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Evaluation of the Energy and Ecological Effects of a Photovoltaic-Thermal System

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Abstract

This paper presents a detailed analysis of the operating parameters of a solar active installation with seven photovoltaic-thermal (PV/T) collectors with a total area of 14 m^2 in a single-family house. A comparative analysis of the work parameters was carried out for the following two locations: Warsaw (Poland) and Andravida (Greece), based on the research of the solar system model created in the TRNSYS 16 program. Considering the months with the best sunshine, from May to August, the average monthly electricity yield in PV/T solar collectors was 206 kWh (Warsaw) and 248 kWh (Andravida). In July, the monthly generation-to-consumption ratio of the PV/T system under the Polish climate conditions was 82%, and under the Greek climate conditions—99%. The heat recovery from PV/T solar collectors in July in the climate of Greece was estimated at 264 kWh and is 29% higher compared to the heat recovery in a hybrid solar installation located in Poland. The generation of electricity in the PV/T solar system instead of a coal-fired power plant can contribute to the avoidance of the annual emissions of pollutants by: 14.00–19.11 kg of SO_2, 2.72–3.72 kg of NO_X, 5.44–7.43 kg of CO, 1330.86–1816.79 kg of CO_2, and 1.09–1.49 kg of particulate matter, depending on the location.

Keywords: photovoltaic-thermal collector; simulation; system modeling; energy yield; emissions; air pollution

1. Introduction

The essential goals of the European Union's (EU) energy policy until 2030 are as follows: reduction in the greenhouse gas (GHG) emissions by at least 55% compared to 1990 levels, improvement of the energy efficiency by at least 36% compared to the 2007 forecast, and achieving at least a 40% share of energy from renewable sources in total energy consumption [1]. According to the REPowerEU plan, a binding renewable energy target of 42.5%, with the ambition to reach 45%, is intended to ensure energy security and make sustainable energy more accessible [2]. As part of EU commitments, in 2030, Poland should reach 23% share of renewable energy sources (RESs) in gross final energy consumption, and reduce the GHG emissions by 30% compared to 1990 levels, reducing the use of coal in electricity generation to 56% and increasing energy efficiency by 23% compared to the forecasts of primary energy consumption from 2007 [3].

The use of RES contributes to the reduced impact on the natural environment by decreasing the emission of harmful substances, especially GHGs. Air pollutants introduced

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into the atmosphere resulting from the energetic combustion of fossil fuels adversely affect the climate, the environment, and human health. In 2023, the households in Poland were responsible for the emission of 105.6 thousand tons of sulfur dioxide (SO_2), 53.9 thousand tons of nitrogen oxides (NO_X), 1324 thousand tons of carbon oxide (CO), 348.4 million tons of carbon dioxide (CO_2), and 201.9 thousand tons of particulate matter (PM) [4]. Photovoltaic (PV) systems cause negligible GHG emissions during operation, saving 0.53 kg of carbon dioxide (CO_2) emissions per unit of electrical energy. By 2030, the development of photovoltaics can prevent the emission of 69–100 million tons of CO_2, 68–99 thousand tons of NO_X, and 126–184 thousand tons of SO_2 [5].

In 2024, the share of RES in Poland was 16.7% and 25.3% in Greece [6]. Taking into account the years 2010–2023, the amount of electricity generated from renewable sources in gross electricity consumption increased in Poland nearly four times, from less than 7% in 2010 to almost 26% in 2023, and in Greece from 12% to 48% [4]. In 2024, the worldwide photovoltaic capacity increased to at least 2247 GW_p, and PV systems supplied a total of 2437 TWh of electricity [7]. In 2024, the share of PV technology in Greece accounted for 21.4% of total electricity production [8], and in Poland the share of PV sources in renewable energy installations for electricity generation was 10.6% [9]. At the end of 2024, the capacities of power stations using photovoltaics in the Polish National Power System reached a level of approximately 20.2 GW_p, and Greek photovoltaics reached an installed capacity of 9.3 GW_p [9].

By the end of 2024, the cumulative solar thermal capacity reached an estimated 544 GWth, thanks to the installation of 777 million m^2 of solar collectors. The annual solar thermal energy yield in 2024 was 443 TWh, which correlates to savings of 47.6 million tons of oil and 153.5 million tons of CO_2 [8]. The total installed capacity in operation in 2023 was 4109 MW_{th} in Greece and 2476 MW_{th} in Poland [7].

The use of photovoltaic/thermal (PV/T) solar collectors is not widespread worldwide, although their technology has been known since the mid-1970s [10–13]. The hybrid PV/T system was first proposed and studied by Martin Wolf in 1976 [14,15], but it was only since the 1990s that research and development on PV/T technology have been intensified [16]. In 2018, the International Energy Agency Solar Heating and Cooling Program introduced the application task to improve the performance characteristics and modeling of collectors and PV/T systems, and to promote the dissemination of PV/T technologies on the market [17]. Worldwide, by the end of 2024, a cumulated PV/T collector area of about 1.7 million m^2 was installed with a total thermal capacity of PV/T collectors of 866 MW_{th} and a nominal PV power of 316 MW_p [7]. The PV/T system can save up to 16 tons of CO_2 in 20 years of operation, which is 36% more compared to the PV system [18].

Yazdanifard and Ameri [15] conducted studies of exergy performance of several types of PV/T installations to demonstrate strengths and weaknesses and to propose new PV/T technologies. The essential advantages of a PV/T system include: simultaneous generation of electricity and heat for useful purposes, extending the life of the PV panel [5,19,20], providing a smaller assembly area compared to the area occupied by two independent systems [21], ease of integration with the building, reduction in solar system costs [22], and reduction in heat losses from the collector when solar cells operate as a selective absorber [23].

The total energy efficiency of the PV/T system is affected by the configuration design and heat dissipation system used, the materials of both a PV module and a thermal collector, weather parameters such as solar radiation, outdoor air temperature, and wind speed, the working fluid used, operating temperatures of components, working conditions [13,15,18,24,25], and could achieve 60–80% [26].

Joshi and Dhoble [12], based on the literature, reported that the electrical and thermal efficiencies of non-concentrated water type PV/T systems are in the range of 10–12% and 50–70% respectively, and of non-concentrated air type hybrid systems are 9–12% and 40–60% respectively. Huang et al. [27] stated on the basis of experimental research that the thermal efficiency of the unglazed PV/T system with polycrystalline silicon PV panel located in Taiwan reached 35.33–47.21%, and the PV conversion efficiency was in the range of 12.77–14.46%. Nualboonrueng et al. [28] performed experimental tests of two solar installations with amorphous and monocrystalline silicon PV/T collectors located in Bangkok (Thailand), on the basis of which the average annual thermal efficiency of PV/T collectors in the range of 49–51% was determined. The average annual electrical efficiency of the tested collectors was determined at a level not exceeding 5% (4.0–4.6%). Sopian et al. [22] tested the designed nanofluid and nano-PCM PV/T system under the tropical climatic conditions in Bangi, Malaysia. In this case, the highest electrical efficiency of the proposed hybrid system was equal to 13.7%, the highest thermal efficiency was 72% and the highest overall efficiency was 85.7%.

On the basis of numerical research using the Successive Substitution method, Hamdoon et al. [29] found that for a packing factor equal to one, the hybrid PV/T solar domestic hot water (DHW) system is able to cover the demands of DHW between 61.7% and 83% and electricity from 24.5% to 43.9% for a single-family building with five occupants located in Mosul, Iraq. The total area of the PV/T collectors was 9 m^2. In turn, Herrando et al. [18] determined that a hybrid PV/T system with monocrystalline silicon cells with a total area of about 15 m^2 and with a collector flow-rate of 5.56×10^{-6} m^3/s can cover 50.7% of the annual electricity demand and 35.6% of the total DHW demand for a typical terraced house with four inhabitants in London.

The PV/T systems have been the subject of theoretical, experimental, and simulation studies for many years. The most suitable tool for the simulation studies of hybrid systems is an Artificial Neural Network using MATLAB and TRNSYS software [12].

Myhan et al. [30] developed a mathematical model of a hybrid solar collector, which was implemented in the MATLAB R2014a program, and then conducted simulation studies using multi-year real weather data for the city of Kolobrzeg (Poland). They found that the PV/T collector achieves the highest energy efficiency if it is oriented south and the elevation angle is 34.1°. Kallio and Siroux [31] conducted model studies using MATLAB/SIMULINK and presented the results of an energy and exergy analysis of the hybrid solar collector efficiency for the following two sites: Strasbourg (France) and Tampere (Finland). In addition, they compared the operating parameters of the PV/T solar collector and the PV panel, taking into account the operating temperature of the PV cell, efficiency, and electric power. Kalogirou [32] developed a model of the PV/T system in the TRNSYS program for the climatic conditions of Nicosia (Cyprus), and he found that the solar hybrid system increases the average annual efficiency of the PV system from 2.8% to 7.7%, and covers 49% of the DHW demand, thus increasing the average annual system efficiency to 31.7%. He determined the optimal water flow rate through the PV/T system at the level of 6.94×10^{-6} m^3/s.

