THE PERFORMANCE OF A HEAT PIPE BASED SOLAR PV/T ROOF COLLECTOR AND ITS POTENTIAL CONTRIBUTION IN DISTRICT HEATING APPLICATIONS

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ABSTRACT

Photovoltaic–thermal water collectors have the ability to convert solar energy into electricity and heat, simultaneously. Furthermore, the combination of photovoltaic–thermal solar collectors with a water cooling system can increase significantly the electrical and thermal efficiencies of the system, which can improve the total thermal efficiency of buildings. In this paper, the findings of six experimental configurations of solar-thermal collectors are presented and analysed. Five of the solar-thermal panel configurations were implemented with a cooling cycle. Two of the solar-thermal panels were equipped with monocrystalline silicon modules, the other two collectors were equipped with polycrystalline silicone modules, one of the collectors was based on heat pipe technology and was equipped with a cooling system, while the last collector did not include any cooling cycle. The duration of the experiments was four days during the September of 2014 and they were conducted under different solar radiation conditions. The second part of the paper presents the simulation results for five of the solar-thermal panels connected with a cooling water tank (volume of 500 litre), a domestic hot water tank (volume 350 litre) and a water-water heat pump, in terms of covering the hot water demands of a single family dwelling. The results showed that the hybrid solar collectors would be able to cover approximately 60% of the dwelling's hot water needs for days with low levels of solar radiation, while for days with high solar radiation they could cover the hot water requirements of the family by 100%.

Keywords: photovoltaic–thermal water collector (PV/T); heat pipe; heat pump (HP); domestic hot water (DHW); solar hybrid collector HP-PV/T

1 INTRODUCTION

The combination of photovoltaic/solar and thermal energy systems into one integrated system is known as a hybrid photovoltaic/thermal (PV/T) solar system. These systems are characterized by two distinguished parts; the photovoltaic technology part, which converts the thermal energy of the solar radiation into electricity, and thermal technology part, which facilitates the energy conversion from solar radiation to thermal storage [1,2]. Thus, the PV/T solar systems can produce simultaneously electricity and heat. The conventional configurations of photovoltaic and solar-thermal systems have both advantages and disadvantages, but once combined together as PV/T panels they offer an alternative and very promising system for low-energy consuming residential applications [3–5].

PV/T collectors vary in designs and technical aspects according to the resigned application [6,7]; however, all of them shall follow the requirements of architectural integration, as they are set by the International Energy Agency, which states that integrated solar thermal collectors can be installed either on the buildings' front face or on their rooftops [8,9].

Flat plate PV/T collectors can be classified into the following categories, depending on the type of working fluid used: water PV/T collectors, combined water/air PV/T collectors and air PV/T collectors. Another categorization of PV/T collectors can be done based on whether or not an absorber collector underneath the flat plate is present. In any case though the basic parts of every flat plate PV/T collector are a glass cover (glazed or unglazed), solar cells, encapsulated materials and the absorber collector (optional). The collectors' absorber has a significant function in the PV/T system; it cools down the PV cell and uses the waste thermal energy to produce hot water or hot air. In this way the efficiency of the PV module increases significantly [4,10].

The hybrid PV/T systems can address issues like the low efficiency rates of PV collectors [11], their high cost, the architectural uniformity of buildings and the limited space on rooftops, which until today consist the reasons that hold back the wider implementation of solar panels in buildings. The hybrid PV/T collectors offer higher electrical efficiency due to their cooling system, they provide architectural uniformity by aesthetical designs, they minimize the required space on rooftops and they are characterized by a reduced payback period [12,13]. Combination of water and/or air type collectors can be categorized according to the flow pattern of the water or air. In water type PV/T collectors, the parameters under consideration are the shape of the collector, the channel size and the type of the working medium, the flow pattern of the medium and the absorber technology.

Temperature is another important factor influencing the performance of PV collectors. An increase in the temperature of the PV panel causes the decrease of the collector's efficiency and its exposure to high thermal stresses. The increase of the PV panel's temperature by 10^{o}C can lead to a decrease of its electrical efficiency by 2 to 5%. For example the typical electrical efficiency of PV panels under nominal operating temperature of 25^{o}C is 15%. When the PV temperature increases to 45^{o}C, the electrical efficiency of the panel is in the range of 13.5 to 14.4 %, depending on the type of PV panels. [14,15]. The integration of PV panels, with thermal collectors as hybrid photovoltaic thermal PV/T panels enables more efficient cooling of the panel and the simultaneous production of thermal and electrical energies. Some of the most widespread PV/T collector technologies or heat exchangers are based on water cooling or air cooling systems [14–17]. According to the literature the use of active cooling techniques is able to decrease the operating temperatures of the PV panels by 20%, while to increase their electrical efficiency by 9% [18,19]. A popular cooling system with great application potentials is the integration of PV panels with heat pipes [20,21].

The heat pipe is a structure with very high thermal conduction that enables the transportation of heat, while maintain almost constant temperature. Heat pipes are considered to be thermal super conductors due to the high heat rates they transfer across small temperature gradients. On their simplest form heat pipes are called thermosyphons and their operation relies on gravity, whereas the heat is transferred only from the lower to the upper end of the pipe. The heat pipe which allows the bi-directional transfer of heat is called wickless. The main structure of heat pipes is an evacuated tube partially filled with a working fluid that exists in both liquid and vapor phase. The Figure 1 represents the basic steps of operation of heat pipes. The bottom part of the heat pipe is the evaporator and the top part is the condenser. When a high temperature is applied at the evaporator section of the heat pipe, the working fluid existing in the liquid phase evaporates and flows with high velocity towards the cooler end of the pipe – the condenser. As soon as the vapor reaches the condenser section, condenses and gives up its heat. Then the liquid working fluid returns to the evaporator part of the pipe, by the influence of gravity [22]. A series of straight heat pipes joined in one structure can be considered as a heat recovery device. Its advantages are high thermal conductivity, passive and reliable operation, uniform temperature distribution, affordable cost and no need for external pumping system as in the conventional exchangers.

Heat pipe based heat exchangers find application in many industries as heat recovery and energy savings systems, while their operation has been investigated by several researchers. In his paper Jouhara examines the potentials of energy and cost savings in conventional means of dehumidification, by the incorporation of a wraparound heat pipe heat exchanger [24]. A year later Jouhara and Meskimmon examined the energy savings possibilities in air handling units, by implementing a wraparound loop heat pipe heat exchanger in the unit [25]. Another experimental investigation of Jouhara et al regarding a heat exchanger of finned water-charged wickless heat pipes in a modified inline configuration was carried out [26]. Finally, in another paper Jouhara proved that the combination of heat pipe based heat exchangers in air conditioning systems can cool and dehumidification the outside air prior being direct supplied to the system for ventilation [27].

Freezing and corrosion of the heat pipes can be eliminated by carefully selecting the proper working fluid. Hence, heat pipes and solar collectors can be incorporated into a compact design of PV/T collectors. Performances of PV/T systems with different water loads per unit collecting area were also studied [28].

The reuse of the waste thermal energy produced during the cooling process of the solar PV panels remains a challenging aspect of hybrid collectors. To ensure high cooling efficiency the cooling temperature of the collector should be around 25°C; the integration of a heat pump in the PV/T system can facilitate the above [29].

