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Experimental testing of solar photovoltaic/thermal collector as a heat pump source under outdoor laboratory conditions

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Abstract

The integration of photovoltaic-thermal (PVT) and heat pumps appears as a promising technology for the decarbonization of European buildings. Some of the benefits include the simultaneous production of renewable electricity and heat, as well as an improved system efficiency. However, there has been little research dedicated to collectors designed specifically for heat pump integration. This study aims at characterizing the performance of an unglazed and uninsulated PVT collector with fins, acting as a source for heat pump systems. Tests are performed at an outdoor testing facility in Stockholm Sweden, over two weeks in October 2022. Specific thermal output in W/m^2 is presented against temperature difference between ambient and mean fluid temperature for a wide range of boundary conditions. The results show that the PVT collector field can generate a peak thermal power of 9 kW during sunny days, and 5 kW during nighttime operation. In order to meet the peak heating capacity in a Swedish villa, however, the collector field should be at least 40 m^2.

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Keywords:Solar sourced heat pumps, PVT, testing facility, heat exchanger;solar hybrid

1. Introduction

Solar photovoltaic-thermal (PVT) modules can produce electricity and heat simultaneously, thus reducing the amount of required roof area if compared to stand-alone solar PV and thermal systems. At the same time, heat pumps are the most efficient technology to produce space heating and domestic hot water in a highly electrified scenario. There are currently 190 million heat pumps installed worldwide and, according to the Net Zero by 2050 scenario developed by IEA, this number should increase to 600 million by 2030 if climate targets are to be met (IEA, 2022). Therefore, the integration of PVT with heat pumps appears as a promising technology for the decarbonization of European buildings.

When combined with heat pumps, solar thermal systems can provide a higher seasonal performance factor due to the reduction in heat pump electricity use, whereas solar PV allows for the use of less electricity from the grid (Poppi et al., 2018). There are many ways of combining these two technologies, but one that has gained attention in recent years are PVT sourced heat pumps (Sommerfeldt and Madani, 2017). In this configuration, uncovered PVT collectors are connected in series with a heat pump system to act as an additional or sole heat source, in order to lift the evaporator temperature and improve system efficiency (Giovannetti et al., 2019; Hadorn, 2015). The low temperatures in the PVT circuit allow heat to be captured not only from the sun but also from ambient air, thus increasing thermal efficiency to a level on par with a high performance solar thermal system (Sommerfeldt and Madani, 2018; Weiss and Spörk-Dür, 2019). The low operating temperatures also enable the use of cheaper and lighter materials such as plastic, and an improved electrical efficiency due to the cooling effect on the PV cells. The increased electrical power generation can be enough to cover the additional pumping power, making the captured heat from the PVT a free resource (Sommerfeldt and Madani, 2018).

Schmidt et al. (2018) investigated the performance of rear insulated and unglazed PVT collectors acting as the sole source of a heat pump. The results showed that this system configuration was able to cover the space

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heating and domestic hot water demand for winter days down to -10°C, and suggested that better results could be achieved if using uninsulated PVT collectors.

Although solar PVT and heat pump systems have been studied extensively in the past, there has been little research dedicated to collectors designed or optimized specifically for heat pump integration. For example, the heat capture could be enhanced by adding fins on the rear side of the absorber/exchanger, improving heat production even at low solar irradiance levels. A few studies have looked at the performance of PVT+HP systems with unglazed and uninsulated PVT collectors with fins. Chhugani et al. (2020) looked at the performance of an unglazed and uninsulated PVT collector with fins serving as a sole source of a heat pump in a single-family house in Germany. The system was tested under a Hardware in the Loop test environment, and the results showed that the seasonal performance factor (SPF) during the winter months reached daily averages of 3.3. It was suggested that the PVT collectors could replace the noisy heat exchanger in an air source heat pump, while keeping a good system efficiency. Giovannetti et al. (2020) calculated the U-values of a 20m^2 PVT collector array with fins under no solar irradiance conditions according to ISO 9806:2017, and found that they were in the range of 22.9 and 27.0 Wm^{-2}K^{-1} at specific heat flows between 75 and 175 W/m^2.

