Performance of a Solar Heating System with Photovoltaic Thermal Hybrid Collectors and Heat Pump

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The IAFOR International Conference on Sustainability, Energy & the Environment – Hawaii 2017
Official Conference Proceedings

Abstract

The energy consumption in buildings accounts for a large part of the World's CO2 emissions. Much energy is used for appliances, domestic hot water preparation and space heating.

In solar heating systems, heat is captured by solar collectors when the sun is shining and used for heating purposes. When the solar collectors are unable to supply the heat demand an auxiliary heat source is used. Heat pumps can generate this heat. Liquid/water heat pumps have better performance than air/water heat pumps in cold climates but requires installation of a tubing system for the cold side of the heat pump. The tubes are typically placed in the ground, requires a significant land area and increase the installation cost.

A new system design of a solar heating system with two storage tanks and a liquid/water heat pump is presented. The system consists of PVT collectors that generate both heat and electricity. Heat from the collectors is transferred to a domestic hot water storage tank or to a cold storage tank, which is used as the source for the heat pump. When the heat pump charges the warm storage tank, heat is extracted from the cold storage tank, which then can be reheated by the PVT collectors.

In this system, it is possible to have the high performance of the liquid/water heat pump but without the need to install tubes in the ground. The performance of the system with automated energy discharge over several months is evaluated.

Keywords: Photovoltaic thermal hybrid collector, PVT, energy absorber, heat pump, solar

Introduction

Smarter systems for space heating and domestic hot water preparation are needed to make energy consumption more efficient than it is today (IEA, 2014). Heat pumps generate heat from electricity in an efficient way. Generally liquid/water heat pumps are more efficient than air/water heat pumps (Poppi et al., 2016). Liquid/water heat pumps are typically installed with a tubing system either horizontally or vertically inserted into the ground (Kamel, Fung, & Dash, 2015). This requires space and has significant installations costs.

The system concept presented in this article was with a high efficient liquid/water heat pump in a system with PVT collectors. Instead of connecting the cold side of the heat pump to ground tubes, it was connected to a cold storage tank. The PVT collectors were uninsulated and could work as energy absorbers, which could extract low temperatures heat from the ambient when no solar radiation was available.

Method

System description

The system consisted of three PVT collectors of each 3.1 m^2 (see Figure 1). The solar cells had a net area of 2.37 m^2 of each PVT panel. The PVT panels were produced by RACELL Technologies. The PVT collectors faced south with a tilt of 45° and were installed at the Lyngby campus of Technical University of Denmark near Copenhagen, Latitude 56°N. The collectors were connected to two heat storage tanks located in an indoor test facility. A domestic hot water tank could be heated by the PVT collectors via an internal heat exchanger spiral and the cold storage tank could also be heated by the PVT panels. When the temperature level in the DHW tank dropped below the required comfort value, the heat pump heated it up. As the heat pump charged the domestic hot water tank, energy was extracted from the cold storage, which could then be recharged by the PVT collectors.The installed heat pump was a Vølund F1155. This type of heat pump was designed to cover both a space heating and domestic hot water demand and was therefore oversized for the demonstration system presented in this article. The performance of the heat pump in this system was therefore not evaluated in other ways that it proved the system concept.

Figure 1: PVT collectors on roof.

Automated draw offs of hot water were made three times per day to simulate an actual installation in a house. 1.5 kWh of energy was tapped three times per day at 7, 12, 18 hr. This corresponds to three times approximately 45 liters of water at 48-51 °C when the cold-water inlet temperature was 18-20 °C.

Figure 2 shows a simple diagram of the solar heating system concept.

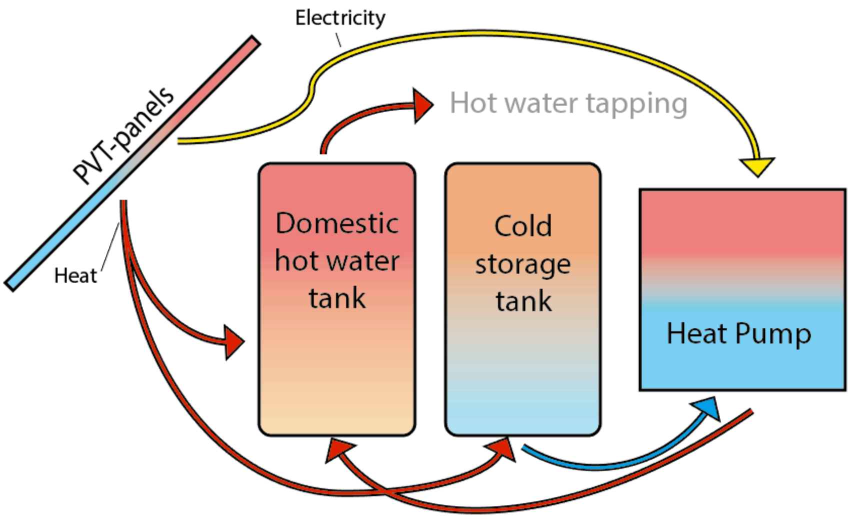

Figure 2: Simple diagram of system with PVT collectors, storage tanks and heat pump.