Kalogirou and Tripanagnostopoulos [20] studied the electrical and thermal performance of the designed, constructed, and tested prototype PV/T panels with polycrystalline silicon and amorphous silicon cells. Using the TRNSYS simulation software, the authors presented the results of testing the following two PV/T systems: a small-scale unit with an aperture area of 4 m^2 and a water storage tank with a capacity of 0.16 m^3 and a large-scale system of 40 m^2 an aperture area and 1.5 m^3 storage tank for the following three different locations: Nicosia (Cyprus), Athens (Greece) and Madison (Wisconsin). Depending on the location, the hybrid PV/T thermosyphon system provided from 222.7 to 532.1 kWh of

electricity, useful thermal energy was 3807–6083 MJ, and solar fraction ranged from 29.3% to 72.6%. In the case of the large hybrid PV/T active system, the PV/T electrical energy was obtained in the range of 2265.5–5640.1 kWh, useful thermal energy was 37,810–54,540 MJ, and solar fraction was 60.7–87.1%.

Dupeyrat et al. [33] conducted simulation studies to compare the performance of the building-integrated PV/T and PV systems with the performance of the standard solar thermal collectors and PV panels for three different weather conditions in France using the TRNSYS 16 program. The increase in electrical output for the equivalent roof area for the combination PV/T and PV was obtained at around 12.7% in Paris, 12.6% in Lyon, and 10.7% in Nice, relative to the separated technologies.

Huang and Huang [34] carried out the simulations of the performance of electrical and thermal of the PV/T system for five cities located in Taiwan using the TRNSYS program. The 1440 W system consisted of six unglazed flat-plate PV/T collectors with a total area of 9.78 m^2. The electrical efficiency of the hybrid solar installation ranged from 11.7 to 12.4%, and the thermal efficiency was 26.78–28.41%. Lämmle et al. [21] compared the performance of unglazed, glazed, and PV/T collectors with low-emissivity coatings operated in four types of solar thermal systems as follows: solar system with a heat pump in a single-family building, domestic hot water system in a multi-family building, and a combi system in a single-family building, including domestic hot water installations and combined systems in single and multi-family buildings for the four European locations of Athens, Davos, Würzburg, and Stockholm. On the basis of on the simulation tests in the TRNSYS 17 program, it was found that PV/T collectors achieve either high electrical or high thermal efficiency, but not both at the same time. This was due to the technological compromise between good optical efficiency versus a high level of insulation. The electrical efficiency of the tested PV/T panels ranged between 148 kWh/m^2 and 182 kWh/m^2. The heat output was between 248 kWh/m^2 for the unglazed PV/T collector and 525 kWh/m^2 for the glazed PV/T collector with low-e. Li and Jing [26] evaluated the operation of the PV/T system with different kinds of solar cells: GaInP, GaAs (thin film), InGaP/GaAs/InGaAs under the meteorological conditions of Xi'an, a typical city in western China, using the TRNSYS-CFD coupled model. It was found that there is an optimal flow rate for thermal energy efficiency to obtain its peak for different solar cells at different concentrations.

Buonomano et al. [35] simulated a water-based building-integrated photovoltaic-thermal BIPV/T system using TRNSYS 17 software. It was found that this hybrid installation in a non-residential high-rise building located in Naples (South Italy) allowed reducing the annual energy demand for space heating by a radiant floor system and hot water preparation from 7.6 to 5.5 MWh/year and from 230.9 to 209.7 MWh/year, respectively. The demand for electricity from the national grid was reduced from 48.0 to 25.9 MWh/year. Jonas et al. [17] described a novel electrical and thermal PV/T collector performance two-node model with one or two thermal capacities. In order to validate the implemented model in TRNSYS, experimental studies of two different types of PV/T collectors for weather conditions Saarbrücken, Germany, were carried out. Tests were made for an uncovered PV/T collector with thermal insulation material on the back of the absorber and a covered PV/T collector with front glazing, and no thermal insulation material. It was demonstrated that the developed model is appropriate for dynamic simulation studies and was proposed as a standardized model. Khordehgah et al. [13] created a solar installation model with PV/T collectors for a single-family building located in London (United Kingdom) in the TRNSYS simulation program. The model was validated based on experiments. The simulation studies allowed determining the efficiency of the PV/T panels at different times of the year and optimizing the system performance. They showed that reducing the temperature of the solar panel by an average of almost 25% causes an

increase in electrical power by almost 15%. Lowering the temperature of the solar panel by an average of nearly 25% resulted in an increase in electrical power by almost 15%.

The fundamental challenge in PV technology remains the inefficient conversion of solar radiation, where commercial modules (e.g., m-Si and CIS) often achieve practical electrical efficiencies below 15% [36]. The remaining approximately 85% of solar energy is dissipated as waste heat, which significantly increases the operating temperature of the cells and leads to degradation of electrical output—typically estimated at 0.4–0.5% per 1 K rise [37]. PV/T systems address this by actively recovering waste heat, thereby achieving combined solar efficiencies exceeding 70–80% while simultaneously cooling the PV cells to maintain electrical performance [36,38].

Prasetyo et al. [37] emphasized the following two primary pathways for enhancing the thermal extraction of PV/T collectors: geometric modifications and application of nanofluid. The first method is based on the integration of fins within the absorber channels. It increases the heat transfer area and promotes turbulence. Meta-analyses indicate that fin modifications improve thermal efficiency by an average of 12.14%, with wavy fins being the most effective, providing enhancements up to 17.1%. Another option is replacing conventional working fluids with nanofluids (e.g., graphene or carbon nanotubes). Studies have shown that this results in a superior potential for efficiency gain. Graphene-based nanofluids, at optimal volume fractions of 1.5–2.5%, can enhance thermal and electrical efficiencies by 22.3% and 11.2%, respectively, due to their superior thermal conductivity.

To address the intermittency of solar energy, PV/T systems are increasingly integrated with advanced storage and concentration technologies. The synergy between PV/T collectors and Phase Change Materials (PCMs) provides significant thermal buffering, which stabilizes cell temperatures and allows for the shifting of peak cooling loads in buildings. Such configurations have demonstrated substantial potential in large-scale facilities, such as school sports centers, where they have been shown to reduce annual CO_2 emissions by over 160 tons [39]. Furthermore, the utilization of Low-Concentration PV/T (LCPV/T) systems, incorporating linear parabolic reflectors or similar concentrating elements, enables the working fluid to reach higher temperature ranges, typically between 40 °C and 60 °C. This elevated thermal output is particularly critical for driving absorption chillers or meeting high-temperature domestic hot water demands, thereby expanding the operational versatility of hybrid solar installations [38,39].

As Zero Energy Building (ZEB) mandates expand globally, the focus of hybrid solar research has shifted toward Façade-integrated PV/T (BIPVT) systems, which require sophisticated control strategies to balance electrical and thermal yields. Recent comparative studies have challenged the efficacy of traditional differential temperature control, often referred to as Mode 1, which is the standard in conventional solar thermal systems. In Mode 1, the collector-side pump is activated only when a specific temperature gradient exists between the collector and the storage tank. However, for PV/T applications, this method can lead to stagnation and reduced electrical efficiency due to inadequate cooling of the PV cells during periods of low thermal demand. In contrast, an alternative operational strategy known as Mode 2 has been proposed, where the pump operates continuously whenever the PV modules generate a threshold level of electricity, such as 5 W, regardless of the temperature difference. Research conducted by Kim et al. [40] demonstrated that Mode 2 can increase annual electrical production by approximately 2.8% compared to Mode 1, as the prioritized cooling of the modules outweighs the minor increases in pump energy consumption and thermal losses.

Complementing these operational advancements is the transition toward more robust mathematical frameworks, specifically gray-box modeling, which bridges the gap between purely physical and data-driven approaches. Unlike black-box models that lack physical

interpretability, gray-box models utilize fundamental thermodynamic equations while simultaneously employing operational data for automated parameter identification. This methodology allows for the precise determination of critical system characteristics, such as optical efficiency and heat loss coefficients, under real-world conditions that laboratory tests according to EN ISO 9806 [41] may not fully capture [42]. By integrating these identified parameters into transient simulation environments like TRNSYS, researchers can develop highly accurate "digital twins" of PV/T installations. This synergy between simplified yet effective control methods like Mode 2 and high-fidelity gray-box modeling facilitates the implementation of Model Predictive Control (MPC) in smart buildings, ensuring that the hybrid system responds dynamically to fluctuating weather patterns and occupancy demands while maximizing carbon reduction potentials.