2. Objective and Methodology

This study aims at empirically characterizing the performance of an unglazed and uninsulated PVT collector with fins designed specifically for heat pump integration. The tests are performed at an outdoor testing facility between the 4th and 20th of October 2022, for different inlet temperatures and flow rates, which provides a wide range of solar irradiance levels (G) and ambient temperatures (T_{amb}). Three different volumetric flow rate ranges are considered: 30 to 35 lh^{-1}m^{-2}, 40 to 45 lh^{-1}m^{-2} and 50 to 55 lh^{-1}m^{-2}. Thermal power output is monitored for the collector array and plotted against the temperature difference between ambient and mean fluid temperature of the collector field ($T_{f,m}$). Linear regression is used to determine the thermal performance curves, and the key parameters such as the slope of the curve, the performance at $\Delta T=0$ and the coefficient of determination (R^2) are presented and discussed. The U-value obtained from the collector field is then compared against the results for the same stand-alone collector and other finned collector designs. Finally, time series data for the days between 15th and 18th of October is presented, looking at daily heat and electricity generation.

2.1. Testing facility

The testing facility is located on the rooftop of the Energy Technology Laboratory at KTH Royal Institute of Technology in Stockholm, Sweden, and consists of a 14 PVT collector array with an area of 20 m^2, connected in series to a 12 kW variable speed heat pump. The array is oriented to the south and has a tilt angle of 45°. It is made up of two subarrays connected in series, where each subarray has seven collectors connected in parallel. The testing facility also includes a hot water tank and air to water heat exchanger for heat dissipation. Figure 1 shows the PVT collector array and mechanical room of the testing facility at KTH.

Figure 1. PVT+HP testing facility at KTH with collector array (left) and mechanical room (right)

The facility allows for two operation modes:

- brine circulates directly into the solar PVT loop
- brine and solar loops operate independently, with a cold storage tank connecting both circuits

For the purpose of this study, only the operation mode in which the tank is bypassed is utilized.

2.2. PVT module

The PVT collector is manufactured by the company Solhybrid i Småland and consists of an extruded aluminum manifold mechanically pressed to the rear side of a glass-glass PV module. The manifold has a trough that fits a 12 mm copper pipe, also mechanically pressed. To increase heat transfer between the different absorber materials, thermal grease is added between manifold and rear glass, as well as between the aluminum trough and the copper pipe. A picture of the PVT absorber can be seen in Figure 2.

Figure 2. Unglazed and uninsulated sheet and tube PVT collector from Solhybrid i Småland

The PV module is an off-the-shelf 60 monocrystalline-cell panel manufactured by Perlight Solar. The electrical ratings and specifications are presented in Table 1. Each PV module is connected to a micro inverter for DC/AC conversion.

Table 1. PV module specifications

Pmax *(Wp)*	Efficiency *(ηel)*	Open-circuit voltage *(Voc)*	Short-circuit current *(Isc)*	Voltage @ Pmax *(Vmp)*	Current @ Pmax *(Imp)*	Temp. coeff. Pmax *(β)*
285 W	17.52%	38.80 V	9.32 A	32.43 V	8.79 A	-0.40 %/°C

The monitoring system consists of a weather station for ambient temperature measurement, dew point and wind speed; a solar irradiance meter for measurement of the incident solar irradiation on the collector plane; a heat power meter for the measurement of flow rate, inlet temperature, outlet temperature and thermal power; the already mentioned micro inverters for electrical power measurement. All the measured data is obtained in 1-minute time steps, except for the electricity generation that is measured every five minutes. A schematic diagram of the testing facility with the monitoring equipment is presented in Figure 3.

