

An Autonomous Smart Energy System for Electricity and Hot Water Production with Adaptive Solar Radiation Control

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Abstract: An autonomous mobile photovoltaic–thermal device (PVTD) was developed to ensure reliable production of both electricity and hot water throughout the year, including during winter and summer seasons. The system creates the required solar radiation intensity even in harsh mountainous and foothill conditions, enabling stable performance under extreme climatic environments. In the experiment, two 200 W monocrystalline silicon photovoltaic (PV) panels and the PVTD were observed simultaneously, and the measurement results were compared through the calculation of power. The backside of the PVTD was equipped with a cooling system. It was also equipped with controllable reflectors that adjust according to seasonal changes in solar flux density. According to the experimental results, it was determined that the amount of energy produced by the PVTD was 1.81 times greater than that of the PV. In addition, by passing cold water at 9 °C through the collector located on the rear front side of the PVTD, usable hot water at 53 °C was obtained at a rate of 20 liters per hour. The experiment was conducted in winter months, under daily air temperatures ranging from –4°C to 5°C.

1 INTRODUCTION

PVs are widely used for energy production, however, most of their commercial versions currently have relatively low efficiency and convert only 13 to 20% of solar radiation into electrical energy under the ideal conditions specified in certification [1]-[3]. In the last few years, the demand for solar energy has risen dramatically due to high population growth, which has driven up the cost of non-renewable energy sources [4]. PVTD systems simultaneously produce electrical and thermal energy, which increases overall efficiency and reduces environmental impact [5]-[7]. Photovoltaic–thermal technologies (PVTD) have addressed the problem of overheating PV cells utilizing several cooling methods. These technologies can improve the electrical efficiency of PV cells and provide thermal energy simultaneously [8]. Advanced materials such as nanofluids are widely used by researchers around the world to increase the rate of heat transfer and to

improve the efficiency of PVTD systems, including PVTDs [9]-[11]. Therefore, PV cooling methods are crucial to improving technology efficiency and prolonging its lifetime. Photovoltaic/thermal (PV/T) is a key to producing thermal and electrical energy, employing different fluids, including nanofluids (NFs) [12]. The effect of reflectors on PVTD parameters has also been widely covered in many works, and their main function is to increase the radiation energy coming from the sun as well as to protect the PV from dust accumulation [13]. Thus, specialists, by choosing the widespread use of PVTDs in solar systems, are trying to determine ways to prevent heat loss between the PVTD and the environment. In this regard, they developed solutions against convection and radiation losses aimed at reducing heat loss [14]-[15]. Specialists have determined that the efficiency of PVTDs can be increased by adopting various approaches. Modern studies are aimed at developing advanced designs for solar collectors. Researchers strive to create solar collectors that describe minimal heat loss and maximum solar radiation collection, which

leads to high performance under average temperature conditions [16]-[17]. This study developed and experimentally evaluated an autonomous smart photovoltaic–thermal device (PVTd) designed for efficient year-round operation under highly variable climatic conditions, particularly in cold mountainous regions. The adaptive reflector system and integrated cooling module significantly enhanced both electrical and thermal output compared to a standard photovoltaic module.

2 METHODS AND MATERIALS

Due to the large number of cooling methods for PVTdS, this has aroused the interest of many scientists to conduct intensive research in this direction. It indicates the necessity of developing a specially constructed device with a solar tracking mode in mountainous and foothill regions. In particular, the fact that the energy produced by PVTdS in the winter months differs significantly compared to that in the summer months, as well as the difference in the rate of change of the temperature of the obtained hot water, causes a number of problems. In addition, in conditions of low air temperature, the possibility of obtaining hot water decreases. In order to eliminate these shortcomings, a device with a special construction was developed. The developed device creates the possibility of obtaining both electrical energy and hot water in the winter months, just as in the summer months. The developed PVTd has several advantages.

