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# Management of Energy Production in a Hybrid Combination of a Heat Pump and a Photovoltaic Thermal (PVT) Collector

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**Abstract**

The purpose of the study is to investigate the energy performance of a PVT collector in combination with a heat pump. First, a test system combining a heat pump and PVT module is built, and then its performance is carefully measured, assessing the electricity and heat production. The paper focuses on increasing the efficiency of a photovoltaic (PV) panel (as part of the PVT module) by cooling it with a heat pump. The main idea is to use the heat generated by the warming panels as a low-temperature source for the heat pump. The research aims to maximize the use of solar energy in the form of both electricity and heat. In traditional PV systems, the panel temperature rise reduces the solar-to-electric conversion efficiency. Therefore, cooling with a heat pump is increasingly used to keep panels at optimal temperatures and improve performance. The tests confirm that cooling the panels with a heat pump results in an 11.4% improvement in electrical efficiency, an increase from 10.8% to 12.0%, with an average system efficiency of 11.81% and a temperature coefficient of –0.37%/°C. The heat pump achieves a COP of 3.45, while thermal energy from the PVT panel accounts for up to 60% of the heat input when the air exchanger is off. The surface temperature of the PVT panels varies from 11 °C to 70 °C, and cooling enables an increase in electricity yield of up to 20% during sunny periods. This solution is especially promising for facilities with year-round thermal demand (e.g., swimming pools, laundromats).

**Keywords:** energy efficiency; heat pump; photovoltaic; PVT module

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## 1. Introduction

Managing energy production is an extremely important issue. This is especially true when the global energy demand is steadily increasing and, at the same time, we are facing the challenges of climate change and limited natural resources [1,2]. Effective management of energy production requires a sustainable approach that takes into account energy efficiency, cost-effectiveness, and social and environmental aspects [3,4].

The first step in managing energy production is to consider the various energy sources available on the market and their characteristics. This includes both traditional sources,

such as coal, natural gas or nuclear power [5–7] and increasingly popular renewable sources, such as solar, wind, and hydropower or biomass [8–11]. The choice of appropriate energy sources depends on a number of factors, including the availability of raw materials, production costs, geographical location, and the energy policy of each country [12]. Another key component of energy production management is the optimization of the production processes to maximize efficiency and minimize costs [13,14]. Therefore, modern technologies enable the use of advanced monitoring, control, and automation systems that can improve the efficiency of power systems and optimize raw material and energy consumption [15,16].

Contemporary approaches to managing energy production increasingly emphasize sustainable production practices and the reduction of greenhouse gas emissions [17–19]. These measures include upgrading the existing infrastructure, developing new low-emission technologies, promoting energy efficiency, and investing in renewable energy sources [20–22]. The introduction of innovative solutions, such as energy storage, the use of smart grids, or the development of renewable energy technologies, plays a key role in building more sustainable and efficient power systems [23,24].

An important aspect of managing the production of usable energy (electricity and heat) is also taking into account consumers' changing needs and preferences [25,26]. Growing environmental awareness and the development of prosumer technologies mean that customers are paying more attention to the way energy is produced, giving priority to environmentally and community-friendly solutions [27,28]. Effective management of energy generation also requires close cooperation between the public and the private sectors as well as between the various players in the energy market [29]. Public-private partnerships and social sector initiatives can contribute to more innovative and sustainable energy solutions that respond to contemporary challenges [30,31].

Currently, it is the hybrid combination of a heat pump and a PV system that is gaining popularity in the context of striving towards sustainable use of renewable energy sources and improved energy efficiency in buildings. This synergy between the two technologies allows for the efficient use of solar energy to heat buildings and produce electricity, thereby reducing both greenhouse gas emissions and operating costs [32–34].

A heat pump uses ambient energy to heat or cool spaces [35–37], while PV panels convert solar energy into electricity [38–40]. The combination of these two technologies maximizes the use of available renewable energy resources, which translates into reduced dependence on traditional energy carriers and a reduced environmental impact [41].

A key component in managing energy production using such a hybrid system is to optimize the use of electricity and heat according to the current needs of the building [42,43] and weather conditions. Intelligent control systems make it possible to monitor energy consumption and adapt heat pump operation to the availability of electricity from PV panels. In addition, when the PV panels produce more electricity than is needed to power the building, the surplus can be used to power the heat pump or can be stored in batteries [44,45]. This enables effective utilization of the energy generated even when it is not immediately needed to power the building, which ultimately leads to a further reduction in running costs [46].

A key aspect of managing energy production in a hybrid heat pump and PV system is also taking due account of environmental and economic factors [47–50]. By using renewable energy sources, reducing $CO_2$ emissions, and reducing the operating costs of a building, such a system can contribute to reducing the environmental impact and improving the financial balance. Therefore, it is important to continuously monitor and analyze the performance of the entire system in order to identify potential areas of optimization and improve the processes of energy production management. In this way, the maximum

benefits of a combined hybrid heat pump and PV system can be achieved, both economically and environmentally [49,51–53].

Recent research confirms the significant potential of PVT-HP systems in improving the energy performance of buildings [54,55]. Experimental studies, such as those by Zhou et al. [56] and Rijvers et al. [57], demonstrate stable year-round operation, with high heating and electrical efficiencies, particularly in colder climates. Simulation and optimization efforts [58,59] highlight how factors like collector design, system configuration, and building orientation influence overall system performance and economic viability.

Comprehensive reviews by Miglioli et al. [60] and Zohri et al. [61] emphasize the growing importance of integrated PVT and heat pump systems as a scalable solution for low-emission building energy systems. The incorporation of smart controls, hybrid configurations, and multi-source inputs enhances system flexibility and resilience. These findings further support the development of efficient, user-responsive, and environmentally friendly energy systems for nearly zero-energy buildings.

The aim of this study is to analyze the energy performance of a PVT collector (panel) in a hybrid combination with a heat pump. Therefore, the first step is to build a test system that integrates a heat pump with PVT panels. In the next step, its operation is investigated in detail by analyzing the production of both electricity and thermal energy. This paper takes a closer look at the topic of increasing the efficiency of PV panels by using heat pump cooling. The assumption is that the system will use the heat from the panels as they become increasingly warmer as a low-temperature source for the heat pump. A system designed in this way enables an increase in the efficiency of PV panels as well as the utilization of the thermal energy of such panels for the needs of the building (heating, domestic hot water preparation, heating for processes).

Research into the hybrid combination of a heat pump with a PV system aims to maximize the use of available solar energy, in the form of both electricity and heat. With traditional PV systems, an increase in the temperature of the panels can result in a decrease in the efficiency of converting solar energy into electricity [62,63]. Therefore, the use of heat pump cooling is becoming an increasingly popular solution, mainly in places where electricity and heat is needed. That makes it possible to keep panels at a low temperature and improve their efficiency.

## 2. Materials and Methods

### *2.1. Experimental Set-Up*

In order to carry out the testing on which the calculations are based, the following equipment and meters, which are available at the Centre for Sustainable Development and Energy Saving at the AGH University of Science and Technology in Miękinia, are used. A photograph of the system is shown in Figure 1.