The PVT collectors were connected to the tanks via 20 m forward and 20 m return copper pipes with at outer/inner diameter of 22/20 mm. The pipes were insulated with Aeroflex with a thickness of 19 mm.

The PVT solar heating system ran continuously subject to real weather conditions for several months with various control strategies implemented to evaluate its performance. Minor changes in sensor placement and set point temperatures for the control of the heat pump were made during the test period to achieve better performance of the system.

Measurements

Absolute temperatures in the tanks, liquid flow temperatures in the pipes, temperature differences, flow rates, electricity generation and electricity consumption at various key locations in the system and ambient were measured and logged. Five junction thermopiles made from thermocouples type TT were used to determine the temperature differences across in- and outlet of the collectors as well as across the hot and cold-water temperatures for the domestic hot water tapping. The total and the diffuse irradiances on the PVT panels were measured by pyranometers, the wind speed was measured with a cup star wind sensor and the infrared radiation exchange between the sky and the collector surface was determined by a pyrgeometer.

The energy flows in the different loops were calculated and accumulated values of selected periods were made to evaluate the performance of the system. The solar energy on the PVT panels accumulated over the periods, were also determined to evaluate the efficiency of the collectors and system.

The PV part of the PVT panels was not in operation in the first periods, when the system was running.

Control system

Figure 3 illustrates sensor location and the control strategy of the thermal part of the solar heating system.

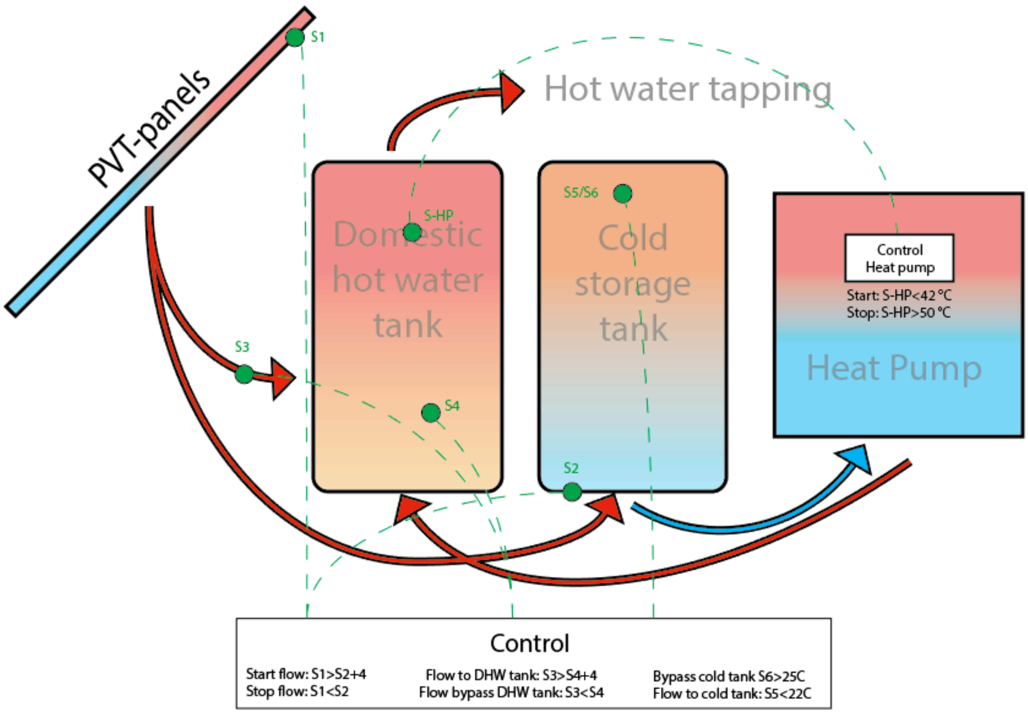

Figure 3: Control strategy and dimensions of system.