In particular:

- During the winter months, when ambient air temperature is low, additional reflectors allow for the collection of sufficient solar radiation flux density, thereby enabling the production of electricity and hot water comparable to that of summer conditions.
- The device is equipped with a special construction capable of solar tracking even in uneven terrains, due to its ability to move along two axes.
- Through the regulation of reflectors, it becomes possible to artificially generate a solar radiation flux density of around 1000 W/m² both in summer and winter, ensuring stable performance.
- To prevent the surface of the PV module from contamination, the reflective planes are used at night as protective covers against dust accumulation.

Table 1: Geometric dimensions of the components forming the PVTd.

Parameters		
1	Geometric dimensions	Size
2	Width of the PV frame, d	30mm
3	Surface area of the PV, S _{FEB}	0.9126m ²
4	Total surface area of the reflectors, S	1.8252m ²
5	Thickness of the reflector, d _{ref}	0.4 cm
6	Thickness of the back cover, d _q	0.4 cm
7	Surface area of the back cover, S _q	0.9236m ²
8	Total weight of the PV, kg	8.55kg
Physical and technical characteristics		
1	Maximum power of the PV, P _{max}	200W
2	Efficiency of the PV, η	21.9 %
3	Open-circuit voltage of the PV, U _{oc}	21.6V
4	Short-circuit current of the PV, I _{sc}	12.22A
5	Fill factor of the PV, FF	0.76
6	Reflectance coefficient of the side reflectors R, m	0.5, 1.17x78, 2.78x0.58, 1
7	Water capacity of the heat collector based on cellular polycarbonate, V m ³	0.007316m ³
8	Battery, A·h	100Ah
9	Inverter, W	1000W



Figure 1: General view of the PVTd and reflector arrangement.



Figure 2: Structural layout of the PVT thermal collector.



Figure 3: Electrical control and power conditioning subsystem.

In Figures 1, 2, and 3, the general view of the PVT composed of a PV with a power of 200 W is presented. In order to reduce the energy losses caused by the increase in the surface temperature of the PV through cooling, and to obtain additional thermal energy, a photovoltaic-thermal device was developed. The developed PVT is equipped with a cellular polycarbonate-based thermal collector and reflectors (Figures 1–2). In Figure 1, the structural

parts of the PVT for the reflector are shown, in particular, the PVT consists of 4 reflectors. Of these, Reflectors 1 and 2 are installed on the two side surfaces of the PVT, respectively. The geometric dimensions of the reflectors are equal, and the surface area of each is 0.9126 m^2 (Table 1). Reflectors 3 and 4 are installed at the top and bottom parts of the PVT, and each has a geometric surface area of 0.4563 m^2 . In general, the surface area of one reflector placed on the two side surfaces of the PVT is equal to the total surface area of Reflectors 3 and 4 (Figure 1). The PVT has a solar tracking mode, and a special construction capable of rotating 360° was developed. Furthermore, the PVT was specially designed for uneven areas, including mountainous and foothill regions (Figures 1–2). The control system for the electrical energy generated by the PVT consists of a battery (100 A/h) and an inverter (1 kW), and is systematized in a state protected from special external negative effects (Figure 3). The 4 reflectors that make up the PVT serve to ensure that, across seasons, the changes in solar radiation flux density reach values in the range of 1000 W/m^2 to 1200 W/m^2 . That is, in winter, 4 reflectors are used; in spring, two side reflectors and one top reflector; and in summer, two side reflectors are installed to achieve the required radiation. In particular, the distribution of the reflectors is carried out taking into account the percentage of daily sunshine duration and the values of daily solar radiation.

To ensure thermodynamic rigor and comparability with existing PV/T studies, the following governing equations are included.

$$Q_w = \dot{m} \cdot c_p \cdot (T_{\text{out}} - T_{\text{in}}) \quad (1)$$

where, \dot{m} -mass flow rate of water (kg/s), c_p -specific heat of water ($\sim 4180 \text{ J/kg}\cdot^\circ\text{C}$), T_{out} , T_{in} -outlet/inlet temperatures ($^\circ\text{C}$).