Beyond energy savings, PV/T technology contributes to the Sustainable Development Goals (SDGs) by mitigating the urban heat island effect. Unlike conventional PV panels that radiate heat back into the atmosphere, PV/T collectors absorb this energy for productive use, thereby reducing the environmental thermal load [36]. Multi-objective optimization using Artificial Neural Networks and Genetic Algorithms (ANN-GA) further confirms that optimized hybrid PV/T systems can reduce building-level CO_2 emissions by over 60% across various climatic zones [38].

The present article aims to provide a comparison of the electrical and thermal yield of the same photovoltaic-thermal active system with polycrystalline silicon PV panels, operated under two different climatic conditions, i.e., those of Poland and Greece. The research was carried out using the TRNSYS 16 software. The created installation model was calibrated on the basis of the device manufacturer's data. To the best of the authors' knowledge, there are not many studies, both experimental and numerical, where the results of monthly and annual energy yields of PV/T panels in moderate climate locations have been presented and discussed. So far, most of the studies concern the localization of PV/T panels in hot, humid, and dry climates [12,22,27,28]. It is therefore interesting to know the benefits of using hybrid PV/T collectors and their ability to cover the energy demand of the building, also in new locations. Furthermore, analyzing two distinct locations (Poland and Greece) enables a comparative assessment of the performance of the same PV/T collector design under different climatic conditions, thereby providing insights into the potential benefits associated with the integration of these systems into buildings in different climates. Taking into account the fact that the share of solar energy in the use of RES is still unsatisfactory, the aspiration to popularize such a solution is fully justified. Additionally, this paper describes the reduction in fossil fuels as a result of using the solar installation with PV/T panels situated in Warsaw and Andravida, and thus the possibility of the avoidance of air pollutant emissions into the atmosphere. Thus, the article addresses another research gap by assessing the ecological impact of this PV/T installation under two contrasting climatic conditions.

2. Materials and Methods

2.1. Description of a Solar System with PV/T Modules

A solar installation with seven hybrid photovoltaic PV/T panels with a total gross area of 14 m^2 was subjected to simulation tests. Each panel is made of 72 polycrystalline silicon (pc-Si) cells with dimensions of 156 mm × 156 mm. Commercial hybrid collectors E-PV/T 2.0v2 with the single-glazing and Roll-Bond aluminum exchanger as an absorber in an aluminum frame were adopted [43]. Thermal and electrical parameters of this PV/T module are shown in Table 1.

Table 1. Operating parameters of the PV/T panel [43].

Thermal and Electrical Parameters	Value
Aperture area	1.812 m^2
Diameter of the collection pipe	0.018 m
Fluid content	0.0012 m^3
Maximum operating pressure	6 bar
Maximum operating temperature	85 °C
Collector efficiency	56.7%
Peak power for 1000 W/m^2	320 W_p
Short-circuit current	8.88 A
Rated current	8.46 A
Open-circuit voltage	45.13 V
Nominal voltage	37.85 V

The PV/T collectors are mounted on a south-facing roof of the building at an angle of 18° to the level, due to the angle of the building's roof. The PV/T panels are connected with an inverter with 98% efficiency. The tested electrical installation is not equipped with an energy storage system. The total power of the electrical installation is 2.24 kW. Hydraulically, the PV/T solar collectors are connected in two parallel rows, while within each row, 3 and 4 collectors are connected in series. The fluid mass flow rate through one collector is 0.025 kg/s. The working fluid in the solar collector circuit is a mixture of water and propylene glycol with a concentration of 50%. The DHW storage tank is a fully mixed tank with a capacity of 0.5 m^3. The collector circuit is connected to the storage tank through an external heat exchanger.

The hybrid solar system should cover part of the thermal needs for DHW heating and electricity demand in a single-family house with a cubic volume of 826 m^3. An average number of five inhabitants was assumed.

2.2. Description of Components Used in the TRNSYS Model

The hybrid photovoltaic-thermal solar energy system was modeled using TRNSYS 16 software. The program is a complete and extensible simulation environment, mainly used in the field of renewable energy engineering and building simulation. In order to develop an appropriate model of the tested installation, it was necessary to introduce constant parameters for individual components and input information.

The PV/T panel, as the Type 50b component, was described using the following parameters: collector area, collector fin efficiency factor, collector plate absorptance, collector plate emittance, collector slope, number of glass covers, loss coefficient for bottom and edge losses (see Table 2). Then, the input data for this component were defined as follows: fluid mass flow rate in a solar collector circuit (0.05 kg/s), cell efficiency at reference conditions (15.5%). Inlet fluid temperature was entered as the temperature of the fluid flowing out of the pump in the solar circuit. Weather data such as ambient temperature, incident radiation, and wind speed were entered as output parameters from the Type109-TMY2 component. The Meteonorm 7 library (No. 123750 for Warsaw, No. 166820 for Andravida) was used to obtain climate data for the Warsaw and Andravida locations [44]. The following parameters were obtained as output parameters: outlet fluid temperature, rate of useful energy gain, and electrical power output.

The component of Type 48a is a device used to convert direct current (DC) generated in a photovoltaic power system into alternating current (AC).

Table 2. Type 50b—design parameters in TRNSYS 16.

Component	Description	Value
PV/T collector	External dimensions (width × length × depth)	2 m × 1 m × 0.062 m
	Collector plate absorptance	0.92
	Collector plate emittance	0.09
	Transmittance absorptance product	0.90
	Loss coefficient for bottom and edge losses	0.30 W/(m^2·K)
	Temperature for cell reference efficiency	25 °C
	Packing factor	0.875
	Collector fin efficiency factor	0.96
	Number of glass covers	1
	Collector slope	18°

The effectiveness of the external heat exchanger for a Type 91 component was reported as of 90%. The specific heat of the working medium (of hot side fluid) was assumed to be 3.6 kJ/(kg·K), and the specific heat of water (of cold side fluid) was assumed to be 4.19 kJ/(kg·K). The input data were the fluid temperatures at the inlets to this heat exchanger (20 °C/10 °C) as well as the flows on the hot and cold side (0.05 kg/s and 0.028 kg/s). The hot-side inlet temperature assumes the value of the outlet fluid from the PV/T panels. The output parameters for this component were: hot and cold side outlet temperatures and heat transfer rate.

In the case of the next component, i.e., the Type 4a storage tank, the input parameters were: environment temperature (22 °C), flow rates in the hot and cold circuit (0.028 kg/s), and tank loss coefficient (0.008 W/(m^2·K)).

In order to take into account the daily profile of the domestic hot water consumption and the temperature of cold water supplied to the storage tank in the simulations, the Type 14 component was used. Figure 1 presents the daily DHW consumption profile adopted for simulation. As a result of the performed calculations, the following information was obtained: average tank temperature, energy rate to load, and energy rate from heat source.

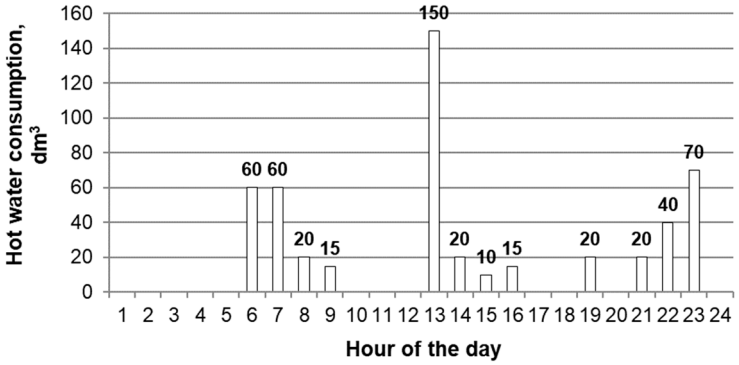


Figure 1. Histogram of daily hot water consumption in the building.

For the Type 114 pump in the solar circuit and the pump in the tank circuit, the input parameters were: inlet fluid temperature (as appropriate output temperatures), inlet fluid flow rate, overall pump efficiency (60%), motor efficiency (90%), and rated power of the 40 W. Outlet fluid temperatures were obtained as output parameters. The Type 2b pump operation controller is an on/off temperature difference controller. The temperature difference between the outlet fluid temperature of the PV/T collectors and the water temperature in the lower part of the storage tank were used for regulation.