When the temperature on the back of the PVT panel near the outlet (S1) was 4 K higher than the bottom of the cold tank (S2) the flow in the collector loop started. The flow ran until the temperature of the PVT panel dropped below the temperature in the bottom of the cold tank. If the temperature in the pipe immediately before the DHW tank (S3) was 4 K higher than in the lower part of the DHW tank (S4), then the flow was directed through the heat exchanger spiral of the DHW tank. When the temperature in the pipe before the DHW tank dropped to the same temperature as in the lower part of the DHW tank, then the flow bypassed the DHW tank. As long as the temperature in the top of the cold tank (S5/S6) was below 25 °C, then the flow from the solar collector loop was directed through the cold storage tank. Otherwise, it was bypassed. The maximum temperature in the cold tank was due to the maximum allowed inlet temperature in the cold side of the heat pump of 30 °C. When the temperature in the top of the DHW tank (S-HP) dropped below 42 °C, then the heat pump started and charged the top of the DHW tank to 50 °C via the top spiral.

Test periods

The system ran continuously in four individual periods between August 2016 and January 2017. The system was not in operation in some periods due to development of the system and maintenance of the measurement equipment. In the beginning of the test period, the PV generation was not active due to incomplete installation of the inverter for the PV part of the system.

Sensor S2 was located on the outer surface on the bottom of the cold storage tank during the initial testing and was moved to a sensor pocket inside the lower part of the tank for the testing from December and onwards.

Flow distribution

To have the best performance of the solar collector array the flow of heat transfer fluid should be similar in each collector. In this case, the collectors were parallel connected and the layout of the connecting pipes may have affected the flow distribution in each collector due to different hydraulic paths, which may have different pressure drops. The flow distribution in the collector array was evaluated by thermal imaging during operation in sunny conditions. Similar temperatures in the three collectors would indicate similar temperature increase across the collectors and therefore similar flow. A FLIR T-Series Thermal Imaging Camera was used for the evaluation.

Collector efficiency

The solar collector loop ran when the solar irradiance raised the temperature in the collector above the tank temperature. In these cases, the PVT panels worked as solar thermal collectors.

The temperature of PVT panels was close to the ambient temperature when there is no solar irradiance. The solar collector loop also started when the temperature of the cold storage tank dropped below the collector temperature, also in the cases when there was no solar irradiance available. This happened typically after the heat pumps had been running and discharged the cold tank. In this case, the PVT panels extracted heat from the ambient and they worked as energy absorbers. In the analysis there is distinguished between when the PVT collectors worked as thermal collectors of solar irradiance and as energy absorbers where it extracted heat from the ambient when there was no solar irradiance available. When the total irradiance on the PVT panel was lower than 50 W/m^2 and the collector loop was running, it was defined as the PVT panels working as energy absorbers.

The thermal and electrical efficiency of the PVT collector was evaluated from the measurement of the system in operation. The dynamic of the system during operation did not allow for completely steady state conditions, which was needed for accurate evaluation of collector performance.

Therefore, periods of 10-30 minutes where the collector inlet temperature and the solar irradiance were more or less stable were selected for the collector efficiency evaluation. In the stable periods, the solar irradiance level was higher than 500 W/

m2, varied less than 50 W/m^2 and the inlet temperature varied less than 1 K throughout the period. In "SEMI" stable periods, solar irradiance varied less than 100 W/m^2 and the inlet temperature varied less than 3 K throughout the period.

The collector thermal efficiency was calculated as:

$$\eta_{th} = ((T_{out} - T_{in})\cdot V\cdot \rho\cdot c_p) / (G_{total}\cdot A)$$

Where T_{out} is the collector outlet temperature, T_{in} is the collector inlet temperature, V is the volume flow rate, ρ is the density of the heat transfer fluid, c_p is the specific heat capacity of the heat transfer fluid, G_{total} is the total irradiance and A is the gross collector area.

The collector thermal efficiency was displayed as a function of the factor:

$$((T_m - T_a)) / G_{total}$$

Where T_m is the collector mean temperature defined at the average of T_{out} and T_{in} and T_a is the ambient temperature. The wind speed at the collector surface affected the thermal efficiency of the PVT panels as it affected the convection heat losses. Each evaluated period were denoted as the average wind speed for the selected periods to show the effect of the wind speed on the efficiency.

The efficiency of the solar cells after the inverter was calculated as:

$$\eta_{PV} = PVout / (G_{total}\cdot A(PV))$$

Where *PVout* is the measured electricity fed into the grid after the inverter and *A(PV)* is the net areas of the solar cells in the PVT panel.