Overall efficiency of the PVT panel is then found by.

$$\eta_{\text{overall}} = (P_{\text{max}} + Q_w) / (G_T \cdot A_c), \quad (2)$$

where, Q_w -is the thermal power gained by the working fluid, determined from the measured inlet and outlet water temperatures, mass flow rate, and the specific heat capacity of water. This value quantifies the amount of solar thermal energy converted into usable heat. P_{max} -is the instantaneous maximum electrical power generated by the PV module under the prevailing (non-standard) operating conditions. It is computed using the corrected values of short-circuit current I_{SC} and open-circuit voltage U_{OC} , along with the power ratio

R_p . Together, these two terms represent the combined thermal + electrical energy delivered by the hybrid panel. G_T is the solar irradiance (W/m^2) measured on the plane of the PVT panel. A_C is the illuminated surface area of the PVT panel (m^2). Thus, $G_T \cdot A_C$ represents the total solar power available to the system during operation.

At night, due to the higher dust accumulation compared to daytime, in order to prevent the efficiency of the PVTD from decreasing, the possibility of maintaining efficiency has been created by covering the front surface of the PVTD with reflectors at night (Figure 4). All four reflectors have also been made capable of being gathered and placed on the front surface of the PVTD.



Figure 4: Front surface view of the PVTD covered with reflectors.

3 RESULTS AND DISCUSSION

In this experiment, the aim was to create the possibility of obtaining in the winter months the same amount of energy as in the summer months by generating additional light intensity through reflectors in winter. The PV with a white protective coating used in the device has a power of 200 W. The experiment was carried out under real open-air conditions at the Institute of Physics and Technology, Helioplatform, after snowy precipitation, on 04.03.2025 from 09:40 to 15:00 in solar tracking mode in the horizontal direction. A

special supporting construction was developed for the PVTD, designed for rotation around one axis and vertical movement fixed to a trailer. At the same time, the same conditions were created for the PV, and the experimental test results were obtained at 20-minute time intervals and the electrical parameters were measured. The experiment was carried out in solar tracking mode with the help of the special construction developed in the device (Fig. 5).

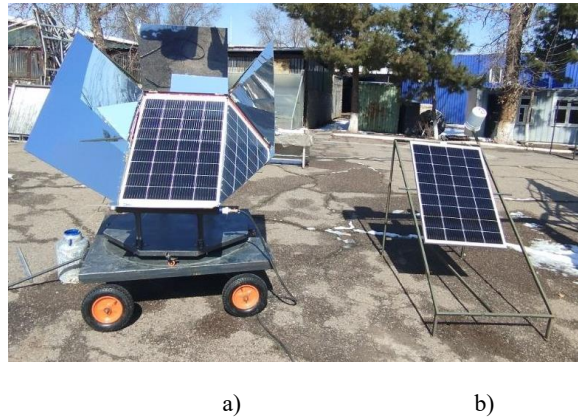


Figure 5: a) Photothermal device b) Photovoltaic battery.

This experiment was conducted under an open sky on cold winter days after snowfall had ended. The purpose of the experiment was to determine, under real conditions, how much additional radiation could be directed to the PVTD compared to the PV, how much more power could be obtained, and how much hot water could be produced in cold winter weather conditions, as well as to confirm the feasibility of obtaining these outcomes.

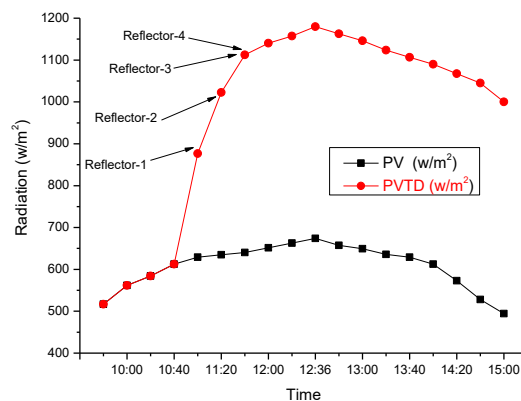


Figure 6: Dependence of perpendicular incident solar radiation intensity on the PVTD and PV surfaces over daytime hours.