2 THE EXPERIMENTAL SYSTEM

2.1 TEST BENCH

The experimental apparatus was sited in Cardiff, UK, where an innovative design of flat heat pipe solar hybrid (PV/T) collector mat with unique internal finning pattern was tested. The flat heat pipes were made from aluminium as the shell material and ammonia as the working fluid. The tests were carried out for four days during the September of 2014 for different weather conditions. The solar panels were placed on a specially constructed apparatus which simulated a full-scale rooftop, facing South with an inclination of 51 degrees. The experiments were carried out for six flat heat pipe solar panels, sprayed with high emissivity paint to operate as thermal solar absorbers. Four of the panels worked as PV/T systems with a PV surface layer, of which two PV/T collectors were equipped with monocrystalline silicon modules and the other two with polycrystalline silicone modules. One of PV/T collectors equipped with the monocrystalline silicon modules and one of PV/T collectors equipped with the polycrystalline silicone modules were cooled by attached manifold on the heat pipe condenser side. To reduce the interface resistance, thermal interface material was placed between the manifold and the heat pipe collector. The construction of the panel and its cross section are shown in Fig 2 and Fig 3. Each panel had a length of 4m and 0.4m in width.

The working fluid flow rate was constant through each of the cooling manifolds and equal to 1l/min. To monitor the thermal behavior of the systems the test bench was equipped with 25 Teflon insulated K-type (NiCr/NiAl) thermocouples. Six thermocouples were used to record the working fluid's temperature at the inlet and outlet of each of the cooling manifolds, one thermocouple for recording the ambient air temperature, and several other thermocouples placed on the surface of the solar collectors. The points where the temperatures were recorded can be seen in the schematic of Fig 4. The temperature data were recorded by a data logger with computer interface. The levels of solar radiation were measured by a pyranometer (Kipp & Zonen CM11), with the same inclination rate with the solar panels. The temperature and solar radiation measurements were recorded in 1sec intervals. The voltage and the current were measured, as well. Figure 5 shows the experimental apparatus of the hybrid solar installation.

The experiments run for four days in the September of 2014, between 9:00 to 16:00. The experiments were carried out for six flat heat pipe solar panels, sprayed with high emissivity paint (T-paint). Only two of the panels were sprayed with T-paint, while the others had additional Photovoltaic modules. Two PV/T panels were equipped with monocrystalline silicon modules (PV_m, PV_m/T), other two PV/T panels were equipped with polycrystalline silicone modules (PV_p, PV_p/T); one panel was cooled on the condenser side of the heat pipes, while the rest of the panels were uncooled. The PV panels had a surface of A_{PV}=0.89 m^2, while the heat pipe collectors had a surface area of A_{th}=1.36 m^2. The water flow rate was constant for each cooled panel. Every panel was equipped with insulated thermocouples; two thermocouples in the uncooled panels, four thermocouples in the cooled panels, two thermocouples on their panel surfaces, two thermocouples on the manifold surfaces and two thermocouples on the inlet and outlet of the heat exchanger.

The study was carried out for the following systems:

T – thermal solar collector based on heat pipes

PV_m – monocrystalline (PV) panel

PV_p – polycrystalline (PV) panel

PV_m/T – monocrystalline (PV) panel with cooling system based on heat pipes

PV_p/T – polycrystalline (PV) panel with cooling system based on heat pipes

2.2 DATA ANALYSIS

The parameters under investigation during the experiments were the cooling flow rate, the temperatures of the inlet and the outlet of the PV panel, the PV and PV/T panels' temperatures, the levels of solar radiation and the ambient air temperatures.

The thermal energy produced by the PV panel is given by the following formula:

$$Q_{Th} = m \cdot cp \cdot (t_{out} - t_{in}) \quad (1)$$

The thermal efficiency of the heat pipes is given by the expression:

$$\eta_{Th} = \frac{Q_{Th}}{G \cdot A_{th}} \quad (2)$$

The efficiency of the cooling effect is given as follow:

$$\eta_c = \frac{t_{PV} - t_{PV/T}}{t_{PV}} \quad (3)$$

These tests aimed to demonstrate the impact of the cooling on the energy efficiency of the PV/T collectors. During the tests several series of measurements were carried out. The expected outcomes of the cooling system are the increase of the electrical efficiency of the PV panel and the use of the recovered heat of the system for domestic hot water (DHW) applications. This paper presents the results of four series of experiments, which included constant water flow through the PV panel for cooling purposes. The experimental outcomes are shown in Figures 6, 7, 8 and 9, while the daily recorded data are represented in Table 1.

Day 1 – 4.09.2014

The results of the first day of experiments (04.09.2014) are shown in Table 1 and Figure 6, which illustrates the operation of the systems with and without cooling cycle, with low and frequent changes of the solar radiation (daily average: 2.5kWh/m^2). The temperature of the PV panel was comparatively low, between 27 and 40°C. The second configuration of the PV/T panel with a cooling system was able to maintain slightly lower temperatures, between the range of 23 and 27°C. It is obvious in Figure 6 that when the water flow stopped, between 10:30 am and 11:30 am, the temperature of the PV/T solar collector increased. Moreover, the system equipped with the heat pipes was able to convert up to 40% of the solar energy into thermal energy. However, it was observed that when the water flow was being stopped or interrupted the efficiency of the system was slightly decreasing.

Day 2 – 5.09.2014

The results of the second day of experiments (05.09.2014) are shown in Table 1 and Figure 7, which illustrates the operation of both cooled and uncooled systems, with almost stable of solar radiation profile. During the second day of the experiments the weather was cloudy, with the solar radiation levels reaching up to 2.61kWh/m^2. At the beginning of the experiment the PV temperature was considerably high, between 33 to 52°C. The decrease of the solar radiation caused a drop in the panel's temperature, with the cooling temperature being at 35°C. The PV panel with a cooling system showed temperatures between 25 and 35°C. Finally, the heat pipe solar panel achieved efficiency of approximately 50%.

Day 3 – 8.09.2014

The results of third day of experiments (08.09.2014) are presented in Table 1 and Figure 8, which illustrates the operation of both cooled and uncooled systems with minor changes of the solar radiation. The solar radiation levels that the day were high and reached up to 5.32kWh /m^2. The temperature of the PV panel was significant higher than the rest of the days, between 40 to 56°C, while the PV panel with cooling system maintained a temperature between 28 and 33°C. The system equipped with the heat pipes was able to convert up to 48% of the solar energy into thermal energy.

Day 4 – 9.09.2014

The results of the fourth day of the experiments (09.09.2014) are presented in Table 1 and Figure 9 which illustrates the operation of both cooled and uncooled systems at high and constant intensity of solar radiation. The weather conditions that day were clear and solar radiation of 5.19kWh/m^2. The temperature of the PV panel was in the range of 40 and 60°C, while the PV panel with cooling system showed temperatures between 28 and 33°C. In the absence of solar radiation the initial conditions and the overall temperature profiles of both the uncooled and cooled PV panels were the same. However with the presence of solar radiation, the panel without cooling system showed increased temperatures. In addition, the heat pipe solar collector showed an efficiency of 48% approximately.