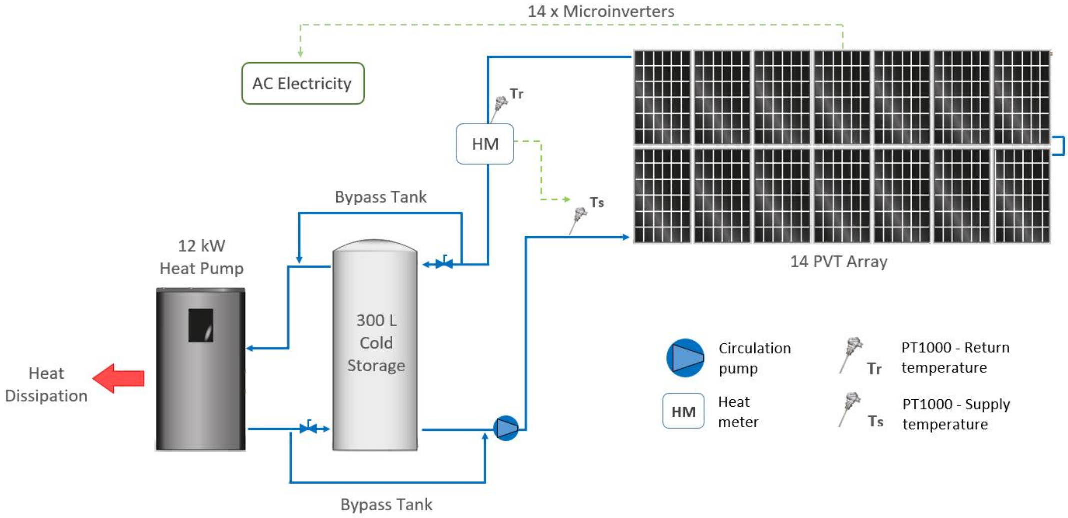

Figure 3. Test rig diagram

3. Results and discussion

Firstly, the weather data for the period of study is presented in Figure 4. The range of ambient and dew point temperatures is 2 to 16°C and 0 to 13°C, respectively, throughout the experiments. Regarding in-plane solar irradiance levels, there is a wide range of conditions, from zero to around 1000 W/m^2. Looking at the daily solar irradiation on the collector plane, the sunniest day is October 9th with 5.1 kWh/m^2, and the lowest is October 5th with 0.4 kWh/m^2.