- A PVT (photovoltaic thermal collector) collector of 230 Wp with a temperature coefficient −0.45%/°C;
- A 2 kW air-to-water heat pump didactic system. The device consists of 3 modules: an air heat exchanger (heat source), a heat pump module, and a water tank module (heat sink);
- A micro inverter with a rated power of 220 W;
- Measuring instruments: grid analyzer Nemo D4-DC, IME, Varese, Italy (power measurement accuracy ±1%), thermal imaging camera Flir I30, FLIR Systems, Wilsonville, OR, USA, heat meter Apator LQM III DC, Apator SA, Toruń, Poland (heat energy measurement accuracy ±1.5%), refractometer, pyranometer Kipp & Zonen—CMP3, Kipp & Zonen, Delft, The Netherlands (solar irradiance measurement accuracy ±10%), and a professional PV tester Metrel MI3108 Eurotest PV, Metrel d.o.o., Horjul, Slovenia

(power measurement accuracy ±2.5%, voltage measurement accuracy ±1.5%, and current measurement accuracy ±1.5%).




**Figure 1.** On the left is the tested PVT panel, on the right, a photo of the test hybrid heat pump (HP), system with the PVT collector as the low-temperature source of heat.

The experiment is conducted in two variants. In the first one, the low-temperature source is supported by an air heat exchanger (which is a standard heat source for the didactic heat pump). A schematic of the system connections is shown in Figure 2.

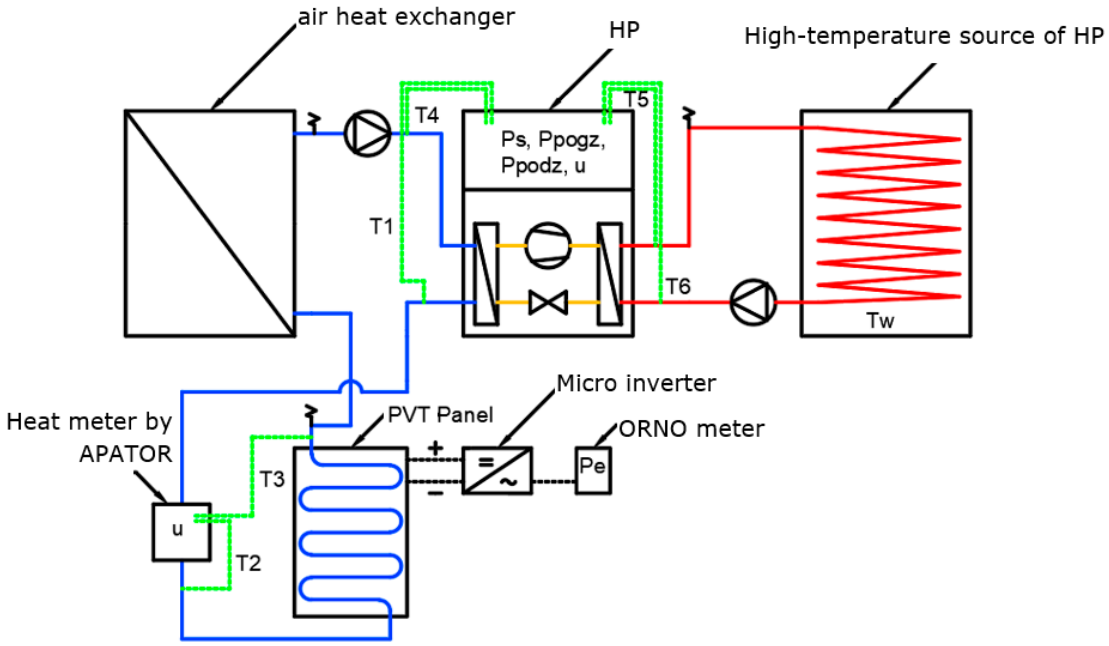



**Figure 2.** Schematic of the test system of the hybrid combination of a HP, PVT panel, and air heat exchanger.

The system is composed of three circuits. The most important of them is the circuit of the low-temperature source of the heat pump into which the PVT collector is incorporated. The system uses a water solution of propylene glycol as the heat transfer medium between the PVT module, the auxiliary air exchanger, and the heat pump evaporator. Measurements made with a refractometer demonstrate that this solution has a freezing point of −15 °C.

The aqueous glycol solution is first heated in the PVT module and then is further heated in the auxiliary exchanger; in the evaporator, it transfers heat to the thermodynamic

cycle of the heat pump. Along the way, the temperature of the antifreeze is measured at four locations between the PVT module and heat pump evaporator, i.e., T1—at the outflow from the HP evaporator, T2—before the PVT module, T3—between the PVT module and the auxiliary air heat exchanger, and T4—at the inflow to the HP evaporator. At the sink side of the heat pump, two temperatures are measured, i.e., T5—at the outflow from the HP condenser and T6—at the inflow to the HP condenser. The measurement locations are marked in green in Figures 2 and 3.

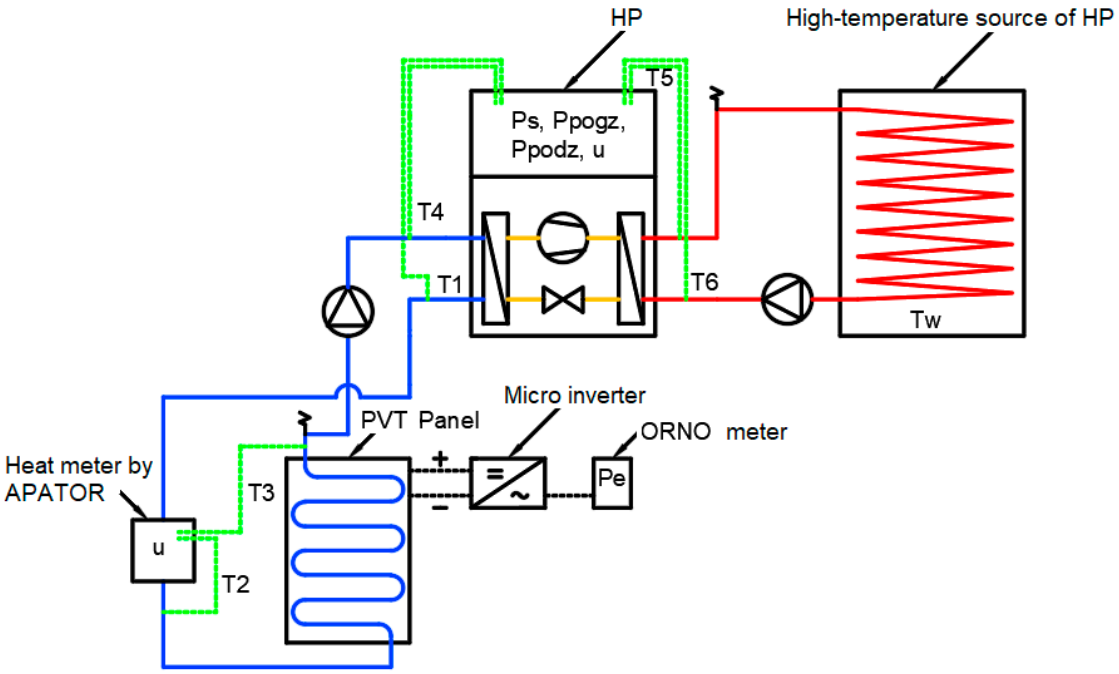



**Figure 3.** Schematic of the test system of the hybrid combination of an HP and a PVT panel as the low-temperature source.

