 °C, with a maximum of 4.4 °C.

The heat gain from the BIPVT collectors and its thermal efficiency are presented in Figure 11. In this figure, the thermal efficiency and heat gain of the BIPVT collector increased according to the increase in the solar radiation from 8 a.m. However, from 11 a.m., the thermal efficiency decreased continuously in spite of the increase in the solar radiation. This occurred due to the increased inlet temperature of the BIPVT collector, as caused by the temperature increase of the thermal storage tank. It was found that the total heat gain from the collector was 9.7 kWh while the average thermal efficiency of the system was 30%.

The experimental results also showed that the electrical efficiency of the BIPVT collector decreased according to the increase of the PV temperature of the BIPVT, from 25 °C to 45 °C, under the test conditions (see Figure 12). These experimental results demonstrated that the BIPVT collectors with the heating system performed better in terms of electrical efficiency, with a maximum of 18.9%.

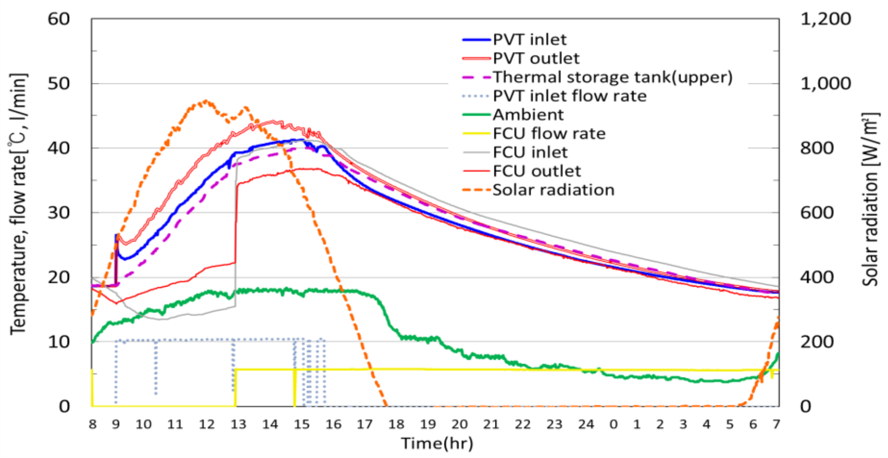

Figure 10. Thermal Performance of the BIPVT Heating System

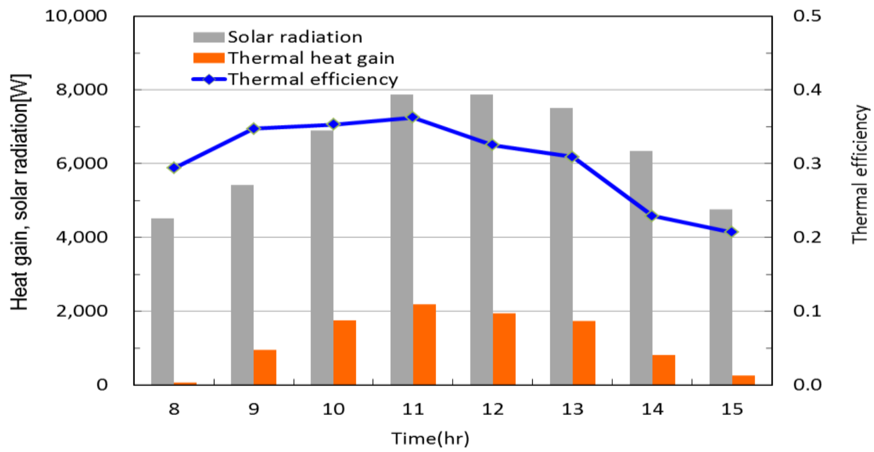

Figure 11. Heat Gain of the BIPVT Collector with the Heating System

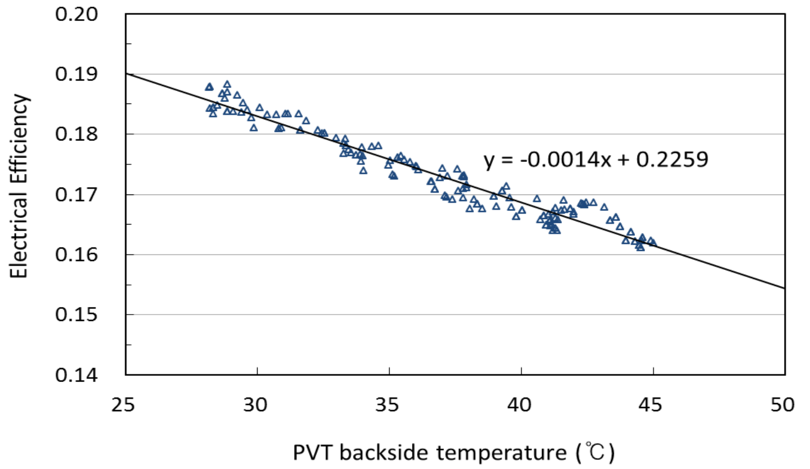

Figure 12. Electrical Efficiency According to the BIPVT Backside Temperature

With regard to the heating performance and contribution level of the BIPVT system in the experimental house, the heating energy supplied by the BIPVT and the auxiliary heater were analyzed. The heating supply energy (Q) is calculated by the following equation:

$$Q = M\,Cp\,(T_h - T_c) \quad (4)$$

M heating flow rate [L]
Cp specific heat [J/kg K]
T_h heating supply water temperature [°C]
T_c tap water temperature [°C]

From the experimental results, the heating energy demand level for the experimental house was found to be about 9.4 kW under the condition of an initial temperature of the thermal storage tank of 18 ^{o}C, with a heating flow rate of 370 ℓ and a heating water temperature of 40 ^{o}C. The heating energy supplied by the BIPVT system and the auxiliary heater are presented in Figure 13. This figure shows that the heating water temperature reached more than 40 ^{o}C from 2 p.m. to 3 p.m., then decreasing after 3 p.m.

As shown in the figure, it can be deduced that it is possible to heat continuously for about three hours using the BIPVT system without using auxiliary heater. After 3 p.m., the temperature of the thermal storage tank decreased and the energy supplied from BIPVT system also decreases. Accordingly, the heating energy supplied to the auxiliary heater increases. Finally, it was found that the heating energy for the experimental house can be reduced by 47%, as the heat gained from PVT system pre-heated the water used for the heating system.

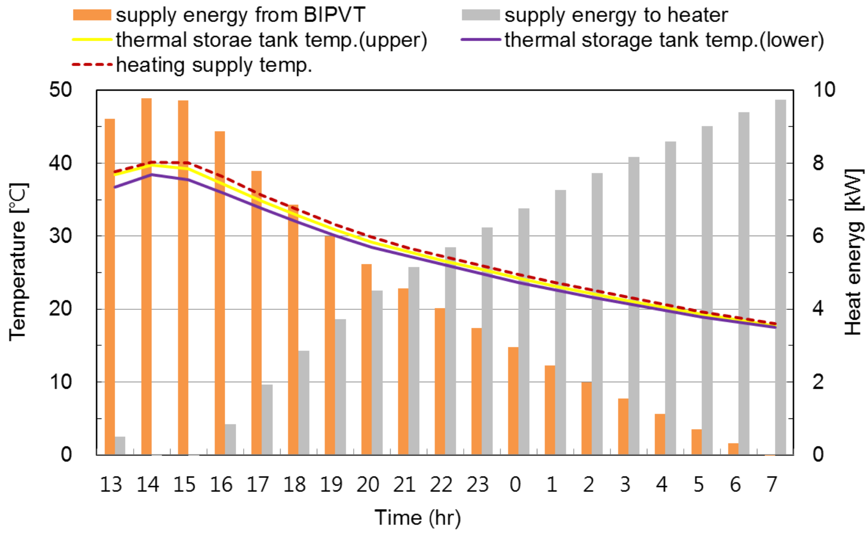

Figure 13. Supply Heating Energy from the BIPVT and the Auxiliary Heater

4. Conclusion

In this paper, the energy performance of a heating system combined with a water-type PVT collector integrated into the roof of an experimental house was analyzed.

According to the experimental results, for the heating system with the BIPVT collector, it was confirmed that the respective thermal and electrical efficiency levels of the BIPVT collector were 30% and 17%, on average. In particular, regarding the electrical efficiency, the results showed a high performance level, with the STC efficiency exceeding 16.5% when the heating system with the BIPVT collector was running. This occurred due to the relatively low temperature of the fluid which was circulated into the BIPVT collector from the thermal storage tank while the BIPVT collectors generated hot water. Therefore, a heating system with a BPVT collector is very favorable for increasing the energy performance of buildings. It was also confirmed that the water temperature of the thermal storage tank rose by 40 °C and could be utilized as a heat source for heating, meaning that the required energy in a building with such a BIPVT collector can be reduced. Although the heating supply water temperature was low, the heating energy for the experimental house can be reduced dramatically by 47% at a heating water temperature of 40 °C. It can therefore be concluded that the BIPVT collector can reduce the required heating energy for a building by approximately half by heating with low-temperature heating water.

In conclusion, although the heating contribution can differ depending on the operating conditions of the heating system, such as the insulation level and/or heating water temperature, a heating system with a BIPVT collector is very useful in buildings, and the effectiveness of such a system was confirmed in this study.

Acknowledgments

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