The Type 25c system printer allowed saving the simulation results of the selected parameter in the form of a .txt file. Owing to the use of the component of the Type 65 (a plotter), it was possible to generate graphs showing the variability of output parameters over time. Figure 2 shows a schematic of the installation with PV/T panels created using TRNSYS 16 tool.

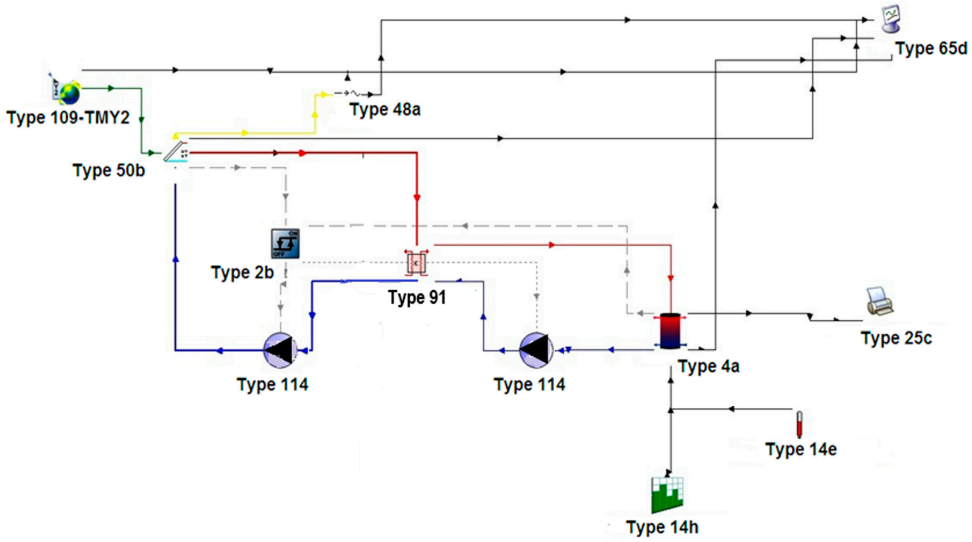


Figure 2. Hybrid photovoltaic-thermal system in TRNSYS 16.

The whole-year simulations were carried out having a time step of 60 min.

2.3. The Weather Data

The Meteonorm library [44] was used for the locations in Warsaw (Poland) and Andravida (Greece), which contains the data necessary for the simulations related to the ambient temperature, wind speed, and solar radiation incident on the surface of the PV/T modules. The weather data are loaded into the program through the Type109-TMY2 component. Warsaw is located in the east-central Poland, and its geographic coordinates are 52°13′56″ N (latitude) and 21°00′30″ E (longitude). Andravida (latitude: 37°54′0″ N, longitude: 21°16′0″ E) is a town in the northwest of the Peloponnese peninsula of Greece. Warsaw has a warm humid continental climate (it is Dfb zone), and the climatic conditions of Andravida are typical Mediterranean (it is Csa zone). The average annual outdoor air temperature for Warsaw was 7.8 °C and 17.3 °C for Andravida. Figures 3 and 4 show the course of the ambient temperature changes throughout the year for the considered localizations, and Figures 5 and 6 present the course of changes in total solar radiation.

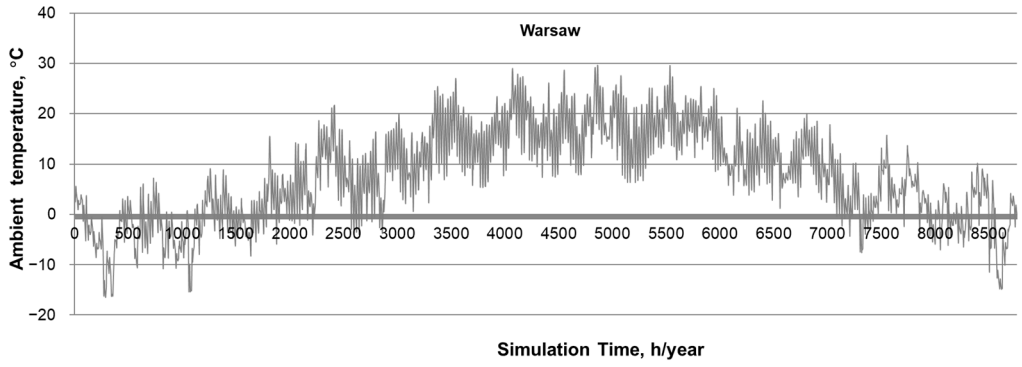


Figure 3. Variability of the ambient temperature for Warsaw.

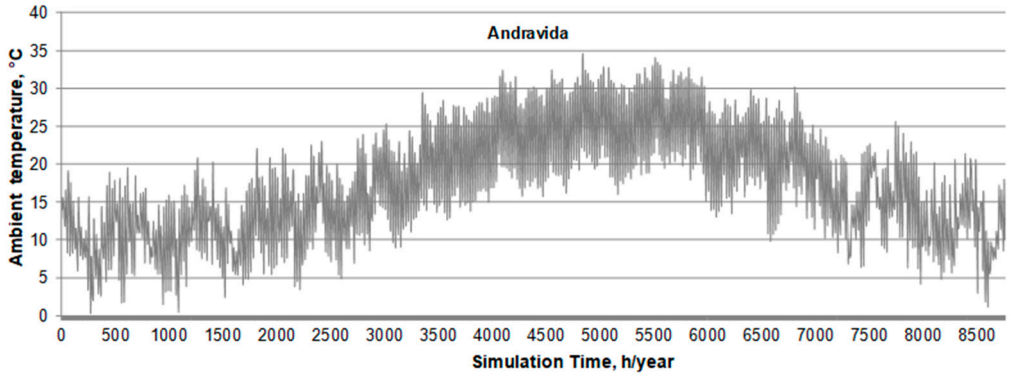


Figure 4. Variability of the ambient temperature for Andravida.

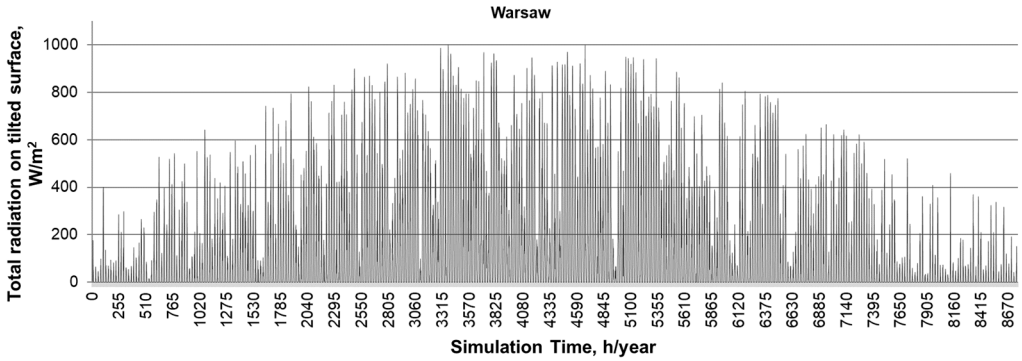


Figure 5. Solar radiation variability for Warsaw.

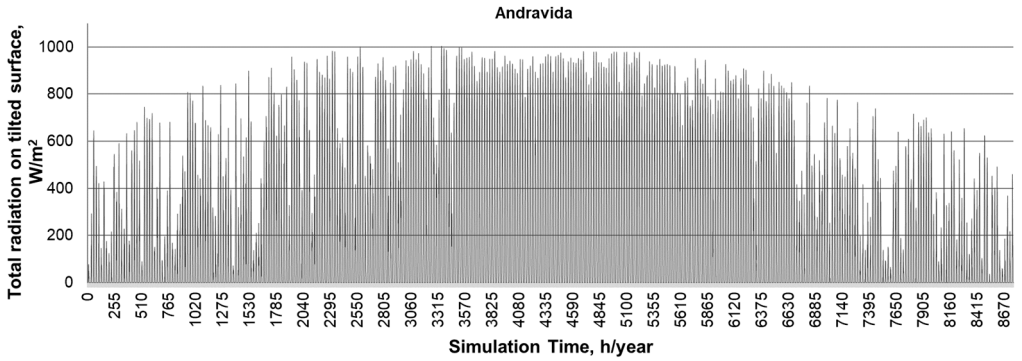


Figure 6. Solar radiation variability for Andravida.

2.4. Energy Demand for the Building

On the basis of the electricity consumption balance in the building, including all electrical devices, lighting, and power tools, the annual electricity demand in the building was set at 3727.43 kWh/year. The values of the electricity demand for individual months are shown in Section 3. The annual energy requirement for domestic hot water heating for five persons (35 dm^3/(d·per)) was determined at the level of 3011 kWh/year (10.84 GJ/year). The model assumes a domestic hot water temperature of 55 °C and a cold water temperature of 10 °C, which is consistent with standard engineering design practice and the requirements of Polish legislation [45].