The PVT collector is placed in an unshaded location at a 30° angle towards the south. It is connected to a micro inverter converting the direct current generated by the solar panel into alternating current and adjusting the parameters of the converted current. A grid analyzer is connected to the system, which monitors the instantaneous power of the current generated by the PV system and the amount of energy produced.

A schematic of the second variant of the experiment is shown in Figure 3. The two systems differ with regard to the presence of a hydraulic circuit of the low-temperature source of heat of the HP. The auxiliary air heat exchanger module is omitted in this variant, so that the PVT collector is responsible for all the thermal energy from the low-temperature heat source.

### *2.2. Data Analysis*

Calculations are made using Formula (1):

$$\eta_e = \frac{P_e}{I \cdot A} \cdot 100\%, \quad (1)$$

where $\eta_e$ is electrical efficiency, $P_e$ is electrical power (W), I is solar irradiance ($W/m^2$), and A is PV panel surface ($m^2$). For the PVT panel tested, the manufacturer reports a decrease in efficiency of approx. $-0.45\%/°C$.

With the measured temperatures and the solar fluid flow rate, it is possible to calculate the amount of heat transferred to the HP. The heat power given off is calculated using Formula (2):

$$P_{th} = \mathrm{V}\cdot\rho\cdot\mathrm{c_w}\cdot\Delta\mathrm{T}, \quad (2)$$

where $P_{\mathrm{th}}$ is the thermal power (kW), V is the liquid flow rate (L/s), ρ is the liquid density, equaling 1.03 kg/L, $\mathrm{c_w}$ is the specific heat of the liquid, equaling 3.84 kJ/kg·K, and ΔT is the inlet and outlet temperature difference (K).

Temperatures are measured at different locations in the system, which makes it possible to calculate not only the energy given off from the whole system but also the energy from the PVT panel alone and the air exchanger only.

The thermal efficiency of PVT collectors is much lower than that of classical solar collectors. This is due to the design and intended use of the device. The instantaneous thermal efficiency of the PVT collector is calculated using Equation (3).

$$\eta = \eta_0 - \mathrm{a_1}\cdot\frac{\mathrm{T_p} - \mathrm{T_o}}{\mathrm{I}} - \mathrm{a_2}\cdot\frac{(\mathrm{T_p} - \mathrm{T_o})^2}{\mathrm{I}}, \quad (3)$$

where η is the thermal efficiency of PVT module, $\eta_0$ is the optical efficiency of the PVT module (0.5 for tested PVT module), $\mathrm{a_1}$ is the heat loss correction value (equaling 10.55 $\mathrm{W/(m^2\cdot K)}$, $\mathrm{T_p}$ is the temperature of the PVT module, $\mathrm{T_0}$ is the ambient air temperature, $\mathrm{a_2}$ is the heat loss correction value (equal to 0.012 $\mathrm{W/(m^2\cdot K^2)}$, and I is the solar irradiance ($\mathrm{W/m^2}$).

## 3. Results and Calculations

### *3.1. The Course of the Experiment*

The experiment was conducted in August 2022 at the Centre for Sustainable Development and Energy Saving at the AGH University of Science and Technology in Miękinia. The system operated for a total of 3 days, mainly from 8 a.m. to 3 p.m. Data were collected manually from all the meters installed in the system.

Stable weather conditions prevailed during the testing. The weather was predominantly sunny, with some cloudy spells. Measurement readings were taken every 5 min. As a result of the experiment, the 134 measurement readings were collected for the system with the heat pump running and 58 measurement readings for the PVT panel operation. Over the three days, 174 images were taken with a thermal imaging camera, and 12 current-voltage characteristics of the operating PVT panel were obtained.

### *3.2. Electricity Generation*

The main factors that have an impact on the electrical power generated in PV panels are the intensity of solar radiation and the efficiency of the cells. Assuming a constant efficiency of the panel, the current generated is directly proportional to the intensity of solar radiation. However, the efficiency of the panel also depends on some external factors. The biggest influence on the change in panel efficiency is its operating temperature. As the temperature increases, the voltage of the maximum power point $\mathrm{U_{MPP}}$ decreases, while the current of the maximum power point $\mathrm{I_{MPP}}$ increases [64]. As a result, these fluctuations lead to a reduction of the maximum power output $\mathrm{P_{mpp}}$ and also the efficiency of the panel.

The correlation obtained is shown in Figure 4. The theoretical efficiency that the PV panel should achieve for the given temperatures is given in brackets. The red line indicates standard test conditions (STC) (T = 25 °C).