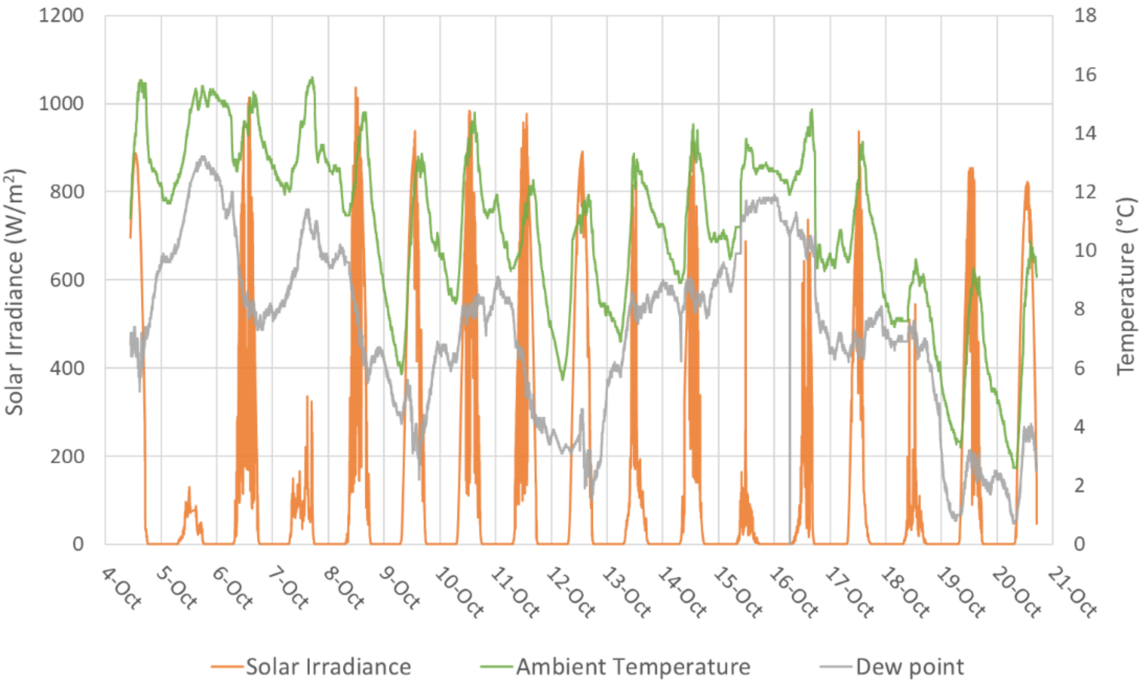

Figure 4. Weather data between 4th and 20th of October

The results for specific thermal production of the PVT collector in W/m^2 are presented against the temperature difference between ambient and mean fluid temperature of the collector field, separated by solar irradiance levels and volumetric flow rates.

3.1. Volumetric flow rate of 30 to 35 lh^{-1}m^{-2}

Figure 5 shows the results when the volumetric flow rate is set in the range of 30 to 35 lh^{-1}m^{-2}. In this case, the thermal output can reach a value of 425 W/m^2 for solar irradiances in the range of 700 to 900 W/m^2 and a ΔT of around 13 K. It can also be seen that, even at low solar irradiance levels (200 - 400 W/m^2), the thermal output of the collector field can be over 300 W/m^2 for ΔT=14K, which shows the importance of the heat exchange with ambient air. However, such high ΔTs can be a limitation for the heat pump as ambient air temperatures approach the evaporator's limit. Looking at lower temperature differences of 6K or 7K, we can see that the thermal output goes from just over 100 W/m^2 for low solar irradiances, up to 300 W/m^2 for the upper range. For the 14 PVT collector array, this equals a total thermal power production between 2 and 6 kW fed directly into the heat pump evaporator.

Linear regression is used to represent the thermal performance curve of the collectors as a function of temperature difference between ambient and mean fluid temperature of the collector field for different solar irradiance levels. The key parameters of such curves, such as the slope of the curve in W/K, the thermal output at a ΔT=0 and the coefficient of determination (R^2), are shown in Table 2.