2.5. Model Calibration

In order to confirm the correctness of the PV/T model, the values of the thermal power of the hybrid collector, obtained on the basis of the simulation in TRNSYS software, were compared with the data provided by the manufacturer [43]. The manufacturer presents a graph of the dependence of the collector thermal power as a function of the

difference between the average temperature of the fluid in the solar circuit and the ambient temperature, taking into account the degree of cloudiness. For a cloudless sky (blue sky), this relationship can be expressed by the Formula (1):

$$Q_{thcol} = -30 \cdot \left(\overline{T}_{fluid} - T_a \right) + 1100 \text{ W} \quad (1)$$

where

- Q_{thcol}—collector thermal power, W;
- $\overline{T}_{fluid}$—average temperature of the fluid, °C;
- T_a—ambient temperature, °C.

The peak thermal power of this collector was determined at 1100 W with the incident solar radiation equal to 1000 W/m^2. The calibration process was carried out for one PV/T collector with a gross area of 2 m^2. The PV/T model was well-calibrated with this parameter (Figure 7). The relative error of the simulated thermal power of the collector ranges from 2.3% to 5.2%.

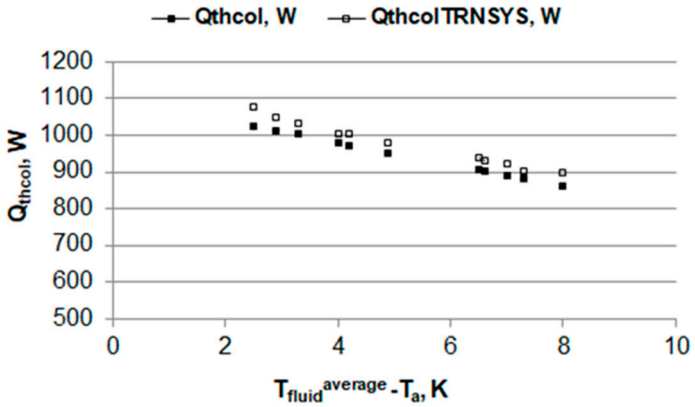


Figure 7. Comparison of simulation results and manufacturer's data for model calibration.

Hourly electrical efficiencies were also used to calibrate the model. The conducted electrical power output simulations enabled the determination of electrical efficiency based on the Formula (2):

$$\eta_{el} = \frac{Q_{el}}{A \cdot G} \quad (2)$$

where:

- η_{el}—electrical efficiency;
- Q_{el}—electrical output, W;
- A—collector surface area, m^2;
- G—global irradiance, W/m^2.

The electric power of the tested PV/T module with a gross area of 2 m^2 was estimated by the manufacturer at 320 W$_p$ with a solar radiation intensity of 1000 W/m^2, which gives an electrical efficiency of 15.5%. Figures 8 and 9 show the impact of weather conditions on the instantaneous electrical efficiency of the hybrid solar collector on the example of two days in July.

When analyzing the simulation results for the summer months, it was determined that the average electrical efficiency of the PV/T system was 12.2%. For example, on 1 July at noon (τ = 4356 h/year), the electric power of the PV/T collector was 210 W$_p$ with a solar radiation intensity of 911 W/m^2 and an ambient temperature of 20 °C, which corresponds to its electrical efficiency of 11.5%.

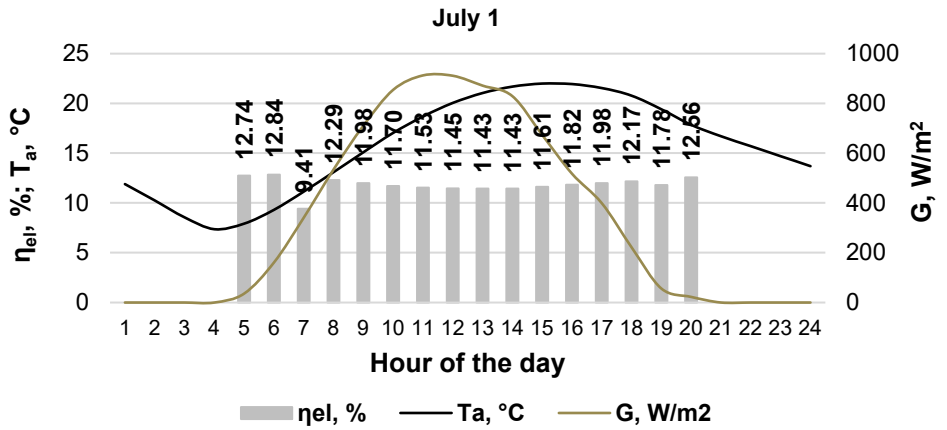


Figure 8. Hourly electrical efficiency of the hybrid solar collector on 1 July.

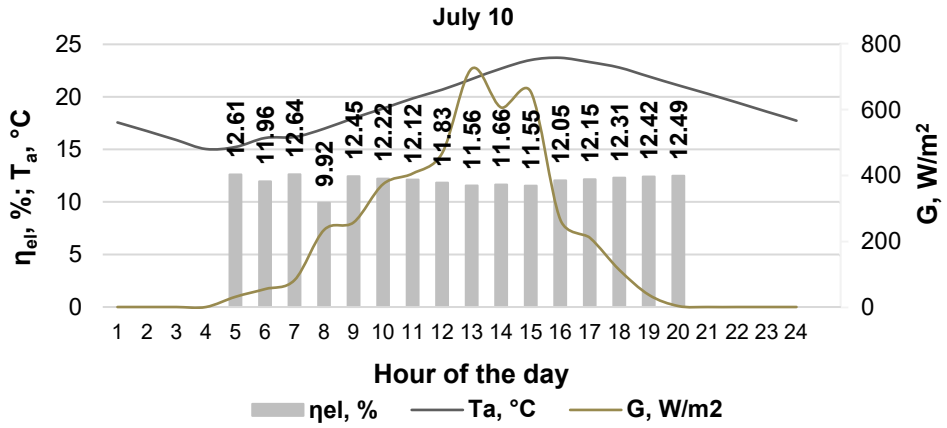


Figure 9. Hourly electrical efficiency of the hybrid solar collector on 10 July.

The calculated PV/T module efficiency is in good agreement with the values reported in the literature, which typically range between 9% and 14.5% [12,22,27]. At the same time, the obtained electrical efficiencies are approximately 2.5 to 3 times greater than the values reported in [28], which do not exceed 5% for Bangkok weather conditions.

2.6. Ecological Analysis—Reduction in Annual Air Pollutant Emissions

To assess the ecological effect of the PV/T system operation, simulation results related to the annual electricity production and annual energy production for hot water preparation were used. A solar installation with PV/T collectors allows for a reduction in the consumption of electricity generated in a conventional power plant as a result of the combustion of fossil fuels and supplied from the power grid to the building, as well as for saving energy consumption that would be obtained from conventional heat sources. Photovoltaic conversion combined with heat recovery enables a reduction in fossil fuel consumption. Therefore, ecological analysis comes down to determining the amount of pollutant emissions avoided as a result of using a PV/T installation.

To determine the amount of fuel saved in the power plant, the reduction in primary energy required for electricity generation and supply was determined on the basis of Equation (3).

$$\Delta Q_P{}^{El} = w \cdot \Delta Q_F{}^{El} \text{ kWh/year} \quad (3)$$

where:

- w—coefficient of a consumption of non-renewable primary energy for the generation and delivery of electricity; for electricity from the power grid w = 2.5 [46];
- $\Delta Q_F{}^{El}$—final energy saved for the electricity generation, kWh per year.

The most common heating devices for heating hot water in single-family homes are boilers burning natural gas, fuel oil, or solid fuel. Therefore, three heat source options were considered in the subsequent analysis. In Variant No. 1, a bi-function condensing gas boiler was adopted, burning high-methane natural gas. Variant No. 2 includes a bi-function oil boiler, and Variant No. 3 includes a modern coal boiler burning eco-pea coal, with automatic fuel feeding, cooperating with a hot water tank. In all options, the DHW system is centralized, with a circulating circuit. The circulating pump is controlled by thermostatic systems.

The reduction in annual consumption of the fuel combusted in the boiler can be calculated by Equation (4):

$$\Delta B_a = \frac{\Delta Q_a \cdot 3600}{Q_{CV} \cdot \eta_{tot}} \text{ kg/year, m}^3\text{/year} \quad (4)$$

where

- ΔQ_a—a reduction in the energy demand, kWh/year;
- Q_{CV}—a calorific value of a fuel, kJ/kg, kJ/m^3;
- η_{tot}—an average total efficiency of a system.