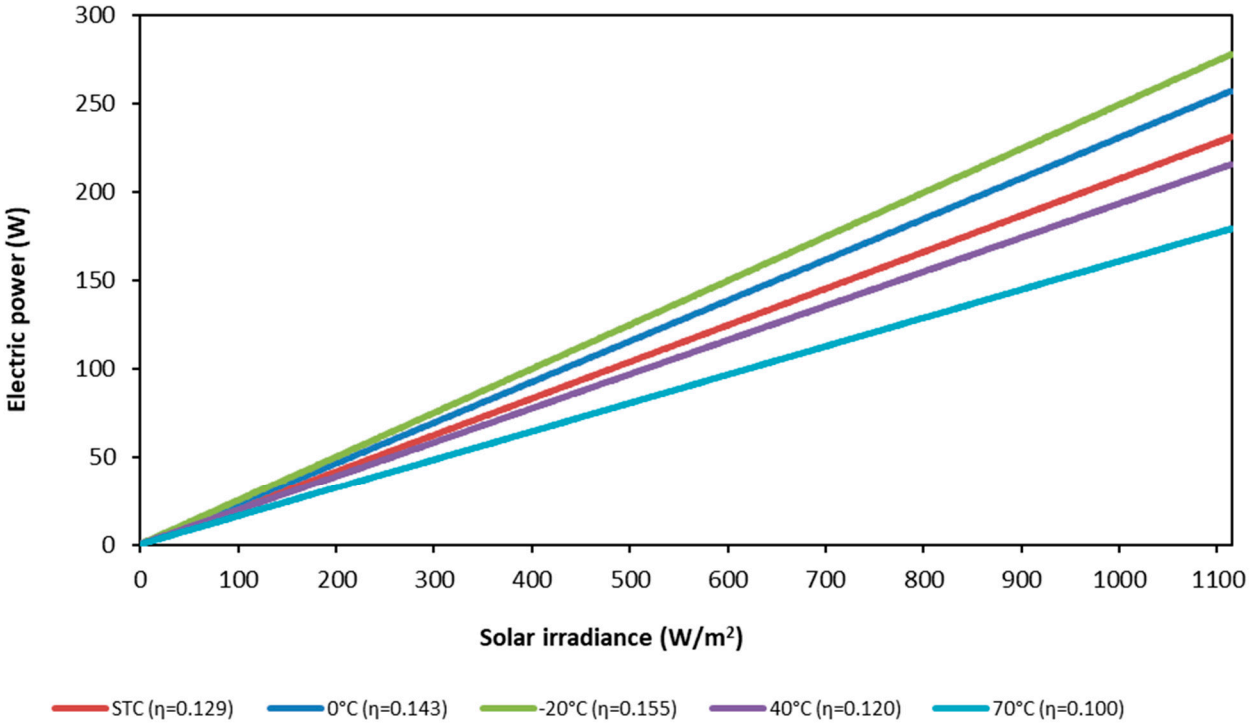



**Figure 4.** Graph of theoretical electric power generated as a function of solar radiation intensity for different operating temperatures of the PV panel [developed based on the data provided in the PVT module datasheet].

During the tests, the temperature of the PVT panel varied from 11 °C to 70 °C. For such a temperature difference, the power difference of the device is 56 Wp, which is 25.3%. In practice, it is not possible to maintain the cell temperature below air temperature. The temperature of the PVT panel is significantly influenced by the intensity of solar radiation, the ambient air temperature, the thickness of the thermal insulation, and the efficiency of the heat transfer.

Figure 5 shows the correlation between the electrical efficiency of the system and the temperature of the panel under test. This is the total efficiency of the system, i.e., of the PVT panel and the inverter. Its average value is 11.81%. It can be seen in the graph that the efficiency decreases with increasing temperature, and the rate of the decrease is −0.37%/°C.

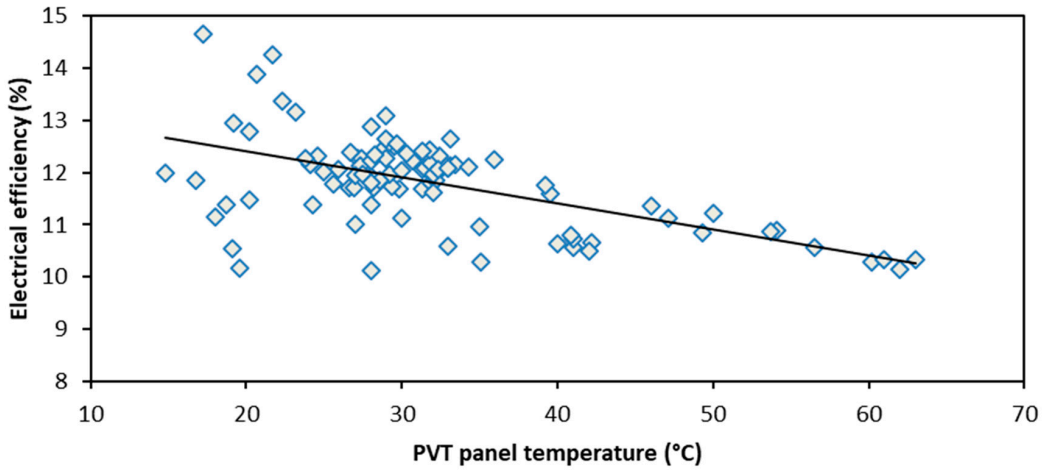



**Figure 5.** Diagram of the correlation between the electrical efficiency of the system and the temperature of the PVT panel under test.

The efficiency graph also reveals a large discrepancy in the values of efficiency at low cell temperatures. This is caused by the uneven heat transfer from the cells, which was the most significant issue in the study. An overview infrared image of the panel is shown in Figure 6, where the variation in cell temperature of the entire PVT panel can be observed.

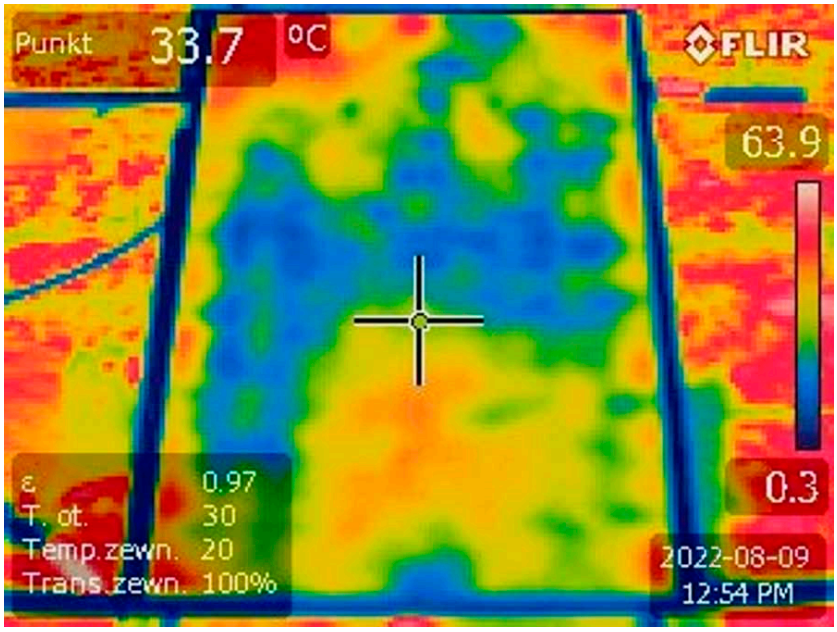



**Figure 6.** Infrared image of the PVT panel during the testing.

Based on the data collected, curves were plotted for the correlation between the power generated and the intensity of solar radiation during heat pump (HP) operation (blue) and without HP operation (red). These curves are shown in Figure 7. The efficiency values calculated on this basis are 12% at an average cell temperature of 28.5 °C and 10.8% at an average cell temperature of 40 °C. An 11.4% improvement in electrical output was observed for the photovoltaic panel cooled by the heat pump compared to the system operating without thermal regulation. Such an increase in efficiency is impressive; however, it should be noted that even better performance can be achieved by cooling photovoltaic modules using alternative methods, such as pouring water over the modules. In the experiment described by Lubon et al., a 20% increase in generated electrical energy was achieved [65].