The above experimental results allowed the identification of the daily mean efficiencies of the systems, in terms of converting solar energy into thermal energy and the effects of the cooling system in the overall efficiency of the system. The thermal collector without PV panels achieved thermal efficiency of 64%. The thermal collector with PV panels showed a clear reduction of its thermal efficiency, about 10-15%. The temperatures of the cooled PV panels were up to 40% lower compared to the uncooled PV panels, maintaining the panels' temperatures close to 25°C. A summary of the results is given in Table 1.

3. ANALYSIS OF COMBINED HEAT PUMP SOLAR PV/T SYSTEM

3.1 The system concept

The tested PV/T system with heat pipe technology allowed the recovery of the waste heat form the cooling process and the simultaneous production of electricity and heat. One of the conclusions obtained from the experimental results is that in order to maintain a high cooling efficiency of the PV panel the temperature of the coolant in the collector must be low and preferably below of 25°C. However, harnessing the power of such low temperatures has many difficulties. In this paper a combination of PV/T panels with a water/water heat pump is proposed, in order to overcome these problems.

A hybrid system of HP-PV/T shows high electrical efficiency and its waste heat can be easily used for DHW applications. The configuration of this hybrid HP-PV/T system is shown in Fig 10. The waste heat from the HP-PV/T collector is transferred to a storage tank (no1). The average temperature of the tank (no1) is maintained between 15 and 30°C. The stored energy in this tank and the produced power by the PV cells supply with electricity the water/water heat pump, which heats up the water at approximately 50°C, which can be used for DHW applications. The volume of the tanks no1 and no2 were 500 and 350liter, respectively. It was assumed that the coefficient of performance (COP) of the heat pump was equal to 4.1 (for fluid temperatures in tank no1 and no2 equal to 20 and 50°C, respectively).

3.2. Calculation steps

In low energy buildings the demands of DHW is the main consideration. The needs of hot water refer to the consumed value of hot water or the energy needed to heat the water. It is quite commonly for hot water demand calculations to assume that a person per day requires about 50litres of hot water. Thus, a family of four members would have a daily demand of DHW of about 10.5kWh. The assumption of energy demand profile used in DHW analysis is shown in Fig. 11.

The experimental data described in the previous section were used as the input data for the performance analysis of the HP-PV/T system, with regards of covering the DHW demands of a single-family dwelling. The data used were the solar radiation levels (G), the ambient temperature (T_a), the temperature of PV/T panels (t_{pv}) and the thermal energy produced by a single thermal collector (Q_{th}). The assumed energy demand profile of hot water was based on Fig 11, with the DHW output temperature being at 50°C, and the water input temperature at 10°C. The initial boundary conditions for each day were the same and they assumed that the temperature of tanks no1 and no2 were 15 and 50°C, respectively.

The formulas used for the calculation of the PV panel's efficiencies and power output, the heat pump's capacities, the DHW thermal energy, the heat balances, the heat losses and the average temperatures of each tank are shown below.

The PV panel efficiency given by:

$$\eta_{el} = \eta_{ref} \cdot \left[1 - \beta \cdot \left(t_{PV} - t_{ref}\right)\right] \quad (4)$$

t_{PV} – PV panel temperature adopted on the basis of measurements

Power output from PV panel given by:

$$Q_{el} = G \cdot A_{PV} \cdot \eta_{el} \quad (5)$$

Thermal energy from the collector (for A_{th} panels area):

$$Q_{th,A} = A_{th} \cdot Q_{th} \quad (6)$$

thermal energy Q_{th} adopted on the basis of measurements

Heat pump thermal energy $Q_{th,HP}$:

$$Q_{th,HP} = COP \cdot Q_{el} \quad (7)$$

assumed COP is 4,1 for t_{T1}/t_{T2}=20/50 °C

Heat pump cooling power given by:

$$Q_{c,HP} = Q_{th,HP} - Q_{el} \quad (8)$$

DHW thermal energy calculated:

$$Q_{DHW} = m \cdot cp \cdot \left(t_{DHW} - t_w\right) \quad (9)$$

Heat balance for the tank no. 1:

$$Q_{T1} = V_{T1} * \rho * cp * \frac{dt_{T1}}{d\tau} = Q_{th,A} - Q_{th,HP} - Q_{L1} \quad (10)$$

Heat balance for the tank no. 2*:*

$$Q_{T2} = V_{T2} * \rho * cp * \frac{dT_{T2}}{d\tau} = Q_{th,HP} - Q_{DHW} - Q_{L2} \quad (11)$$

The heat loss of the tank no. 1:

$$Q_{L1} = A_{T1} * U_{T1} * \left(t_{T1} - t_i\right) \quad (12)$$

The heat loss of the tank no. 2:

$$Q_{L2} = A_{T2} * U_{T2} * \left(t_{T2} - t_i\right) \quad (13)$$

The average temperature of the tank no. 1:

$$t_{T1}' = t_{T1} + \frac{\Delta\tau}{V_{T1} * \rho * cp} * Q_{T1} \quad (14)$$

The average temperature of the tank no. 2:

$$t_{T2}' = t_{T2} + \frac{\Delta\tau}{V_{T2} * \rho * cp} * Q_{T2} \quad (15)$$

3.3 calculation results

The calculations aim to investigate the capability of the tested hybrid HP-PV/T solar collector system to cover the DHW demands of a single four member family dwelling. In the previous sections of the paper five monocrystalline PV/T_m panels were tested. Their electrical efficiency at the reference temperature (t_{ref} = 25°C) and for solar radiation of 1000W/m^2 will be referred as η_{ref}. For mono-Si PV modules η_{ref} is equal to 0.13 and their temperature coefficient ß is equal to 0.004. The analysis of polycrystalline type of collectors give similar results, with their η_{ref} equal to 0.11. The following graphs show the temperature changes in the tanks no1 and no2, according to the data of Figure 11, and the daily balances of heat and electricity for the proposed system.

Figures 12 and 13 show the estimated results of the temperature changes in the tanks no1 and no2 for the HP-PV_m/T for the data obtained from the four day experiments. The temperature of the tank no1 is the result of the cooling system of the HP-PV/T solar collector. During the days which the solar radiation levels were low or medium (day 1 and 2) the 500liter tank (no1) maintained temperatures between 20 and 25°C. For sunny days (day 3 and 4) the tank temperatures reached up to 40°C. This temperature is considered the maximum temperature at which the cooling of the PV cells will be ensured and sufficient. Reducing the tank volume would result a decrease of PV cells' efficiency and a need to compensate with higher coolant temperatures.

The temperature of hot water in tank no2 dropped to 45°C after reaching its peak during the morning hours. However, around an hour later the temperature reached the 50°C. For days 1 and 2 the achieved temperatures in tank no2 were 55°C, which was sufficient to cover the daily DHW demands. For day 3 and 4 the solar radiation was sufficient enough and the temperature in tank no2 was above 50°C.

Figure 14 and Table 2 show the summary of the results for the tested hybrid HP PV/T system. The horizontal line in Figure 14 indicates the daily energy demand for DHW applications. The days are characterized by various amounts of electrical (Q_{el}) and thermal (Q_{th}) energies produced by the tested solar PV/T system. The calculations for the days 1 and 2 showed that in order to maintain a constant temperature at tank no2 it is necessary to provide additional energy ($Q_{el,\,d}$) and heat into the tank no1 (Q_{T1}). The calculations for the days 3 and 4 were characterized by surplus thermal energy (Q_{T1}). The calculations were repeated for various numbers of PV panels and different COP values for all days. Figure 15 shows the share of energy in solar hybrid HP-PV/T for DHW in various configurations.