In this graph, the solar radiation intensity was increased by means of special reflective mirrors, with each reflector being installed at specific time intervals and in a defined sequence, after which experimental results were obtained. In particular, it is clearly visible that the radiation intensities differ depending on the contribution of each reflector (Figure 6). At the initial stage, due to the reflectors, the intensity of light radiation on the frontal surface of the PVTD was increased up to 2 times (Figure 6).

The experiment began at 09:40, and by 10:40 the reflectors were installed at specific time intervals. When the 1st reflector was installed and measured at 11:00, the PV showed 560 W/m², while the PVTD showed 780 W/m², which is 220 W/m² higher. When the 2nd reflector was installed and measured at 11:20, the PV and PVTD registered 565 W/m² and 910 W/m², respectively. Together, the two side reflectors of the PVTD showed 345 W/m² more compared to the PV. Subsequently, when the 3rd and 4th reflectors were installed together and measured at 11:40, the PV registered 570 W/m², while the PVTD registered 990 W/m².

From the following measurements, as shown in this graph, it can be observed that the light intensity increased up to 2 times (Fig. 6).

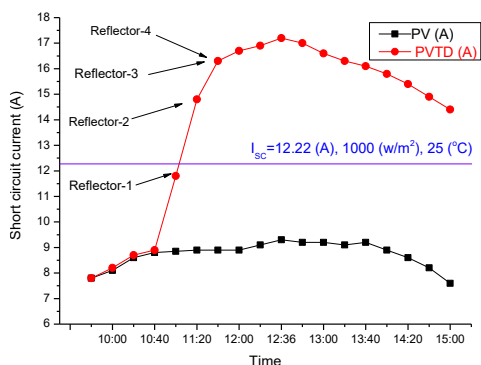


Figure 7: Dependence of the short-circuit currents of the PVTD and PV on daytime.

The graph shown in Figure 7 illustrates the dependence of short-circuit currents on time. Considering the direct proportionality between light intensity and short-circuit current, the installation process of the reflecting mirrors, in particular the contribution of each reflector, makes it possible to clearly observe significant differences in short-circuit current. At 11:00, after the installation of the first reflector, the PVTD produced 11.8 A; at 11:20, after the second reflector was installed, it reached 14.8 A. At 11:40, when the third and fourth reflectors were installed simultaneously and

measurements were taken, the PVTD showed 16.3 A (Fig. 7).

In the same period between 11:00 and 11:40, the PV short-circuit current increased from 8.5 A to 9 A. The reason for these PV values is that the solar radiation flux density during this time interval varied between 560 W/m² and 570 W/m², which correspondingly affected the short-circuit current.

In general, the short-circuit current of the PVTD was found to be 1.95 times higher compared to that of the PV.

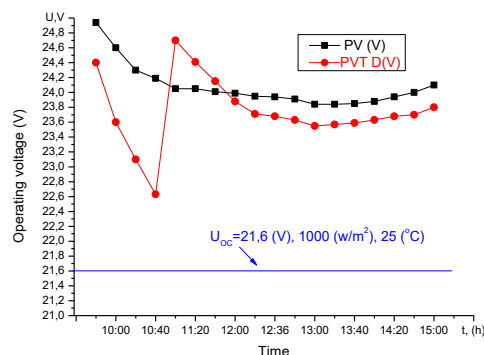


Figure 8: Dependence of the open-circuit voltages of PVTD and PV on daytime.