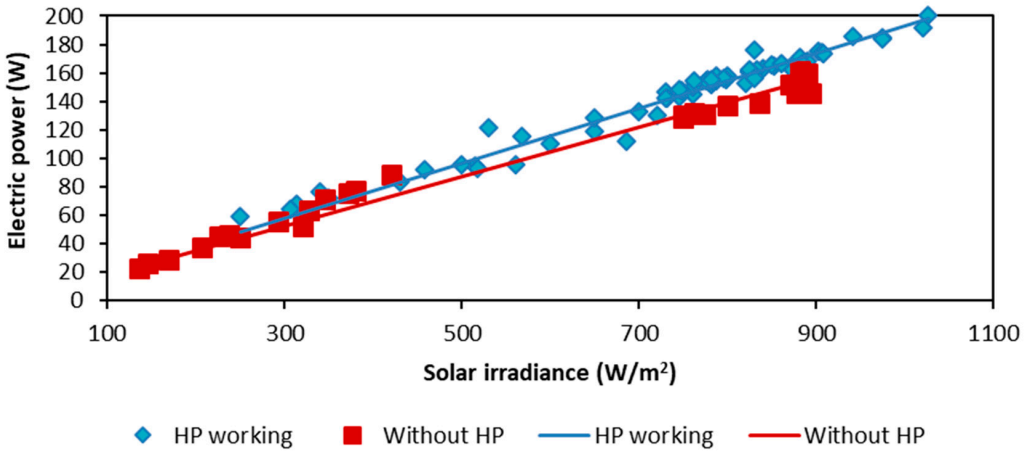



**Figure 7.** Diagram of the correlation between the instantaneous electrical output of the system and solar irradiance.

The three most important of the parameters measured, the ones with the greatest impact on the amount of energy produced, are the instantaneous electrical power, solar irradiance, and the operating temperature of the cells. Based on the data collected, a graph of the correlations between these three parameters was plotted. This graph is shown in Figure 8. As can be seen in the graph, the difference in panel power increases with irradiance growth and cell temperature decrease.

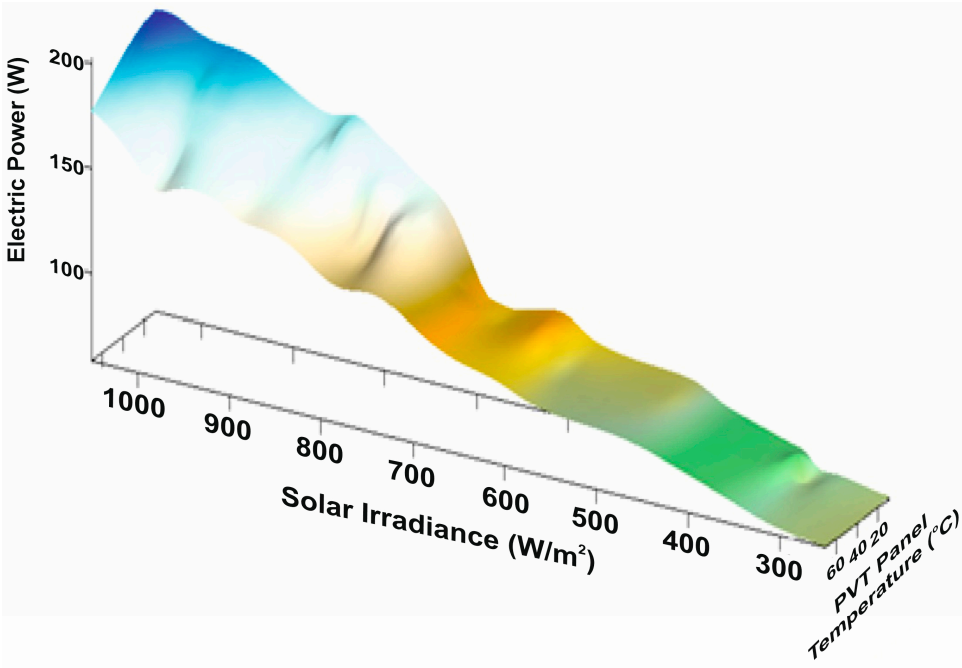



**Figure 8.** Three-dimensional plot of the correlations between power, solar irradiance, and PVT panel temperature.

A separate group of measurements was made using a professional PV system tester. Only 12 measurements were taken with it for three different temperature ranges of the panel. Each reading is provided with a current-voltage characteristic. The data collected with the test meter were taken directly from the PVT panel in operation, bypassing the inverter. Figure 9 shows a plot of the correlation between the electrical efficiency of the PVT panel and the temperature of its cells. The efficiency was calculated using formula (1). The temperature drop in the panel efficiency was calculated to be $-0.41\%/^{\circ}C$. Solar irradiance during the test varied from 663 to 853 $W/m^2$.

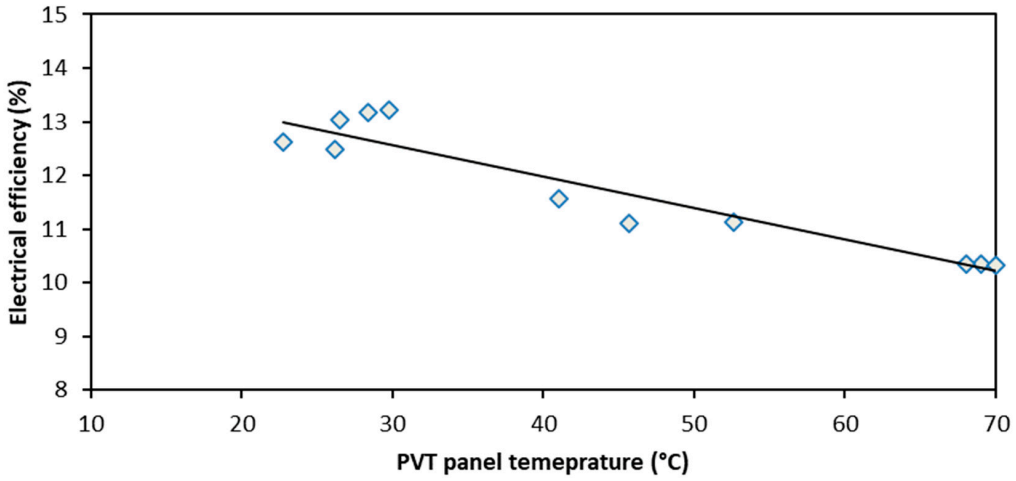



**Figure 9.** Graph of the correlation between the electrical efficiency of the PVT panel and its temperature.

Based on the data collected, lines were plotted to show the correlation between power and solar irradiance. The graph with the lines is shown in Figure 10. The data collected were divided into three groups according to temperature. The first group, $T_a$, was marked in blue. It comprises the results collected during HP operation. The panel temperature for this group is low, between 22 and 30 °C, with an average value of 26.7 °C. The second group, $T_b$ (orange marker), contains data collected at higher panel temperatures. They range from 41 to 53 °C. Their average value is 46 °C. The data belonging to this group were collected shortly after the heat pump was switched off, or in the morning before the panel warmed up. As a result, they have higher values. The last group, $T_c$ (red marker), is made up of data collected during the hottest periods of the day, without the HP running. This group is characterized by the best temperature matching. The temperatures measured range from 68 to 71 °C. The average panel temperature for this group is 69.5 °C.