Day 1 and 2 – 04 and 05.09.2014

During these days the solar radiation was rather limited, with an average value of 2.5kWh/m^2; a value which corresponds to 30% of the daily expected solar radiation for the location. The proposed five solar PV/T panels combined with a heat pump were capable of covering 55-58% of the energy demands for DHW applications. To enable the heat pump operation it was necessary to provide additional 1.1 to 1.2 kWh of electricity from the grid. The energy collected during the 1st day of experiments was lacking by 3.5kWh, while during the 2nd day only 0.6 kWh of additional energy were needed. The calculations were repeated for various numbers of PV panels and different COP values for both days.

Day 3 and 4 – 08 and 09.09.2014

The solar radiation levels of these days were high and close to the daily expected solar radiation for the location. The use of the five solar PV/T panels provided the adequate amount of thermal and electrical energy for DHW use. Moreover, the high levels of solar radiation provided surplus amount of thermal energy stored in the tank no1. In practice, this would result to a decrease of the cooling efficiency of the PV cells for the next day's operation. The calculations were repeated for various numbers of PV panels and different COP values for both days.

4 CONCLUSIONS

In this paper the results of experimental and simulation results regarding the performance of a hybrid flat heat pipe solar (PV/T) collector mat with a unique internal finning pattern and combined with a water/water heat pump were presented. The tests were carried out for four days during the September of 2014 for different solar radiation conditions and for six configuration of solar-thermal collectors and PV panels: two PV/T panels were equipped with monocrystalline silicon modules (PVm, PVm/T), other two PV/T panels were equipped with polycrystalline silicone modules (PVp, PVp/T); one thermal panel was cooled on the condenser side of the heat pipes solar thermal PV panels, while the other did not incorporated any cooling mechanism.

The results of the experimental measurements showed that:

- The conversion efficiency of solar to thermal energy for the solar flat heat pipe collector was between 45.4 to 64.2%
- The conversion efficiency of solar to thermal energy for the integrated heat pipe solar collector with PV panels was between 35 to 52%
- During the tests the temperature of the hybrid flat heat pipe solar PV/T panel did not exceed the 35°C
- During the tests the temperature of the uncooled PV panels reached up to 60°C
- The heat pipe system was capable of providing sufficient cooling, proved by the fact that the temperature of the cooled PV panels was lower in comparison with the uncooled PV panels by 18 to 48%

Based to the above experimental observations it is safe to conclude that the tested hybrid flat heat pipe solar PV/T panels have a reasonable potential for DHW applications.

Moreover, the simulation results of the performance of the five units of PV/T panels in combination with a cooling water tank (volume of 500litre), a DHW tank (volume 350litre) and a water/water heat pump (COP= 4.1) were presented in this paper.

The conclusion of the simulation outcomes revealed that:

- For low solar radiation levels (up to 2.5kWh/m^2 per day) the hybrid solar HP-PV/T systems can provide up to 58% coverage of the required energy demands for DHW applications
- For solar radiation levels higher than 5.0kWh/m^2 per day, the hybrid solar HP-PV/T systems can cover the energy demands of DHW by 100%

In addition, according to the simulations it should be noticed that the thermal energy output of the hybrid solar HP-PV/T system is sensitive to the COP of the system. The simulation results for five units of PV/T panels and for a minimum COP of 3.5 showed that:

- The systems were capable of covering 41% of the required energy demands of DHW applications for low radiation conditions,
- While for high solar radiation conditions greater than 5.0 kWh/m^2 daily, the system was capable of covering the required energy demands of DHW applications by 100%

Finally, it was observed that the thermal energy output of the hybrid solar HP-PV/T panels was related to the number of panels installed. Each unit of PV/T panels was able to supply:

- 12% of the required energy demands for DHW applications under low solar radiation conditions, and
- 23% of the required energy demands for DHW applications under high solar radiation conditions greater than 5.0kWh/m^2 per day

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NOMENCLATURE

G - solar irradiation (W/m^2 or kWh/m^2)
Q - heat flux (W/m^2 or kWh/m^2)
A - surface area (m^2)
η - efficiency
t - temperature (^{o}C)
m - mass flow rate (kg/s)
cp - specific heat capacity (J/(kg K))
$ß$ - Temperature coefficient
ε - Solar contribution in DHW demand
V – volume (l)
ρ – density (kg/m^3)
COP – Coefficient of performance
U – heat loss coefficient (W/m^{2}K)

SUBSCRIPTS

a – ambient
el - electrical
th - thermal
PV - photovoltaic
m - monocrystalline
p – polycrystalline
ref – reference
c – cooling
in - inlet
out - outlet
DHW – domestic hot water
w – cold water
HP – heat pump
T1 – tank no 1
T2 – tank no 2
A – area
L – heat loss
i - internal

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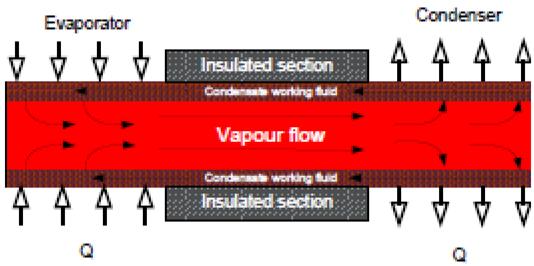

Figure 1: Heat pipe exchanger's working cycle [21]