The total efficiency of the DHW system is the product of the efficiency of heating medium production, efficiency of hot water distribution within the building, efficiency of heat accumulation in the system, and efficiency of heat use. The efficiency of coal-fired power plants for electricity generation is approximately 30–40%. The devices reducing the emission of a given pollutant are not included. The avoidance in emissions of a given pollutant was calculated from Equation (5):

$$\Delta E_{pol} = \Delta B_a \cdot u_{pol} \cdot Q_{CV} \cdot 10^{-9} \text{ kg/year} \quad (5)$$

where u_{pol} is a unit index of pollution emission, g/GJ.

The unit indices of release of the pollutants, taking into account the fuel type and boiler power, are presented in Table 3. These indices were adopted on the basis of the data of the National Center for Emissions Management operative in Poland [47].

Table 3. Emission factors for a given pollutant [47].

Variant Number/Type of Fuel	u_{SO2} (g/GJ)	u_{NOX} (g/GJ)	u_{CO} (g/GJ)	u_{CO2} (g/GJ)	u_{PM} (g/GJ)
1/natural gas	0.4	40	30	57,650	0.5
2/fuel oil	80	70	30	72,480	2
3/eco-pea coal	457	185	515	104,526	29
PP/fine coal	1029	200	400	97,800	80

3. Results and Discussion

3.1. Analysis of the Electrical Yield of the Investigated PV/T System

On the basis of simulation studies, it was noticed that the PV/T system situated in Warsaw supplies 1512 kWh of electricity annually (108 kWh/year and per 1 m^2 of the PV/T collector area), and in Andravida—2064 kWh/year (147 kWh/year and per 1 m^2). Figure 10 shows the monthly electricity yields of this system for both locations compared to the monthly electricity demand for the building. Monthly electricity yields, i.e., above 190 kWh/month, occur in the summer months as follows: from May to August in Warsaw, and from April to September in Andravida. The average monthly electricity yield in PV/T solar collectors (only for the months from May to August) was 206 kWh (Warsaw) and 248 kWh (Andravida). The average annual generation-to-demand ratio was 41% for

Warsaw and 55% for Andravida. For the installation located in Greece, the maximum value of the monthly generation-to-consumption ratio was reached in July. In Warsaw, the highest monthly generation-to-consumption ratio of the PV/T system also occurred in July, equal to 82%. It should be noted that these positive results refer only to monthly values. In daily and hourly settlements, due to the lack of an energy storage system, the building will still draw electricity from the grid despite the high electricity generation from the PV/T system. This is caused by the time mismatch between electricity production and consumption (e.g., electricity is generated during the day, while a significant portion of consumption occurs at night).

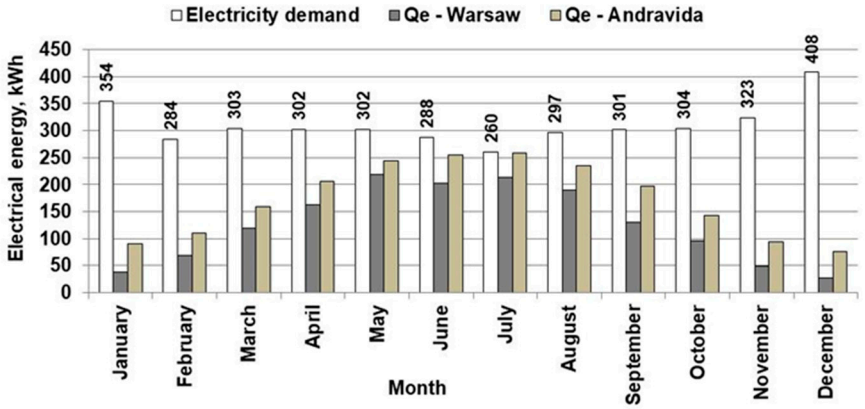


Figure 10. Monthly electricity yields of the PV/T system located in Warsaw and in Andravida.

The obtained results for the annual generation-to-demand ratio in terms of electricity partially agree with those reported in the literature, which range from 25% to 51%, depending on the installation location and system size [18,29]. However, a direct comparison is difficult due to differences in the scale of the systems analyzed in previous studies. Since the present study investigates PV/T installations of identical size, it is possible to clearly assess the impact of building location on the annual electricity generation of the PV/T system. The results indicate that the annual electricity production in Warsaw is 36.5% lower than that achieved in Andravida.

Figure 11 presents the monthly generation-to-consumption ratio of the PV/T installation in individual months for both locations.

Climatic conditions have a significant impact on the electricity production efficiency of the PV/T system. In Andravida, solar radiation intensity in the June–August period remains between 800 and 1000 W/m^2. In Warsaw, the variability of instantaneous total solar radiation during this period is much greater, ranging from 50 to 987 W/m^2. When designing solar energy devices and assessing the expected energy effects, knowledge of total irradiance is essential. The average total irradiance throughout the year is much higher for Andravida, at 1615 kWh/m^2, while for Warsaw it is only 1074 kWh/m^2. Moreover, the average number of hours with directly visible solar radiation in Greece is 2742 h per year, while in Poland it is 2220 h per year. High solar radiation and sunshine duration in Greece are also associated with high outdoor temperatures, which translates into higher electricity yields compared to Polish weather conditions. However, favorable solar radiation conditions can lead to overheating of PV cells and a decrease in the electrical efficiency of hybrid solar collectors. The ambient temperature is also a significant parameter influencing the operation of these types of devices. In Andravida, the outdoor air temperature was always above 0 °C. The annual temperature amplitude for this location was 34.1 K, while for Warsaw it was much higher at 46.1 K.

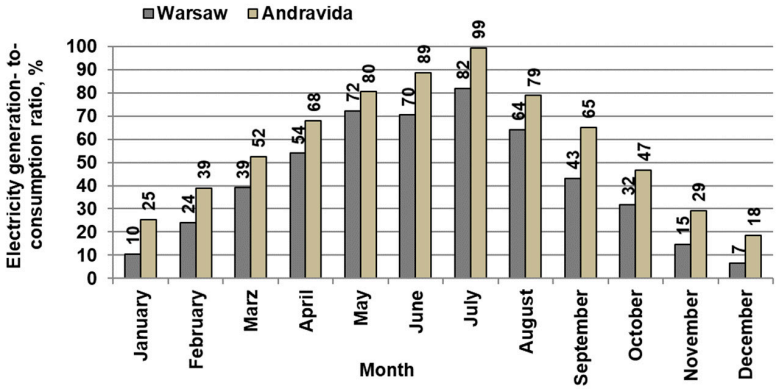


Figure 11. Monthly generation-to-consumption ratio of the PV/T system located in Warsaw and in Andravida.

The electric power of the solar installation reached the highest values in the range from 0.86 kW to 1.138 kW in the period from April to September for Warsaw, and for Andravida—from March to October, in the range from 1.05 kW to 1.123 kW. The average annual value of the electrical power of the solar system operated in Warsaw was 0.355 kW, and in Andravida—0.447 kW. The average annual electric power was determined for the hours in which the installation generates electricity: for Warsaw, it was 4345 h per year, and for Andravida—4358 h. The variations in the electric power of PV/T installation are introduced in Figures 12 and 13.

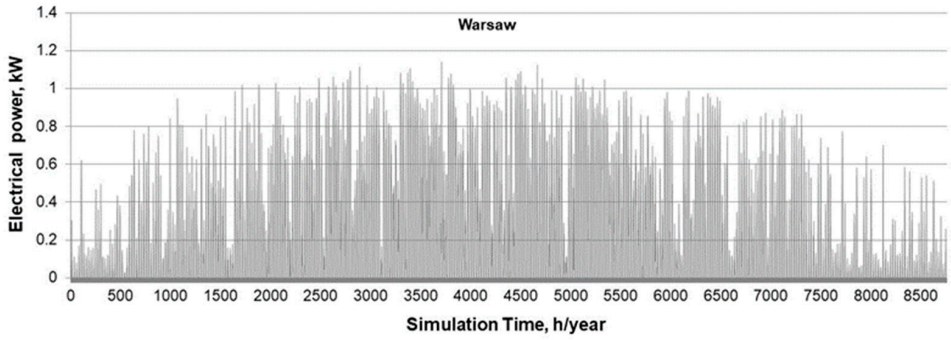


Figure 12. Dynamics of changes in the electrical output power of the PV/T system located in Warsaw.