Results

Energy

The energy balance of the system was set up and the energy amounts for the points of interests were summarized. For the 4 individual test period the system was running continuously and the following values were accumulated and listed in Table 1:

- Solar radiation on the total collector area
- Total solar collector thermal output
- Energy absorber output (<50 W/m^2)
- Electrical output of the PV after the inverter
- Tapped energy for domestic hot water
- Energy discharged from the cold tank by the heat pump
- Energy charged to the domestic hot water tank by the heat pump

	Energy [kWh]			
	19 Aug. – 4 Sept. 2016 (17 days)	**23 Sept. – 20 Oct. 2016 (27 days)**	**21 Oct. – 21 Nov. 2016 (32 days)**	**21 Dec. 2016 – 22 Jan. 2017 (33 days)**
Solar radiation in PVT collectors	732	550	469	267
Total collector thermal output	106	117	138	102
Energy absorber output (<50 W/m^2)	0*	11.5*	20*	46
PV output	NA	NA	NA	28
Tapped hot water	77	122	142	149
Energy discharged from cold tank	47	128	178	179
Energy charged to DHW tank by heat pump	43	131	180	192

Table 1. Accumulated energy quantities for the periods.* non optimal placement of control sensors.

Thermal efficiently of collectors

Figure 4 displays the measured thermal efficiency of the PVT collectors without the PV cells in operation. The efficiency showed to be relatively low because the collectors were uninsulated and the wind caused significant heat losses. Guiding lines representing potential efficiency curves for different wind speeds assuming an optical efficiency of 0.75 are inserted in the figure.

In Figure 4, solid markers represents data from the more stable conditions and the thin markers represents data from measurement in the "SEMI" stable periods. Grey plots represents data for measurements with little or no wind, red plots a wind speed at the collector surface of 0.5 – 0.7 m/s and the black plots represents high wind speeds between 0.8 – 1.5 m/s.