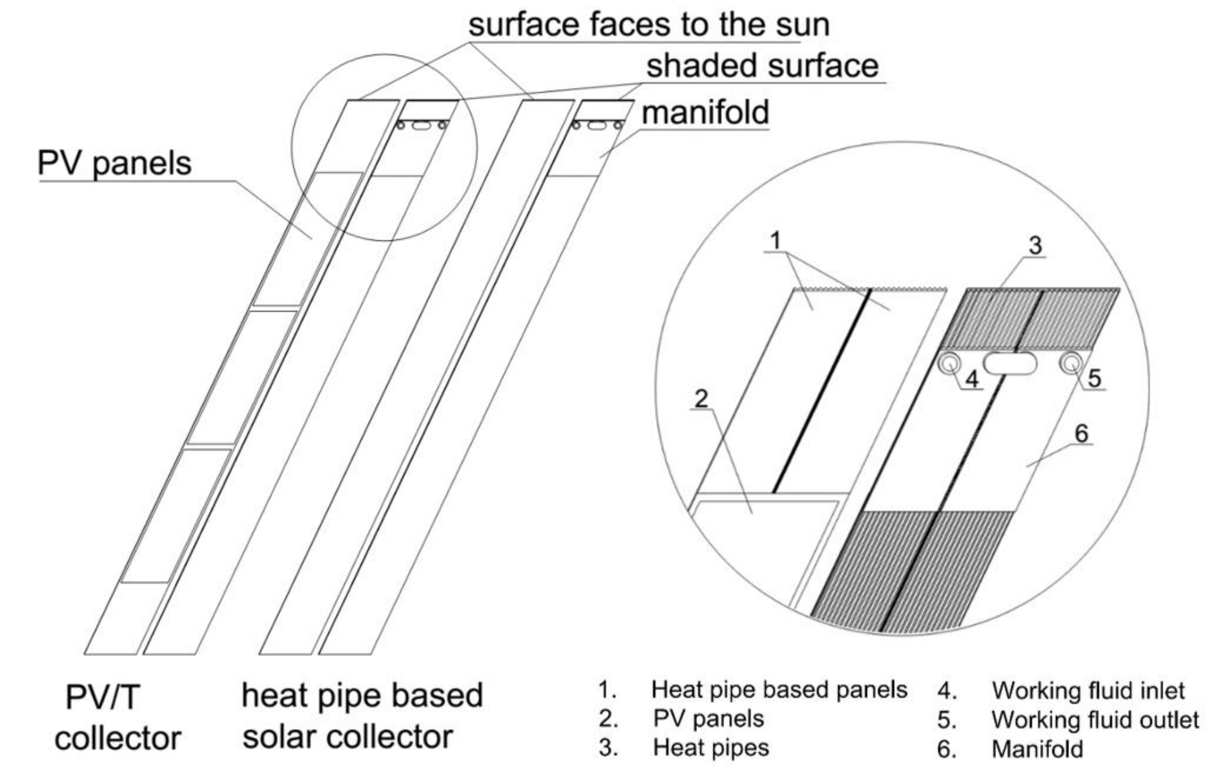

Figure 2: The construction of the hybrid PV/T solar panels

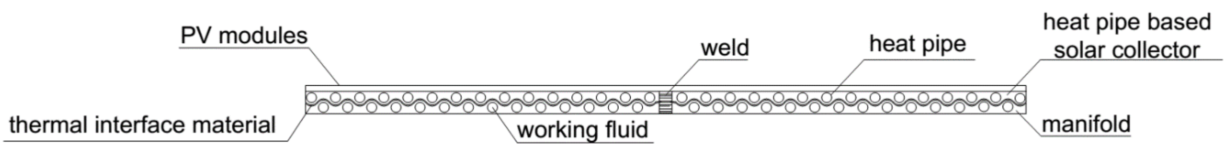

Figure 3: Cross section of the hybrid PV/T solar panels

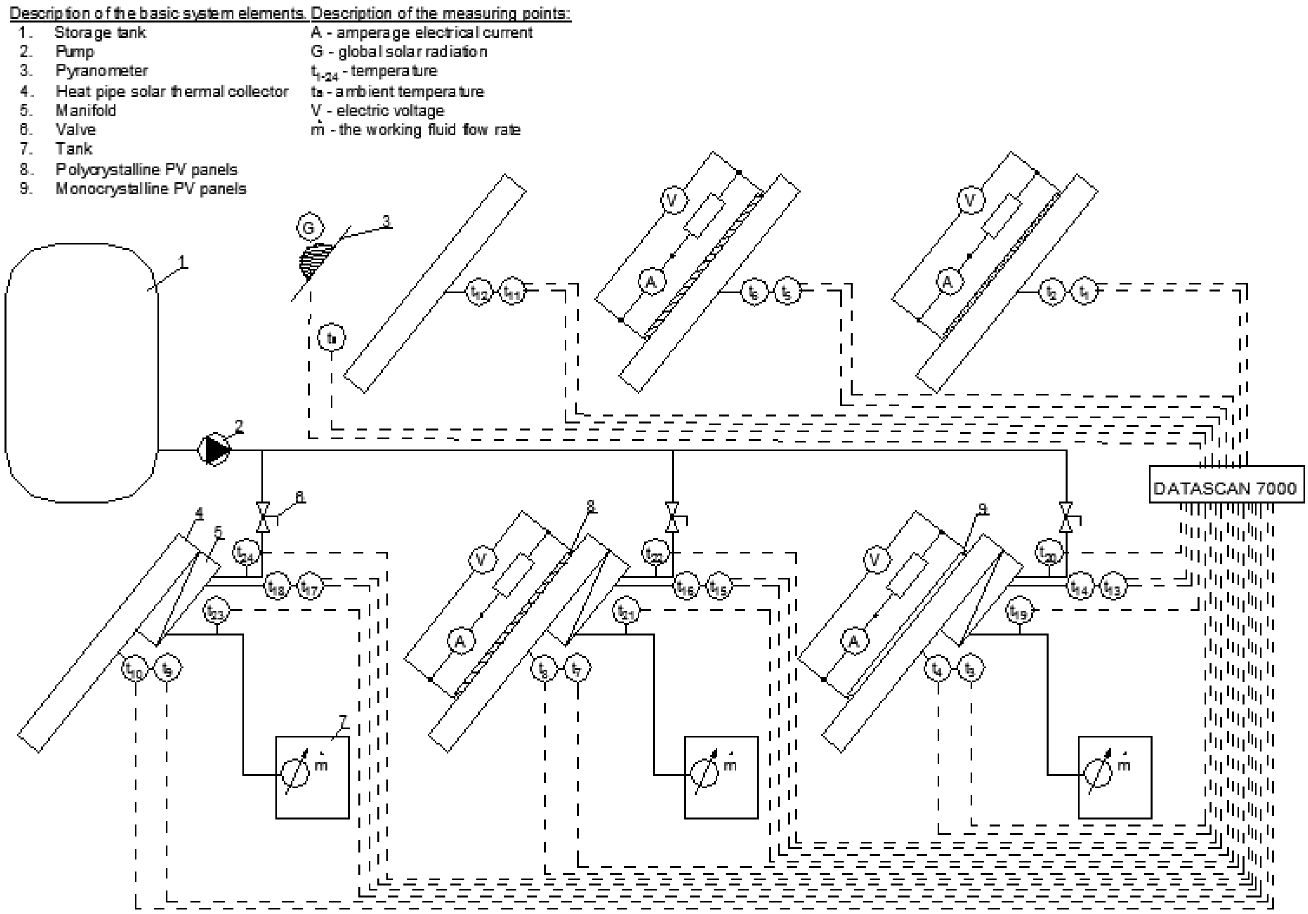

Figure 4: Hybrid PV/T experimental installation

Figure 2: Solar hybrid PV/T test installation view

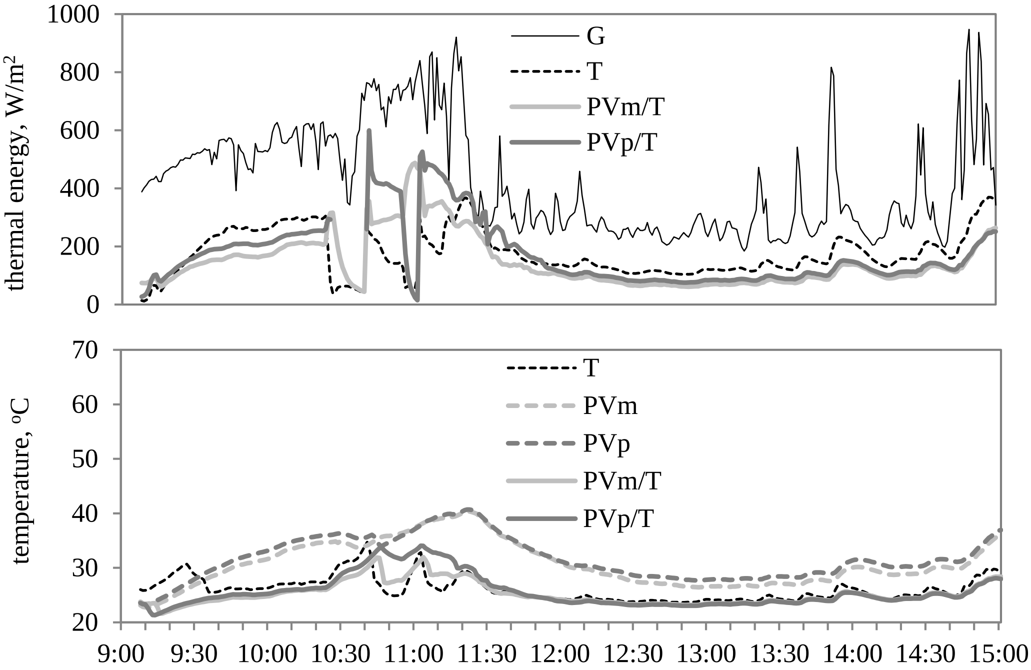

Figure 3: Measurement results for 04.09.2014