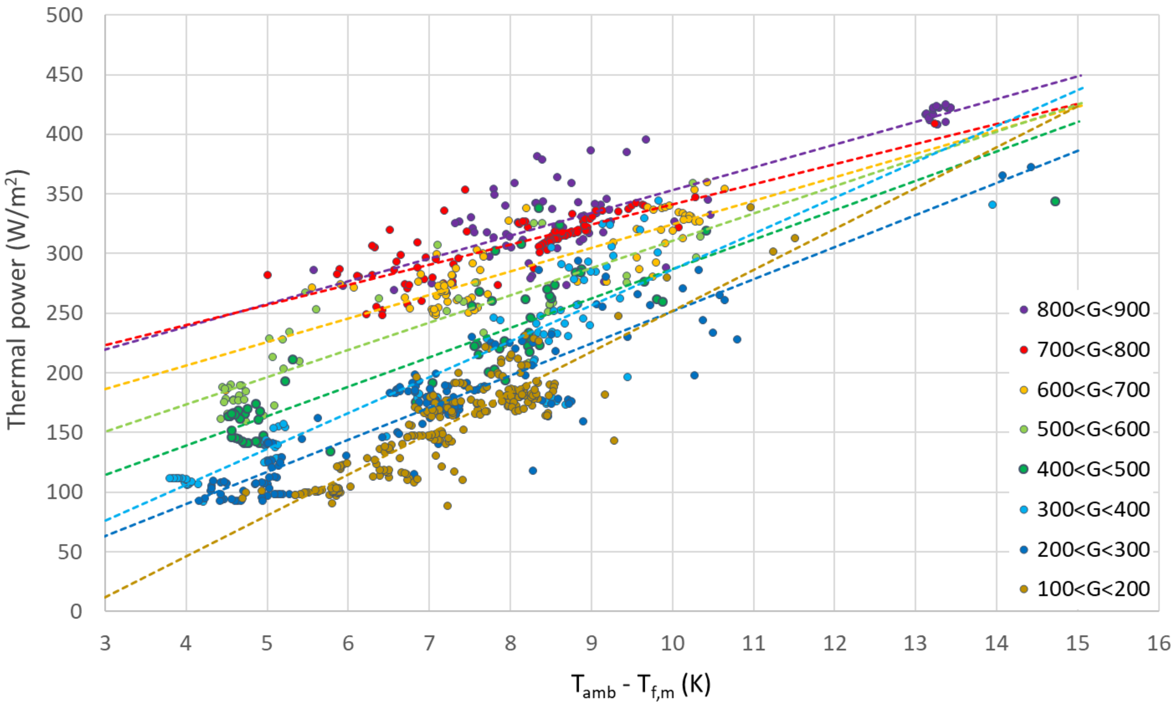

Figure 5. Specific thermal output of collector array as a function of $T_{amb} - T_{f,m}$ for different solar irradiance levels and flow rate of 30 to 35 $lh^{-1}m^{-2}$

As the solar irradiance increases, the U-value of the collector field decreases (i.e. slope of the curve) and the thermal output at ΔT=0 increases (y-intercept). Another aspect to highlight is the fact that the coefficient of determination decreases as the solar irradiance increases. This can be explained by the fact that the PVT collector has a limit on how much heat it can capture based on the flow rate and absorber geometry, so the curve tends to start flattening as we increase the difference between T_{amb} and $T_{f,m}$. The coefficient of determination is between 65% and 82% for all cases, which shows that the presented linear relationships are relatively weak. This is primarily due to missing aspects of wind velocity, sky temperature or thermal capacity in the regression model, as described by (Fischer et al., 2004; Perers, 1997) for quasi-dynamic conditions.

Table 2. Main parameters of thermal performance curve for a flow rate of 30 to 35 $lh^{-1}m^{-2}$

Solar Irradiance W/m^2	HEX U-value $Wm^{-2}K^{-1}$	Y-intercept Wm^{-2}@ΔT=0	R^2
100<G<200	34.3	-90.9	0.78
200<G<300	26.9	-17.8	0.82
300<G<400	30.1	-14.3	0.84
400<G<500	24.6	40.8	0.75
500<G<600	22.8	82.6	0.73
600<G<700	19.7	127.3	0.71
700<G<800	16.9	172.8	0.65
800<G<900	19.1	162.6	0.73

3.2. Volumetric flow rate of 40 to 45 $lh^{-1}m^{-2}$

Figure 6 shows the results when the flow rate is increased by 10 $lh^{-1}m^{-2}$. The specific thermal output can reach a value of approximately 450 W/m^2 for solar irradiances over 500 W/m^2 and a ΔT of around 13-14 K, representing a 5% increase in thermal output if compared to the previous case. For the 14 PVT collector array, this equals an increase in thermal power of 0.5 kW. Looking at a ΔT of 6-7 K we can see that thermal output is in the range of 150 to 325 W/m². For the 14 PVT collector array, this equals a total thermal power production of between 3 and 6.5 kW that could be fed directly into the heat pump evaporator.