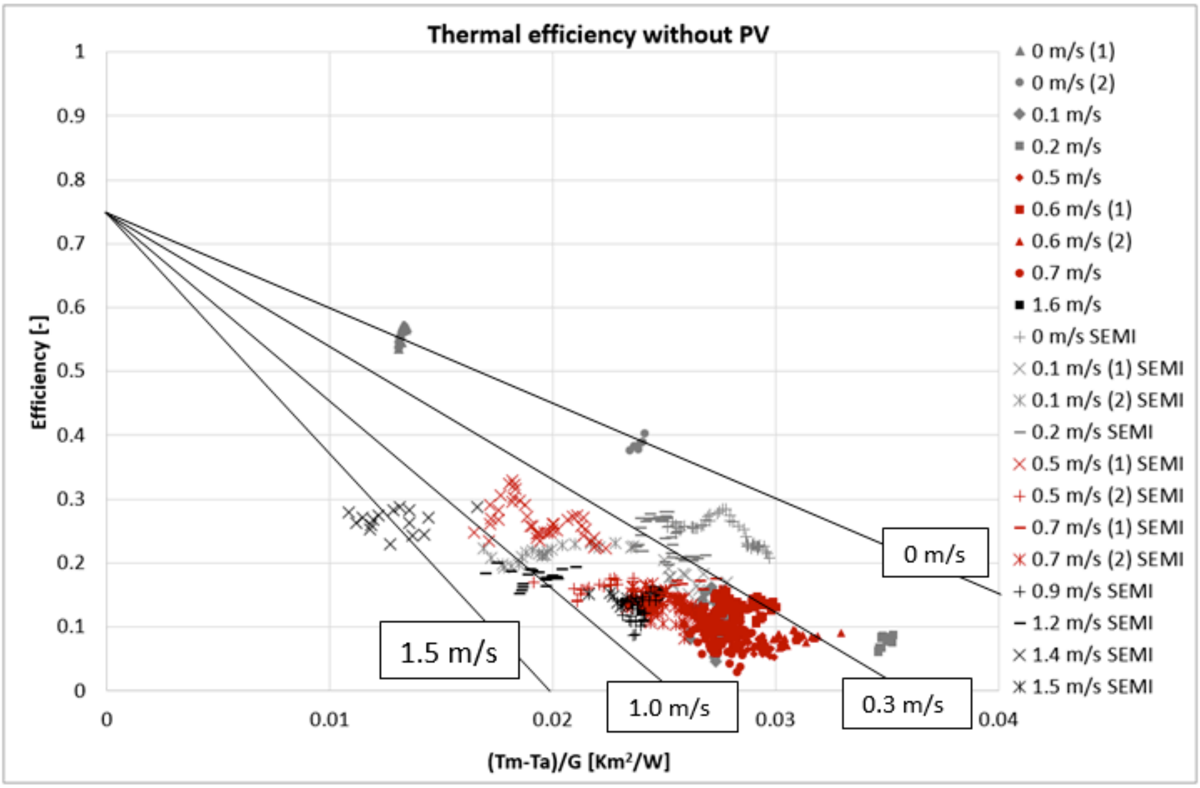

Figure 4: Measured thermal efficiency of PVT collectors in operation without electricity production.

The tendency of the plots in Figure 4 is that the measurement from periods with little or no wind show a higher efficiency compared the measurements from the periods with high wind. This is as expected for the thermal part of the uninsulated collector.
A similar evaluation of a PVT panel was previously made by Perers et al. (Perers, Furbo, & Johansen, 2014). The PVT panel they investigated was insulated on the back, while the PVT panels in this investigation was not insulated and air could pass below them. When comparing the two evaluations it is clear that the uninsulated PVT panels are more sensitive to wind than the insulated PVT panel. This can be seen, by the measurement points being more to the left in the diagram and the guiding lines for each wind velocity are significantly steeper compared to what Perers at al. found.
The average efficiency of the PV part of the PVT panels was measured to be 0.148 for irradiance levels above 400 W/m^2.

Flow distribution in collectors

Figure 5 shows that the temperature in the left PVT collector was lower than the other two. This was because the flow rate was slightly higher through the left collector due to the pipe layout. In each collector, the temperature was highest in the central upper area of the collectors due to the flow direction, the manifold and distribution pipe design.

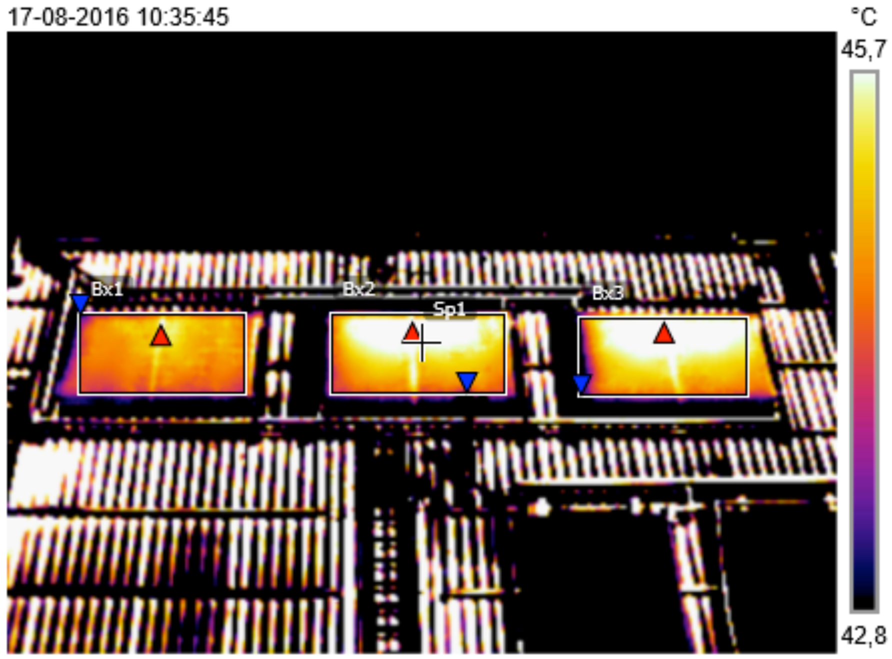

Figure 5: Thermal vision image of PVT collectors during operation in sunny condition.

Conclusion

The investigations showed that the concept with two storage tanks worked well in connection with the uninsulated PVT collectors. On sunny days in the summer, the collectors almost covered the heat demand for domestic hot water preparation. The thermal efficiency of the collectors was relative low as expected and highly affected by the wind speed. The PVT panels were able to extract heat from the ambient when there was no solar irradiance available when the cold storage tank was cooled below the ambient temperature by the heat pump.

Acknowledgement

RACELL Saphire Technologies ApS has developed the PVT panels and the solar heating system concept was developed in collaboration with COWI A/S. The research was funded by the Danish Energy Agency through the EUDP programme grant no: 64014-0561.

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