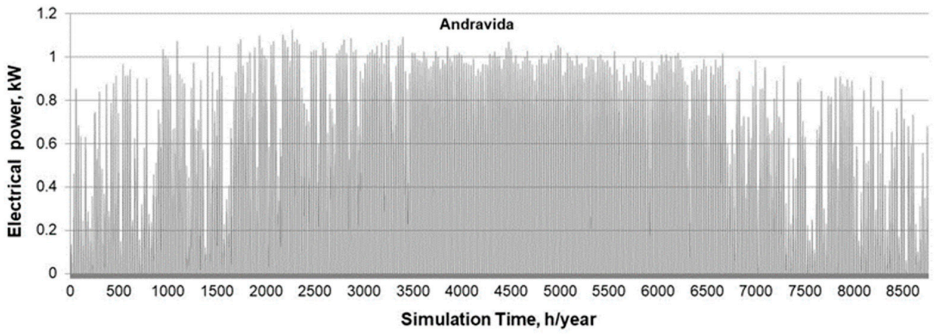


Figure 13. Dynamics of changes in the electrical output power of the PV/T system located in Andravida.

3.2. Analysis of the Thermal Yield of the Investigated PV/T System

The extraction of heat from PV/T collectors is done by circulating a mixture of water and propylene glycol forced by a pump. The external heat exchanger used in the system heats the water directed to the hot water storage tank. The carried-out simulations showed that the PV/T system working in Warsaw reduces annual energy demand for DHW

preparation by 3297 MJ, and the system located in Andravida by 6083.3 MJ. Figure 14 presents the monthly thermal energy yields for both locations in comparison with the monthly energy demand for hot water heating. The average monthly thermal energy yield for the four months from May to August was 169 kWh/month (608 MJ/month) in Warsaw and 243 kWh/month (876 MJ/month) in Andravida. The unit energy yield per 1 m^2 of the PV/T collector area was obtained at the level of 43.4 MJ/(m^2·month) and 62.6 MJ/(m^2·month), respectively. Heat recovery from PV/T solar collectors in July in the climate of Greece was estimated at 264 kWh (951 MJ) and is 29% higher compared to heat recovery in a hybrid solar installation located in Poland.

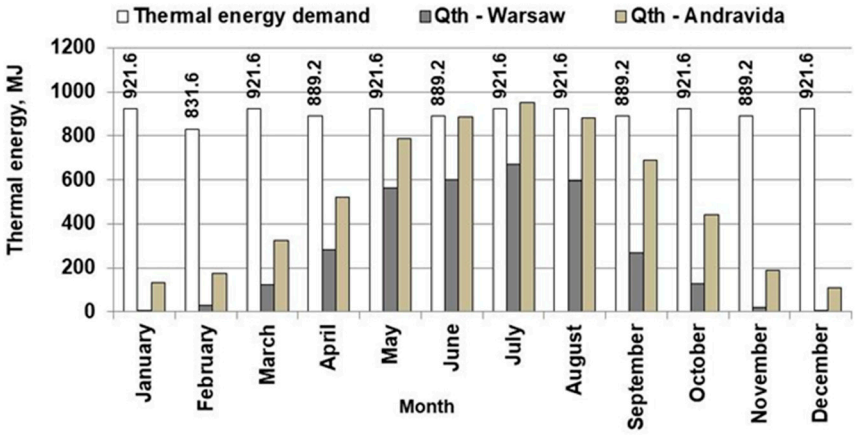


Figure 14. Monthly thermal energy yields of the PV/T system located in Warsaw and in Andravida.

The average annual coverage ratio of thermal needs for this purpose was set at 30% for Warsaw and 56% for Andravida. The installation located in Greece is characterized by the very high thermal demand coverage ratio for three summer months, that is from June to August. In Warsaw, the highest coverage ratio of thermal needs by the PV/T system of 73% was obtained for July. This means a deficit of thermal energy produced by the PV/T system is in relation to heat demand for DHW preparation of 27–99% on a monthly basis. In Andravida, the possible surplus heat generated in July may cover heat losses in the storage system or be stored in the hot water tank. In other months, the thermal demand coverage ratio of the PV/T system is between 5% and 88%. Figure 15 shows the monthly solar contribution with respect to hot water production for both locations.

These results, similarly to those obtained for electricity generation, are only partially consistent with those reported in the literature, which indicates that PV/T systems can cover between 36% and 83% of the thermal energy demand for DHW preparation [18,29]. In this case, the coverage ratio also depends on the system size and installation location. Moreover, an additional factor, namely the number of occupants, has a substantial influence on DHW consumption and consequently on the system's thermal demand coverage ratio.

At the same time, it can be observed that for the Warsaw location, the average annual coverage ratio of thermal energy demand is lower than that of electricity demand (30% vs. 42.7%). In contrast, under the warmer climatic conditions of Andravida, the difference between thermal and electrical coverage is much less pronounced (55.9% vs. 57.5%). This finding contrasts with previously published studies, which typically report more pronounced differences between the coverage ratios of electrical and thermal energy demand achieved by PV/T systems [12,18,29].

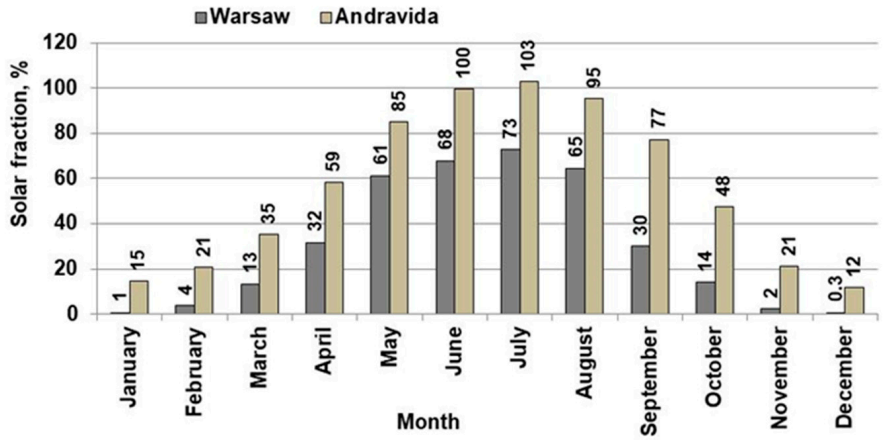


Figure 15. Monthly solar thermal contribution of the PV/T system located in Warsaw and in Andravida.

On the basis of the simulations, the average annual working medium temperature at the outlet from the PV/T panels was determined to be 24.4 °C (the system in Warsaw) and 40.8 °C (the system in Andravida). The average annual temperature of water stored in the tank (Warsaw) reached 23.8 °C and 32.3 °C (Andravida). Figures 16 and 17 show the changes in average monthly working medium temperature and water temperature in the tank for both considered locations. The highest average monthly working medium temperature in the solar hybrid collector circuit for Warsaw was 45.7 °C, and the highest water temperature in the 0.5 m^3 tank was 35.2 °C, and for the solar installation located in Andravida, these temperatures were 60.2 °C, and 45.2 °C, respectively. The obtained average monthly working medium temperature values, ranging from 22 °C to 60.2 °C for Andravida and from 1.7 °C to 45.7 °C for Warsaw, indicate good heat collection conditions from the PV/T panels. No overheating of the working medium was observed. There is a clear positive linear correlation between the average monthly water temperature in the storage tank and the average temperature of the water–glycol mixture, described by an average coefficient of determination R^2 of 0.99.

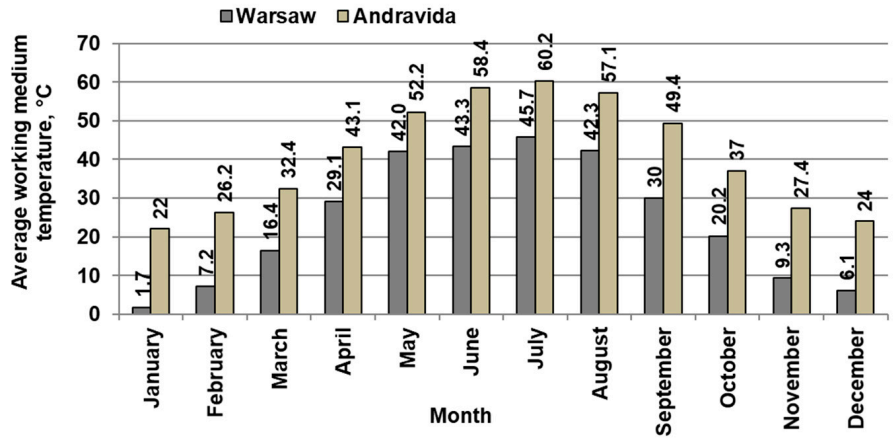


Figure 16. Changes in the average monthly working medium temperature in the solar hybrid collector circuit.