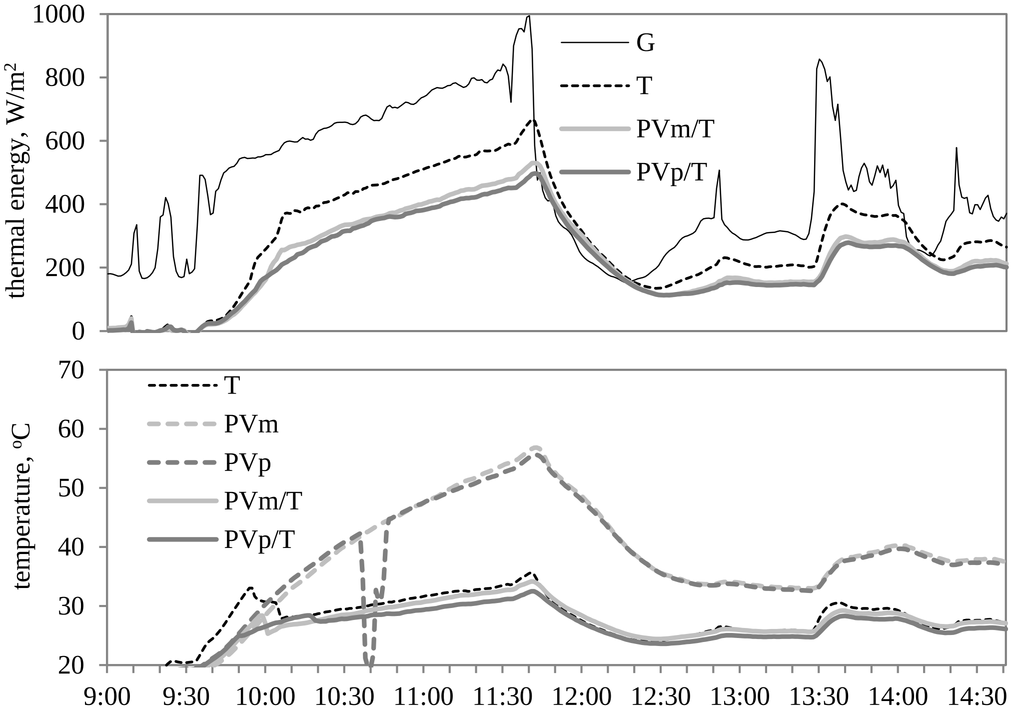

Figure 4: Measurement results for 05.09.2014

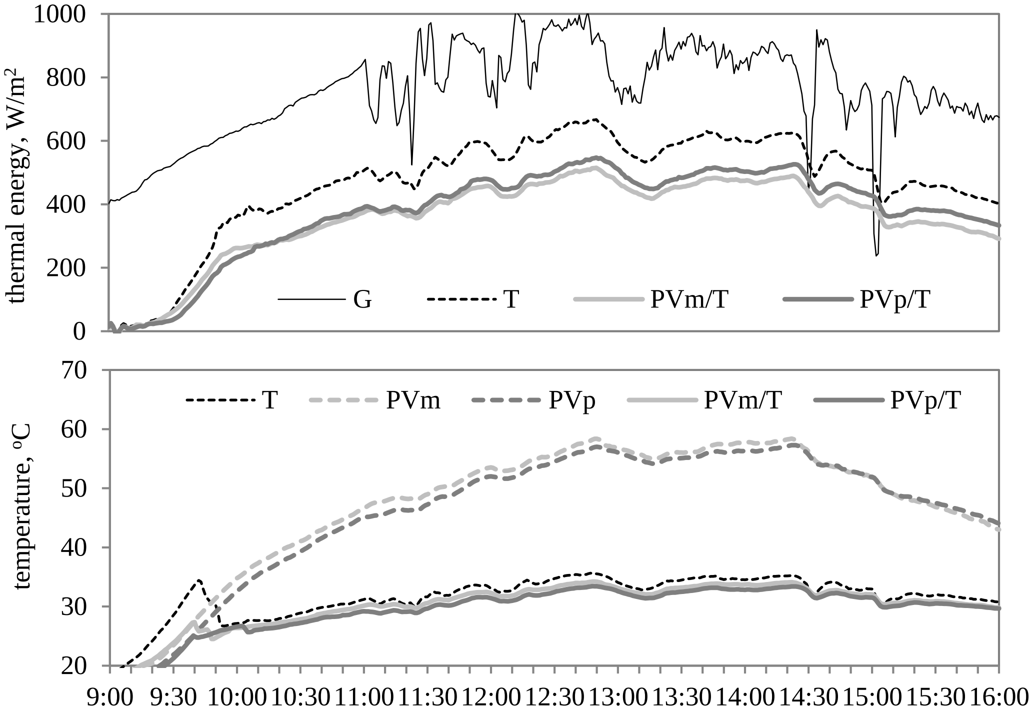

Figure 5: Measurements results for 08.09.2014

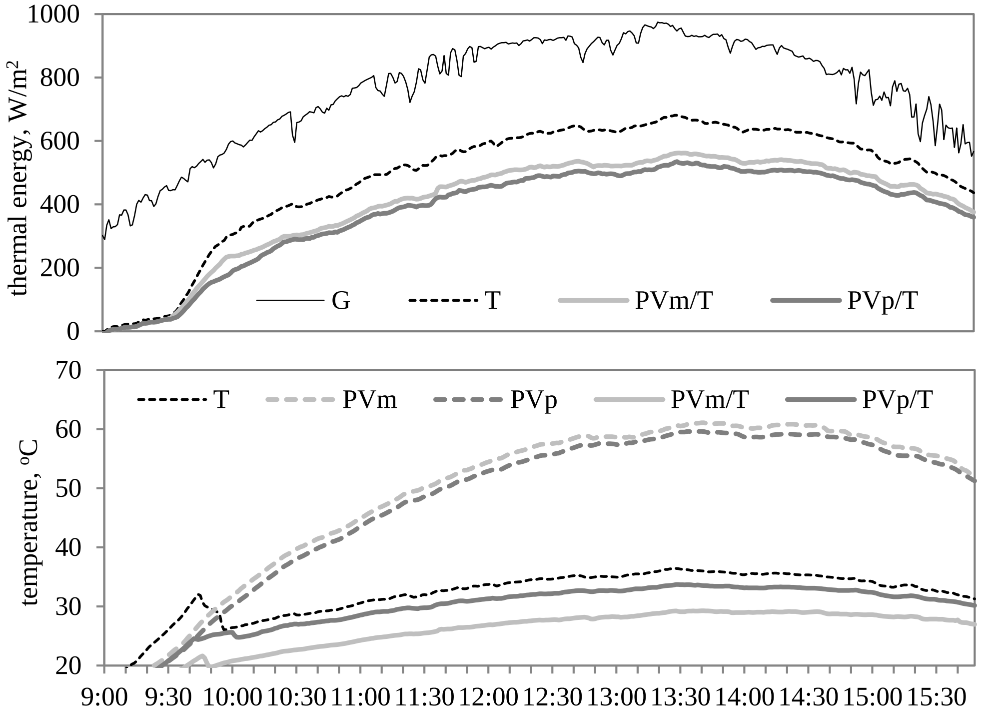

Figure 6: Measurements results for 09.09.2014

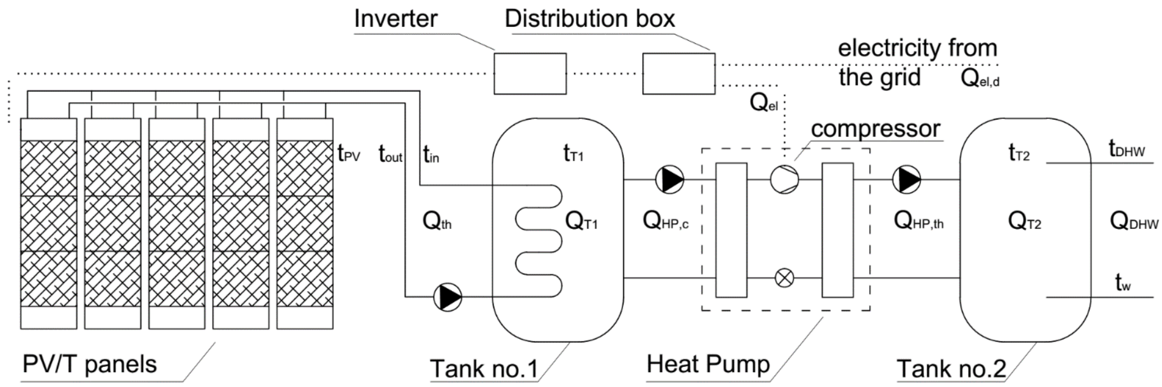

Figure 7: Adopted scheme of combined heat pump solar hybrid HP-PV/T for DHW system