In this graph, the dependence of the open-circuit voltages of PVTD and PV on daytime is shown. It can be seen that the open-circuit voltage values of the PVTD compared to the PV are lower during the day. The reason for this is that the air temperature during the day was in the low range of -4 °C to 5 °C. Since the PV did not heat up sufficiently under the influence of low solar radiation flux density and air temperature, its open-circuit voltage did not decrease significantly.

In addition, in the PVTD, due to the accumulation of light flux density on the front surface through additional reflectors, it heated more. Initially, in the time interval from 10:00 to 10:40, it can be observed that the voltage drop of the PVTD compared to the PV decreased noticeably (Fig. 8). The reason for this is that a collector was located on the back frontal side of the PVTD, and since there was no convection inside the collector, the voltage decreased.

Between 09:00 and 10:40, the open-circuit voltage of the PVTD dropped from 24.4 V to 22.6 V. Afterwards, when 9 °C water was passed through the collector, the voltage temporarily increased to 24.8 V, and then it can be seen that the open-circuit voltage of the PVTD decreased again due to the additional solar radiation flux density accumulated

by the reflectors. Innovative designs of thermal collectors optimize heat dissipation from photovoltaic cells, which is crucial to preventing overheating and reducing efficiency losses [18].

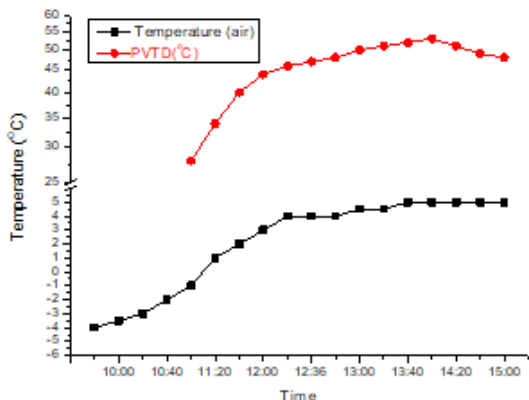


Figure 9: Dependence of air and hot water temperatures on daytime.

In Figure 9, the graphs of the dependence of air and hot water temperatures from the collector on daytime are presented. When water was passed through the collector and measured, the initial hot water results were taken starting from 11:00. The initial results showed 26 °C, and due to the increase of solar radiation flux density on the front surface of the PVT D by means of reflectors, it can be seen that the hot water temperature at the outlet of the PVT D cooling system increased up to 53 °C. Experimental research results were obtained at low air temperatures during the day, ranging from -4 °C to +5 °C. Based on the obtained results, power values were calculated and presented in the following graph.

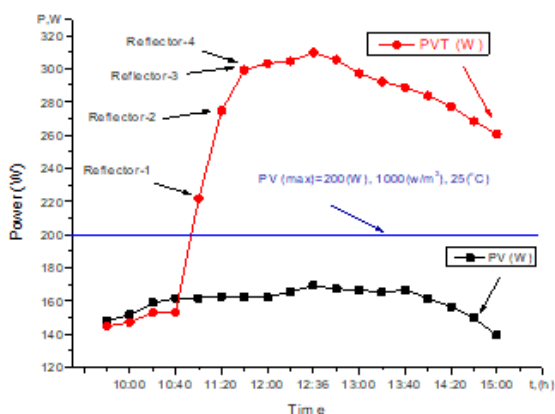


Figure 10: Dependence of PVT D and PV electrical power on daytime.

In the following graph, the overall differences in the electrical power of PV and PVT D are clearly shown. Until 10:40, since water was not passed through the cooling system of the PVT D, there was no open convection with air in the collector on the back side of the PVT D. As a result, the PVT D showed less power because it heated more compared to the PV. Then, at 10:40, due to the reflector and the cooling system, the open-circuit voltage and short-circuit currents improved. After the first reflector was installed, the power reached 221 W, which increased by 44% compared to the initial value. Under the effect of the second reflector, the power reached 274 W and increased by 20% compared to the initial result. When the 3rd and 4th reflectors were installed, the power reached 300 W, increasing by 9.5% compared to the initial value. In particular, the calculation results show that the average values of the electrical power generated by the PVT D during the day differ by 1.81 times compared to the PV (Fig. 10).