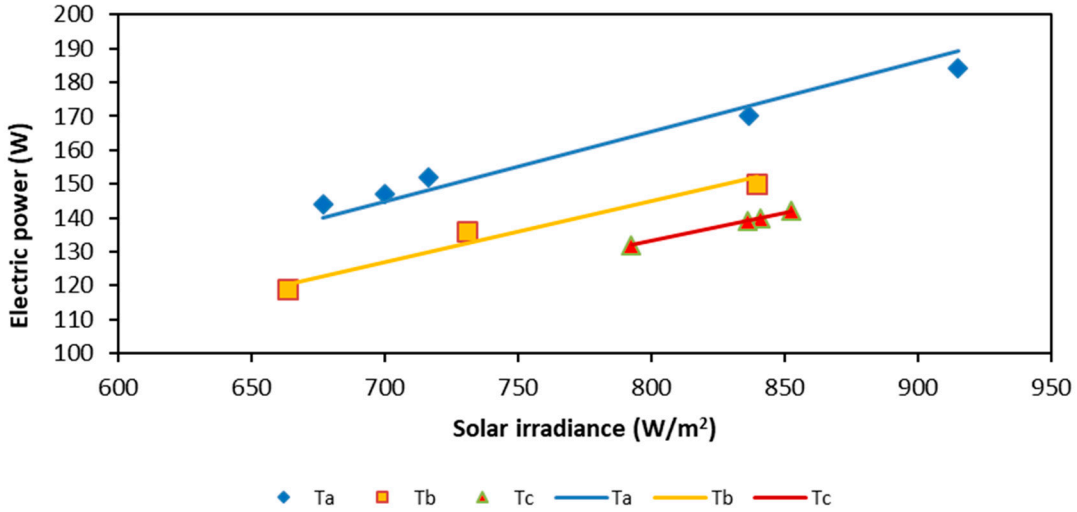



**Figure 10.** Graph of the correlation between of instantaneous electrical output of the panel and solar irradiance.

Based on the lines plotted, the average efficiency of electricity generation by the panel was calculated. This is 12.84% for group A, 11.25% for group B, and 10.34% for group C. Group B achieves 12.3% lower values for power than group A, with a temperature difference of 19.7 °C, while group C achieves 19.4% lower values for power than group A, with a temperature difference of 42.8 °C.

Over the course of the measurements, current-voltage characteristics were recorded for the three temperature groups at a very similar solar irradiance. It can be seen in Figure 10 that the measurement readings lie almost on a straight green vertical line corresponding to approx. 840 W/m$^2$.

In Figure 11, a shift of the I(U) characteristic to the right with decreasing panel temperature can be observed. In Figure 12, an increase in the maximum power of the panel can be observed with a decrease in temperature and a shift of the maximum power point to the right and upwards.

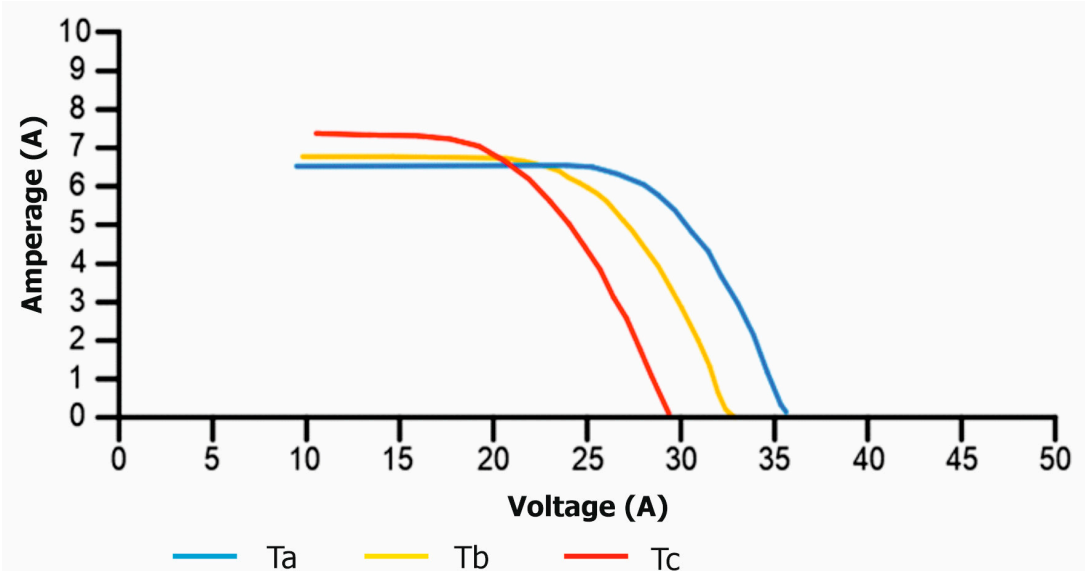



**Figure 11.** Comparison of selected current-voltage characteristics for the three data groups.

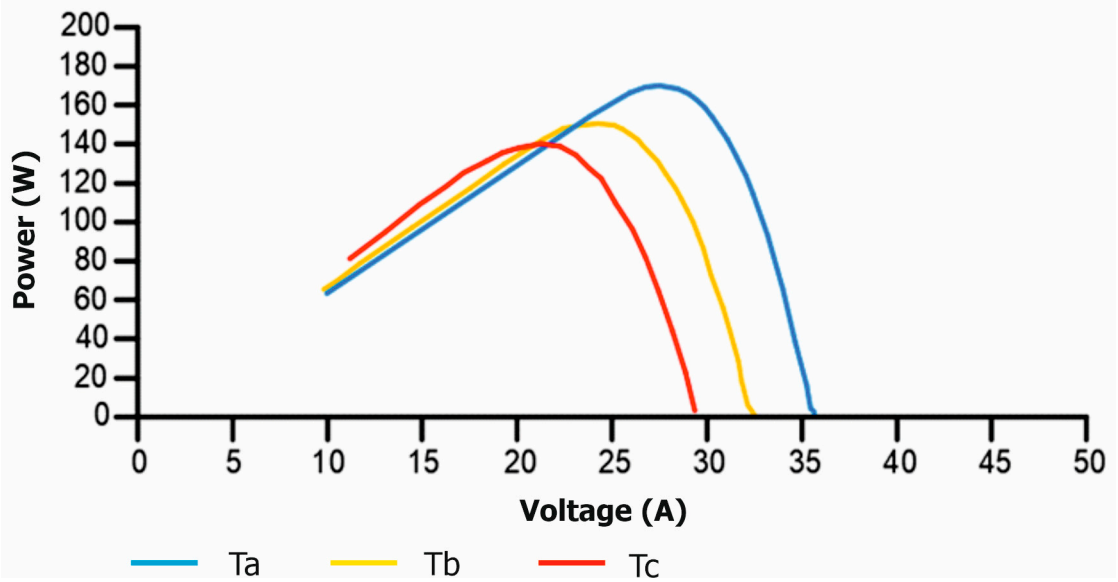



**Figure 12.** Comparison of selected power curves for the three data groups.

### *3.3. Thermal Energy Generation*

The PVT panel serves as a low-temperature source for the heat pump. The data for temperature and glycol flow rates collected during the tests make it possible to analyze the heat transfer in the system.

Figure 13 shows the temperatures as functions of time at the individual points in the low-temperature source system, the ambient temperature, and the panel temperature. The individual symbols, $T_1$, $T_2$, $T_3$, and $T_4$ correspond to the temperatures recorded in the different locations in the system, as shown in Figures 2 and 3. $T_o$ stands for the ambient temperature, and $T_p$ for the temperature of the PVT panel cells read from the infrared images.