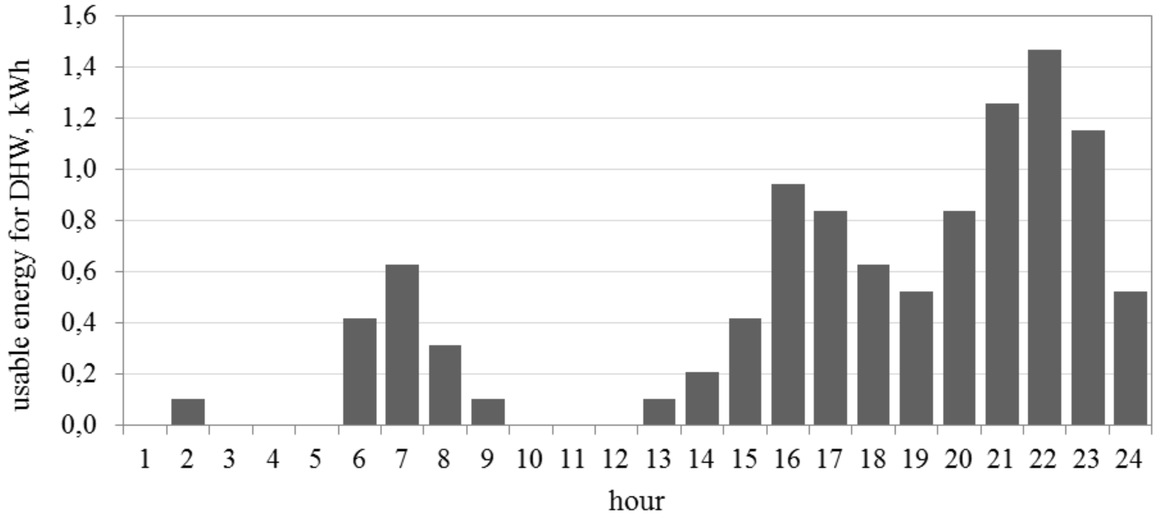

Figure 8: Usable energy for domestic hot water needs

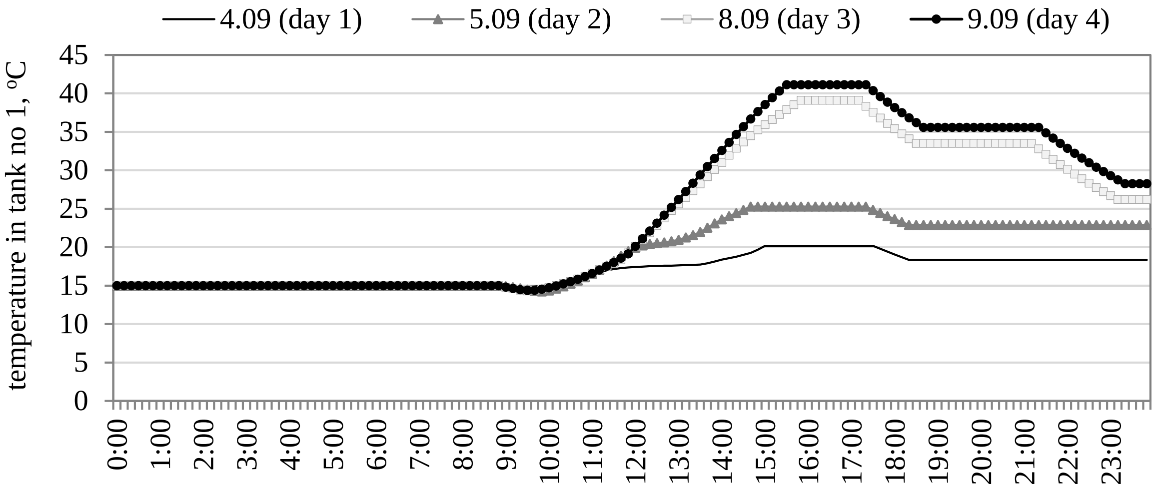

Figure 9: Temperature distribution in tank no.1

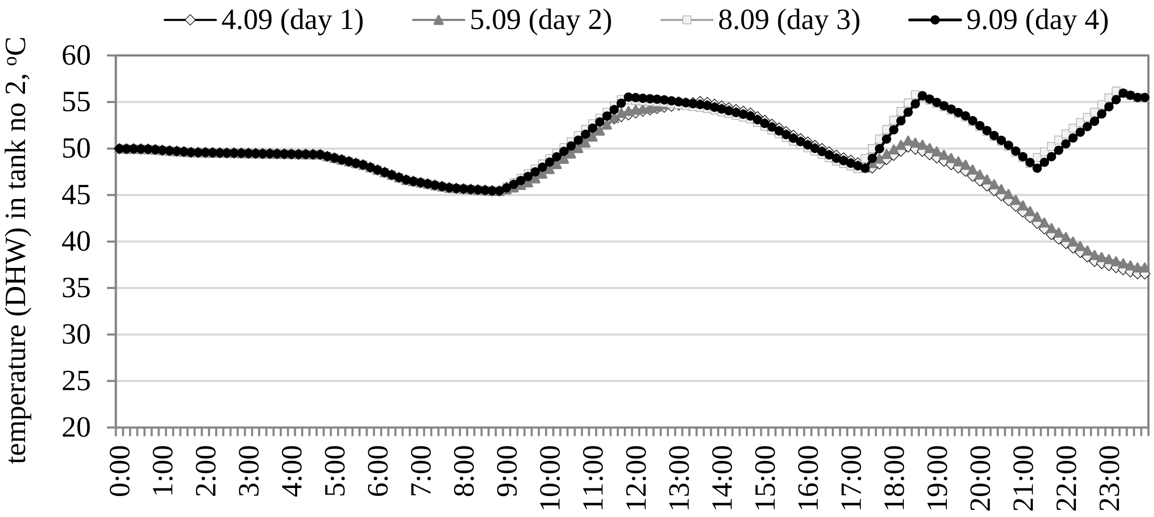

Figure 10: DHW temperature distribution in tank no. 2

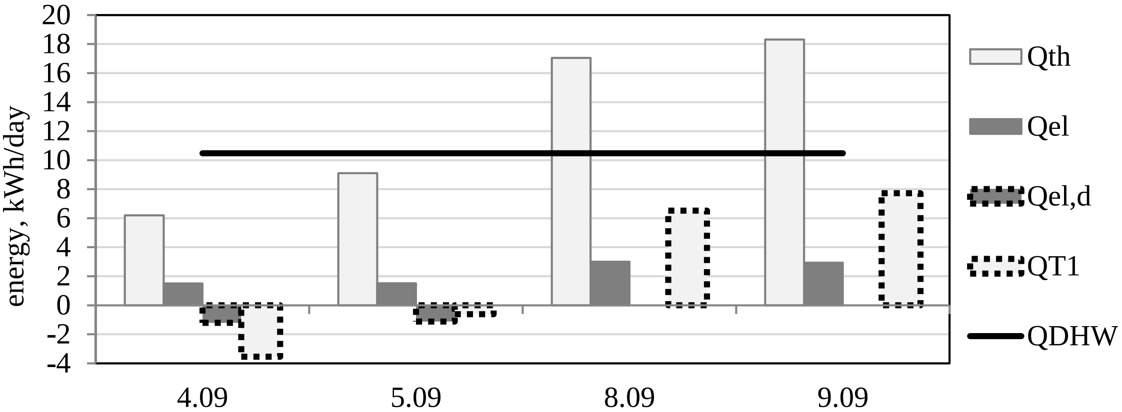

Figure 11: Daily energy balance of heat and electricity

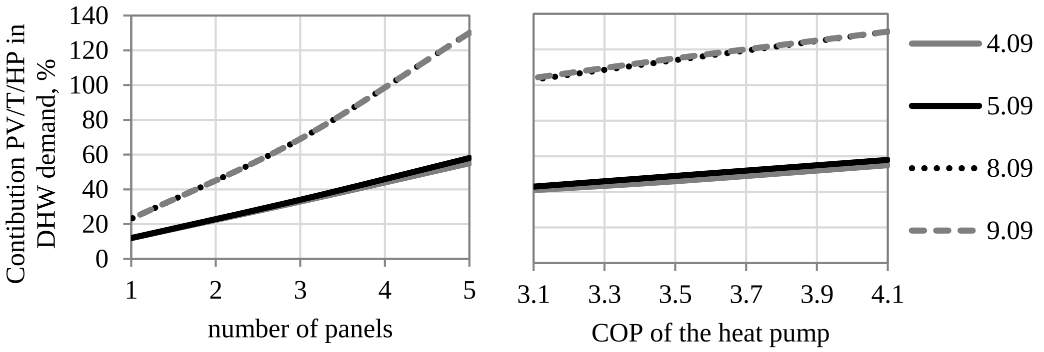

Figure 12: Share of energy in solar hybrid HP PV/T for DHW in various configurations

Table 1. The thermal efficiency and cooling effect

Number of day		1		2		3		4	
Date		*4.09.2014*		*5.09.2014*		*8.09.2014*		*9.09.2014*	
Time of measurement		9:00-15:00		9:00-14:30		9:00-16:00		9:00-16:00	
t_a		18.9 °C		19.5 °C		19.0 °C		19.6 °C	
G		2.50 kWh/m²		2.61 kWh/m²		5.32 kWh/m²		5.19 kWh/m²	
t_{in} / t_{out}		21.5 °C	24.4 °C	22.5 °C	23.6 °C	20.9 °C	28.9 °C	21.0 °C	29.4 °C
η_{th}	T	45.4 %		64.2 %		61.5 %		60.8 %	
	PV_m	-		-		-		-	
	PV_p	-		-		-		-	
	PV_m/T	34.8 %		52.0 %		46.9 %		49.9 %	