The findings of this study are consistent with previous research on PV/T systems and further strengthen existing conclusions. Earlier studies report that conventional PV panels typically convert only about 13–20% of incident solar radiation into electrical power [1]-[3]. In contrast, under the same conditions, the PVT D developed in this work generated 1.81 times more electrical power, mainly due to the combined effect of enhanced irradiance through reflectors and effective water-based cooling.

Previous literature highlights various cooling techniques - such as water cooling, nanofluids, and PCM - as key methods for improving PV/T efficiency [5]-[12]. In our system, four optical reflectors and active water cooling were employed simultaneously. As a result, the short-circuit current increased by 1.95 times, and the maximum output power reached 300 W, significantly exceeding the performance of the reference PV module.

Unlike many earlier studies conducted in warm or stable climates, our experiments were carried out in harsh winter conditions, with ambient temperatures ranging from -4°C to +5°C, using a two-axis solar tracking system. Despite the unfavorable environment, the PVT D maintained stable operation, delivering both sufficient electrical output and usable hot water. Additionally, the use of reflectors as night-time dust protection is a practical feature rarely discussed in the literature, further contributing to long-term efficiency.

In summary, compared with previous studies, the developed PVTD demonstrates the following advantages:

- higher efficiency through combined irradiance enhancement and cooling;
- reliable operation even in cold climate conditions;
- simplified cooling using ordinary water;
- dust protection through the reflector assembly.

4 CONCLUSIONS

Among renewable energy sources, the effective use of solar energy, which is considered the most promising direction, has become a priority area in the development of modern energy. For this purpose, the main electrical parameters of photovoltaic batteries (PV) and photovoltaic-thermal batteries (PVTD) were studied experimentally, and their comparison was carried out. During the research, the minimization of electrical losses in the device was set as the main goal. According to the obtained results, it was determined that the average electrical power produced by the PVTD is 81% higher than the average power produced by the PV. This situation demonstrates the multifunctionality of photovoltaic-thermal batteries and their high energy efficiency.

In addition, during the experiment, even when the air temperature was in the range of -4°C to $+5^{\circ}\text{C}$, it was ensured that hot water with a temperature of 53°C could be obtained at a rate of 20 l/h through the PVTD. This revealed that PVTD technologies are capable of producing not only electrical energy, but also thermal energy in a stable manner.

The overall efficiency of the photovoltaic-thermal device (PVTD) was evaluated based on its electrical and thermal energy outputs. The experimental results demonstrated that the device maintains high conversion efficiency even under real winter operating conditions. The thermal power of the system was determined from the temperature rise of the water flowing through the collector. With a water flow rate of 20 L/h and a temperature difference of 44°C between the inlet and outlet water (from 9°C to 53°C), the thermal power calculated using equation (1) was approximately 1020 W. The maximum electrical power generated by the PVTD reached 300 W, which is significantly higher than the power produced by the standard 200 W PV module used for comparison. For a thermodynamically accurate evaluation, the overall

efficiency was calculated using the total optical aperture area of the PV panel and the reflectors. According to equation (2), the resulting overall efficiency was found to be approximately $\eta_{\text{overall}} \approx 48\%$. Moreover, this efficiency remained stable even under harsh winter conditions with ambient temperatures ranging from -4°C to $+5^{\circ}\text{C}$. The experimental results validate the PVTD as a promising smart-energy solution combining solar electricity generation and thermal heating in a single autonomous platform. The device is well-suited for remote, high-altitude, and off-grid applications where conventional systems underperform due to fluctuating solar conditions.

Such high efficiency is attributed to the following factors:

- the increased solar irradiance intensity provided by the reflectors;
- the cooling collector reducing the temperature of the PV cells and thereby improving electrical efficiency;
- the high heat absorption capability of the thermal collector.

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