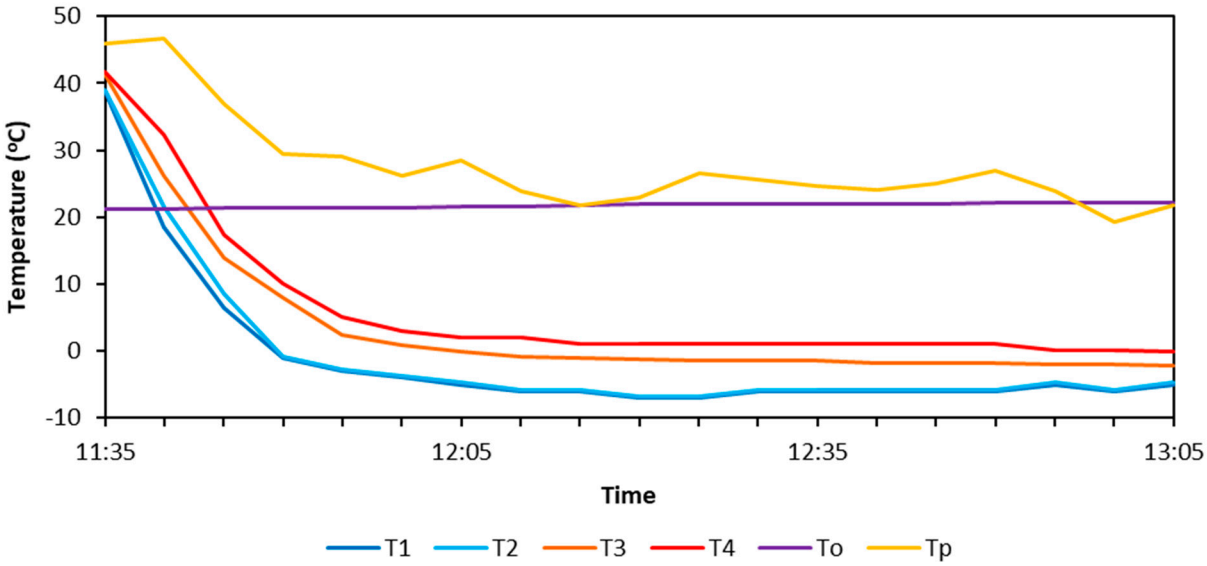



**Figure 13.** Temperatures as functions of time in the low-temperature source system and ambient temperature during the tests.

Figure 13 shows how the measured temperatures change immediately after the start of the experiment (the temperature distribution is shown in Figure 2). Temperatures T1 and T2, recorded by independent measurement systems but located within the same measuring segment—situated between the evaporator of the heat pump and the PVT module—converge to identical values. Temperature T3, measured at the outlet of the PVT module (i.e., located between the PVT module and the air heat exchanger), exceeds the value of T2, which is recorded before the PVT module. This indicates effective thermal energy transfer from the PVT module to the working fluid. Furthermore, temperature T4, measured between the auxiliary air heat exchanger and the evaporator of the heat pump, is higher than temperature T3. This observation implies active operation of the air heat exchanger during the experiment, resulting in additional heat input to the heat pump. It is also noteworthy that the temperature Tp, representing the surface temperature of the PVT module, exhibits a decrease after the experiment commences. This decrease is attributed to the transfer of thermal energy from the PVT module to the circulating solar fluid, which in turn leads to an increase in T3. It can be also observed that the average panel temperature is high compared with the temperature of the working medium in and outflowing from the PVT panel. Despite this, the temperature distribution across the collector surface was very uneven, indicating a problem with proper heat conduction. Based on the infrared images, the minimum and maximum collector surface temperatures were observed. The temperature variation on the surface of the PVT module is shown in Figure 6. The observed problem may be attributed to thermal conduction between the photovoltaic cells and the internal heat exchanger integrated within the PVT module (which transfer heat into solar fluid). The experimental procedure was carried out in two configurations. In the first configuration, the PVT module was thermally supported by an auxiliary air heat exchanger. In the second configuration, the PVT module independently works as the sole heat source for the heat pump evaporator.

Experimental results indicated that the connecting pipes between the PVT module, the air heat exchanger, and the heat pump were exposed to solar radiation, consequently becoming an additional source of thermal energy for the heat pump system. Figures 14 and 15 show graphs of cumulative thermal energy as a function of time. The first figure shows the energy generated when the system was operating with the air exchanger, while the second figure shows the results when the air exchanger was disconnected.