	PV_p/T	39.9 %		49.3 %		49.4 %		46.7 %	
t_{PV}, °C η_c, %	T	26.1 °C	-	27.5 °C	-	31.9 °C	-	32.0 °C	-
	PV_m	30.8 °C	-	37.1 °C	-	47.7 °C	-	49.1 °C	-
	PV_p	31.7 °C	-	36.6 °C	-	46.6 °C	-	47.7 °C	-
	PV_m/T	25.2 °C	18.1%	26.6 °C	28.1%	30.5 °C	36.1%	25.6 °C	47.8%
	PV_p/T	25.6 °C	19.3%	25.9 °C	29.3%	29.7 °C	36.3%	29.5 °C	38.1%

Table 2. Calculation results of hybrid solar HP-PV/T in various configurations

Number of day			1		2		3		4	
Date			*4.09.2014*		*5.09.2014*		*8.09.2014*		*9.09.2014*	
Q_{DHW}			10.5 kWh		10.5 kWh		10.5 kWh		10.5 kWh	
G			2.5 kWh/m²		2.61 kWh/m²		5.32 kWh/m²		5.19 kWh/m²	
Q_{th} / Q_{el}			6.2 kWh	1.5 kWh	9.1 kWh	1.5 kWh	17.0 kWh	3.0 kWh	18.3 kWh	2.9 kWh
$Q_{th,b}$ / $Q_{el,b}$			-3.5 kWh	-1.2 kWh	-0.6 kWh	-1.1 kWh	0.0 kWh	0.0 kWh	0.0 kWh	0.0 kWh
$\varepsilon = Q_{th,HP} / Q_{DHW}$ %	5 panels	COP 4.1	55 %		58 %		130 %		130 %	
		COP 3.8	46 %		49 %		114 %		115 %	
		COP 3.5	41 %		43 %		103 %		104 %	
	COP 4.1	5 panels	55 %		58 %		130 %		130 %	
		3 panels	33 %		34 %		69 %		69 %	
		1 panel	12 %		12 %		23 %		23 %	