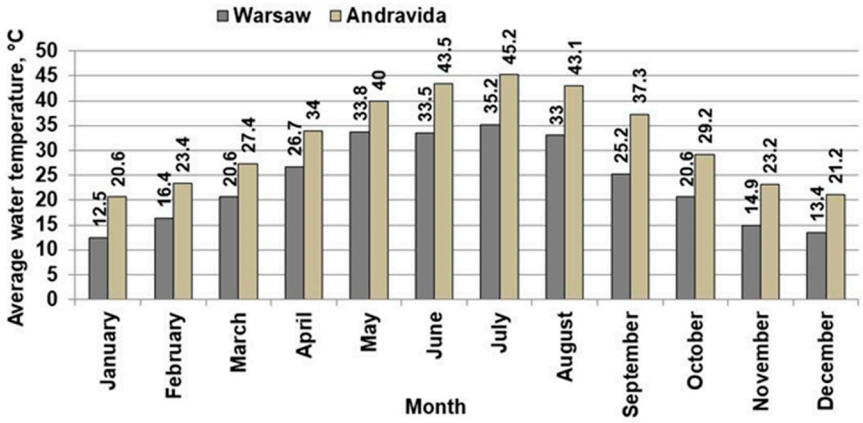


Figure 17. Changes in the average monthly water temperature in the storage tank.

3.3. Analysis of the Impact of the Tested PV/T System on the Improvement of Air Quality

The use of the PV/T system in a single-family house allows for partial coverage of the annual heat demand for the preparation of DHW and the electricity demand. It is possible to reduce the consumption of fossil fuels burned for energy and to avoid the emission of pollutants introduced into the atmosphere.

The calculated reductions in annual consumption of the fuel are summarized in Tables 4 and 5.

Table 4. Reducing the annual consumption of the fuel for electricity generated.

Variant Number	Fuel	Energy Efficiency	Calorific Value	$\Delta B_a{}^{El}$ Warsaw	$\Delta B_a{}^{El}$ Andravida
Power plant (PP)	Fine coal	36.0%	21.00 MJ/kg	648.0 kg/year	884.6 kg/year

Table 5. Reducing the annual consumption of the fuel for heat generated.

Variant Number	Boiler Efficiency	Average Total Efficiency	Calorific Value	$\Delta B_a{}^{DHW}$ Warsaw	$\Delta B_a{}^{DHW}$ Andravida
1	90%	72.0%	36.54 MJ/m^3	125.3 m^3/year	231.2 m^3/year
2	90%	72.0%	43.00 MJ/kg	106.5 kg/year	196.5 kg/year
3	85%	58.5%	25.80 MJ/kg	218.5 kg/year	403.1 kg/year

Tables 6 and 7 present the values of the avoided emissions of individual air pollutants depending on the type of fuel burned and thus the energy source for the locations considered. These values refer to one household (single-family building).

Table 6. Values of the avoided annual air pollutions emissions for Warsaw.

Variant Number	ΔE_{SO2}, kg/Year	ΔE_{NOX}, kg/Year	ΔE_{CO}, kg/Year	ΔE_{CO2}, kg/Year	ΔE_{PM}, kg/Year
1	1.83×10^{-3}	0.18	0.14	263.95	2.29×10^{-3}
2	0.37	0.32	0.14	331.92	9.16×10^{-3}
3	2.58	1.04	2.90	589.24	0.16
PP	14.00	2.72	5.44	1330.86	1.09

Table 7. Values of the avoided annual air pollutions emissions for Andravida.

Variant Number	ΔE_{SO2}, kg/Year	ΔE_{NOX}, kg/Year	ΔE_{CO}, kg/Year	ΔE_{CO2}, kg/Year	ΔE_{PM}, kg/Year
1	3.38×10^{-3}	0.34	0.25	487	4.22×10^{-3}
2	0.67	0.59	0.25	612.42	16.90×10^{-3}
3	4.75	1.92	5.35	1087	0.30
PP	19.11	3.72	7.43	1816.79	1.49

The environmental effect would be even more pronounced if it were considered not just one household, but, for example, 100,000 single-family residential buildings located in Warsaw. Assuming coal-fired energy sources and a balance of main air pollutants emissions in 2023 [4], the percentage of avoided pollutant emissions per year would be as follows: for SO_2, 1.57%, NO_X—0.70%, CO—0.06%, CO_2—0.05%, and particulates—0.06%.

Photovoltaic-thermal hybrid collectors allow efficient use of solar energy. It has been shown that water-cooled PV/T systems partially meet the energy demand, contributing to the avoidance of CO_2 emissions in buildings [48,49]. The benefits of their use, taking into account both energy and ecological considerations, have been demonstrated by researchers. On the basis of the results of simulation studies using the TRNSYS program carried out by Dupeyrat et al. [33] for three locations in France, it can be concluded that PV/T panels provide higher primary energy savings, and thus a greater reduction in pollutant emissions, than installations with separate solar thermal collectors and conventional photovoltaic panels. Herrando et al. [18] compared the CO_2 emissions from a PV/T system in a typical house in London, UK, with pollutant emissions from conventional energy installations. They also showed that a hybrid installation with PV/T solar collectors saves up to 16.0 tons of CO_2 over a 20-year lifetime, 36% more compared to a PV-only system, which achieved savings of 11.8 tons of CO_2.

4. Conclusions

One of the technical solutions enabling the use of solar energy are the installations with hybrid solar collectors, which create the optimal working conditions for solar cell batteries and allow the recovery of waste energy in the form of heat. They are also an example of a conscious and responsible approach to environmental issues.

The results of the conducted research demonstrate a strong dependence of the energy yields of hybrid solar collectors on the climatic conditions of a given location. Considering the year-round operation of a PV/T system, it was found that, regardless of geographical location, it can function as a support system for both electricity generation and domestic hot water preparation. When designing such a solar energy system, it is necessary to equip the water storage tank with an additional heating element or use a second heat source in the DHW installation. Simulation studies of the hybrid solar collector system demonstrate its feasibility even in a warm, humid continental climate. On the basis of these studies, the operating parameters of the PV/T system were determined.

The results of simulation studies performed in the TRNSYS 16 environment show that the effective operation of the PV/T system occurs in the summer months for both locations. In May, June, July, and August, the monthly generation-to-consumption ratio of the PV/T system was between 64% and 82% by the building in Warsaw and from 79% to 99% in the case of the building in Andravida. The solar fraction was determined to be between 61% and 73% (Warsaw) and from 85% to 100% (Andravida) of the thermal demand for DHW production.

The tested PV/T installation located in Andravida is able to generate 36.5% more electricity and obtain 84.5% more useful thermal energy compared to the same PV/T installation but operating in Warsaw.

In winter (January, February, November, and December), the monthly generation-to-consumption ratio of the PV/T system is only 6.6% to 24% in Warsaw, and the thermal demand coverage ratio is from 0.3% to 3.7%, whereas in Andravida the values range from 18.4% to 38.9% and from 11.8% to 21.3%, respectively. In these months, the water in the storage tank does not exceed 30 °C and requires heating by an auxiliary heater.

It was established that as a result of using the solar PV/T system to generate both heat and electricity, instead of using a coal-fired energy source, annual pollutants emissions of 16.58–23.86 kg of SO_2, 3.76–5.64 kg of NO_X, 8.34–12.78 kg of CO, 1920.1–2903.8 kg of CO_2, and 1.25–1.79 kg of particulate matter can avoided, depending on the location. Reducing pollutant emissions also has a beneficial effect on human health and well-being.

Limitations and Future Research

However, further research is needed. Full validation of the PV/T system model on the basis of operational testing is necessary. The obtained annual simulation results, assuming a simulation time step of 60 min, should be compared using a shorter time step, for example, 15 min. The study considered only one heat source, i.e., waste heat generated during PV/T panels cooling, and did not consider the operation of an auxiliary heater (a secondary heat source) in the domestic hot water system. Simulation studies of an extended model of a PV/T system with an electrical energy storage system used in commercial buildings are another challenge.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating Current
ANN	Artificial Neural Network
BIPV/T	Building Integrated Photovoltaic-Thermal
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CIS	Copper Indium Selenide
DC	Direct Current
DHW	Domestic Hot Water
EU	European Union
GA	Genetic Algorithms
GHG	Greenhouse Gas
LCPV/T	Low-Concentration Photovoltaic-Thermal

MPC	Model Predictive Control
PCMs	Phase Change Materials
PP	Power Plant
PV	Photovoltaic
PV/T	Photovoltaic-Thermal
RESs	Renewable Energy Sources
SDG	Sustainable Development Goal
TRNSYS	TRaNsient System Simulation
UK	United Kingdom
ZEB	Zero Energy Building

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