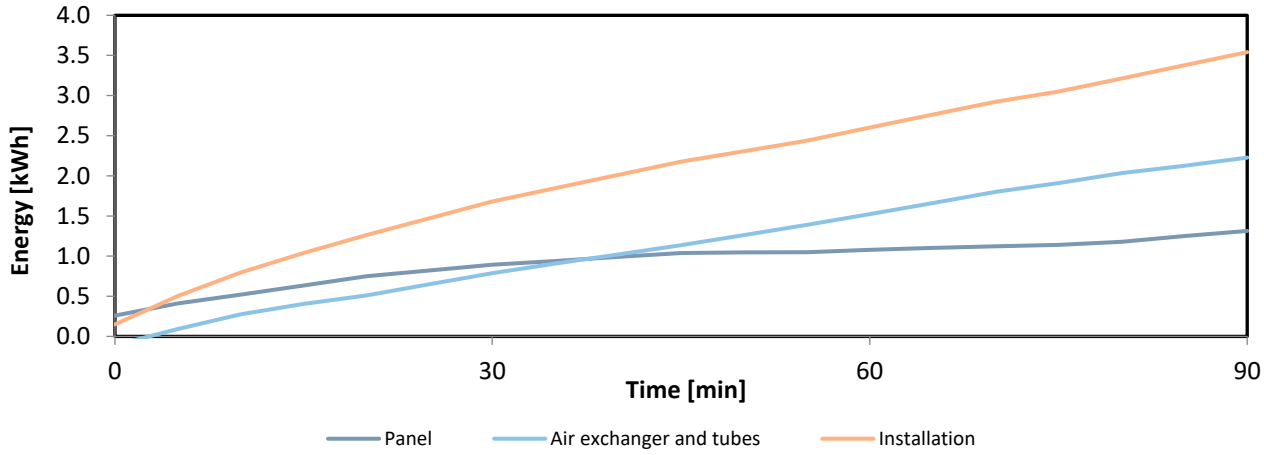



**Figure 14.** Cumulative graph of thermal energy extraction for the system with an air exchanger.

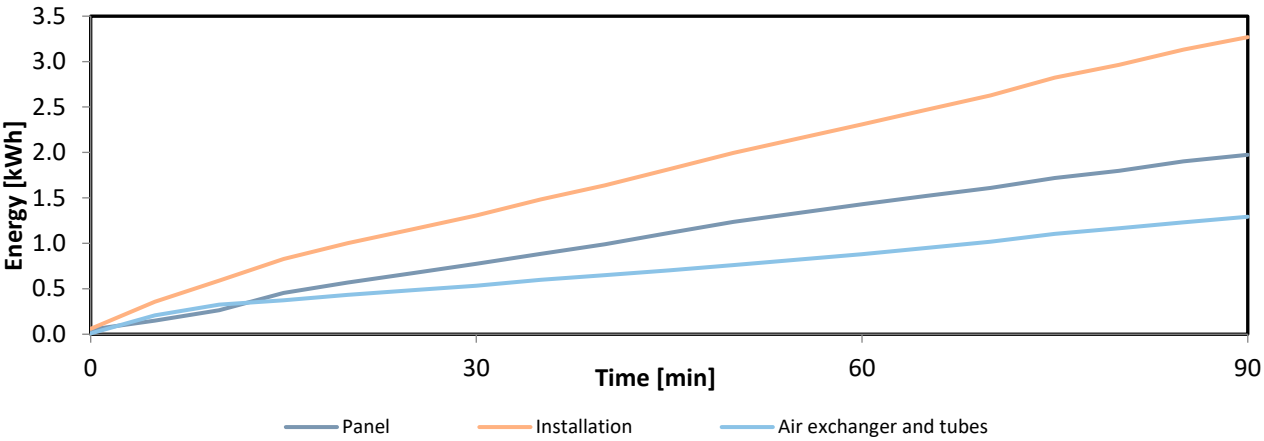



**Figure 15.** Cumulative graph of thermal energy extraction for the system without an air exchanger.

The thermal energy extracted from the PVT panel represents about 40% of the total energy delivered to the heat pump (when the air heat exchanger works) and about 60% of the total energy when the air exchanger was disconnected. The heat extracted from the low-temperature source (PVT module and air heat exchanger) was transferred to the heat pump, where the temperature was raised. The heat was then transferred to an open tank, where it was given off to the water. The amount of heat transferred to the high-temperature source was calculated using Formula (2). The parameter characterizing the operation of a heat pump is the COP. Based on the data collected, the instantaneous COP parameter was calculated for the HP system. The average value of the calculated COP is 3.45. The COP is usually given for specific conditions concerning the high- and low-temperature heat sources. For the system under test, the average water temperature of the high-temperature source was 32.8 °C and the average solar fluid temperature was 2.9 °C. The obtained COP value is relatively low; however, it is important to note that the tests were performed using a didactic (educational) unit. The primary objective of the study was to demonstrate the potential for improving the efficiency of photovoltaic cells through temperature reduction while simultaneously utilizing the recovered thermal energy.

## 4. Conclusions and Remarks

Managing energy production is a complex process that requires taking into account a large number of factors, such as the diversity of energy sources, production efficiency, sustainable practices, social and environmental aspects, as well as continuous improvement

and innovation. The pursuit of sustainable, efficient, and responsible energy production management is crucial to ensuring the stability and sustainability of the energy sector.

Managing the energy production in a combined hybrid heat pump and PV system requires an integrated approach and the use of advanced monitoring and control technologies. Such solutions make it possible to maximize efficiency, minimize operating costs, and reduce greenhouse gas emissions, which contribute to building more sustainable and efficient energy systems.

The conclusions from the study are important for the further development of the technology of combined hybrid heat pump and PV systems. They allow for a better understanding of the potential of this solution and the identification of areas where its efficiency and performance can be further improved. In this way, the technology analyzed in this paper can become an increasingly attractive and competitive option in renewable energy production. Therefore, further research and development of this concept may lead to even greater achievements in renewable energy production and efficient use of natural resources.

Further work in this area should focus on improving panel cooling uniformity, optimizing control algorithms, and testing the system under different climatic and operational conditions to ensure reliability and scalability.

The tests carried out show that it is possible to increase the efficiency of photovoltaic systems by extracting heat from the panels. An 11.4% improvement in electrical output is observed for the photovoltaic panel cooled by the heat pump compared to the system operating without thermal regulation.

The average electrical efficiency of the tested system (PVT panel with inverter) is 11.81%, and the efficiency decreases at a rate of $-0.37\%/^{\circ}\mathrm{C}$ with increasing panel temperature. Based on additional measurements with a PV system tester, a more detailed efficiency decrease rate of $-0.41\%/^{\circ}\mathrm{C}$ is obtained.

The use of cooling can increase the amount of electricity generated by approx. 5% annually. Under favorable conditions (sunny day), the electrical efficiency of PV cells can be increased by up to approx. 20%. Due to the low temperature of the refrigerant, cooling of the panels is possible almost all year round. This also implies that thermal energy is not only extracted from PVT panels but also from the environment through hydraulic hoses.

The experiment shows that the average panel temperatures during operation ranges from 11 °C to 70 °C. The difference in output power of the panel due to temperature differences is up to 25.3%. In classical systems, the PVT panel is cooled by the water used for DHW heating at a relatively high temperature, which causes the temperature of the cells to remain high. This is further increased by the thermal insulation of the collectors, preventing the heat from the cells from being transferred to the environment. In practice, this combination does not bring the intended benefits.

The use of a heat pump allows for more effective panel cooling and maintaining cell temperatures at an average of 26.7 °C (with HP), compared to 69.5 °C (without HP), which translates to a difference in power output of almost 20%. This combination makes it sensible to use PVT panels.

During cooling, in addition to the electrical efficiency of the PV panels, the thermal efficiency of the collector also increases so that the collector can reach an efficiency higher than the optical efficiency. Other parameters, such as the fill factor and the parameters of the current generated, are also improved.

The average COP of the tested system is 3.45, with high-temperature water at 32.8 °C and solar fluid at 2.9 °C. The cell temperatures achieved by the panel typically remain at the level of ambient temperature but can also fall below this value. This causes an increase in the efficiency of the system in terms of electricity and heat generation. On the other

hand, however, the more the cell temperature drops below the ambient temperature, the more thermal energy will be extracted by the system from the ambient air. As a result, the required cooling capacity of the heat pump will increase much more rapidly. In addition, there is a risk that the temperature of the cells will fall below the dew point, which will cause moisture from the environment to condense on the surface of the panel. For these reasons, excessive cooling of the panels should be avoided.

This solution also has its drawbacks. The biggest problem during the testing was the uneven cooling of the cells, with temperature differences of up to 30 °C across the panel surface. In photovoltaic panels, all cells are connected in series. If individual cells operate at different efficiencies, the whole panel will only be as efficient as the weakest cell. This uneven cooling could degrade the overall performance of the panel by up to 3–4%.

Although the efficiencies of photovoltaic cells are improving every year, it is still the case that most of the solar energy reaching the cells is converted into heat. Therefore, a large amount of heat energy is required to cool a PVT panel effectively. The experimental results show that the heat extracted from the PVT panel represents about 40% of the total energy delivered to the heat pump with an air exchanger and about 60% without an air exchanger, demonstrating the significant role of direct solar thermal gain. The solution tested will mainly be suitable for industrial plants with a high heat demand, such as salt production plants.

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