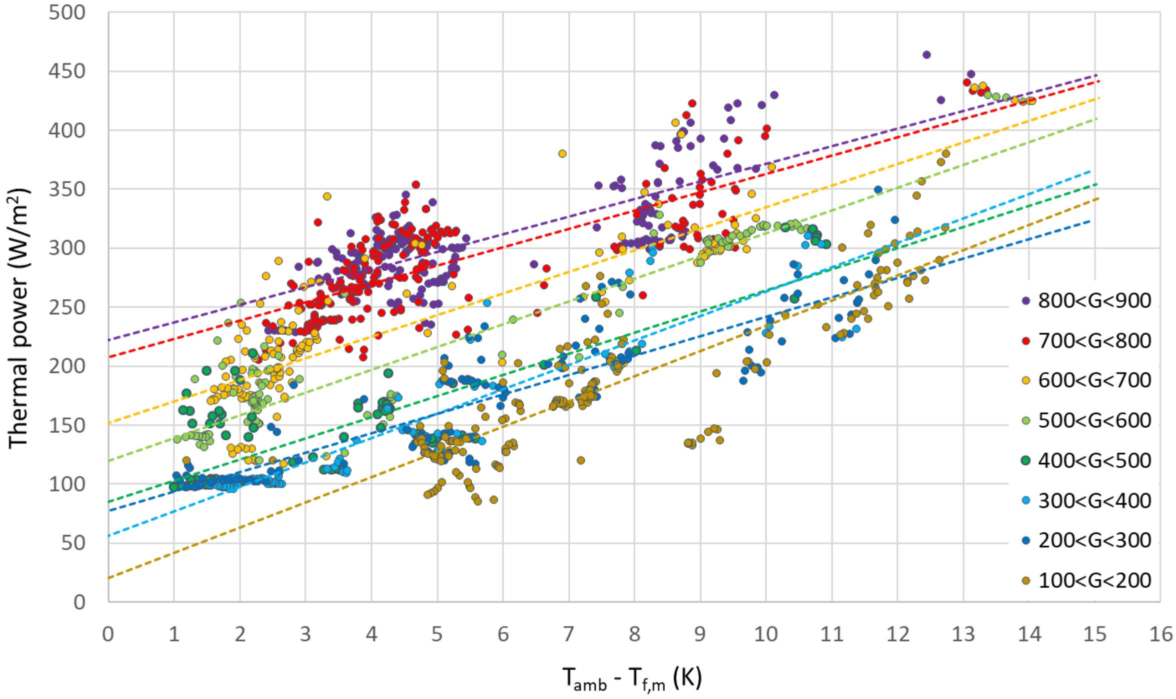

Figure 6. Specific thermal output of collector array as a function of $T_{amb} - T_{f,m}$ for different solar irradiance levels and flow rate of 40 to 45 $lh^{-1}m^{-2}$

The main parameters of the thermal performance curve are presented in Table 3. As solar irradiance increases, the U-value of the collector field decreases and the y-intercept increases, as was observed for the 30 to 35 $lh^{-1}m^{-2}$ case. Another aspect to highlight is that even when there is no temperature difference between ambient and mean fluid temperature, the PVT collector can still generate heat regardless of the solar irradiance level. The coefficient of determination is between 61% and 85% for all cases, which shows that the presented linear relationships are relatively weak, as explained in the previous section. When comparing the values in the Table to the previous case, the U-values of the collector field are lower at higher flow rates, but the specific heat production at ΔT=0 becomes higher as the flow rate increases.

Table 3. Main parameters of thermal performance curve for a flow rate of 40 to 45 $lh^{-1}m^{-2}$

Solar Irradiance W/m²	HEX U-value $Wm^{-2}K^{-1}$	Y-intercept Wm^{-2}@ΔT=0	R^2
100<G<200	21.4	20.3	0.73
200<G<300	16.5	77.1	0.74
300<G<400	20.7	56.4	0.85
400<G<500	17.9	85.4	0.71
500<G<600	19.3	119.9	0.83
600<G<700	18.3	151.8	0.74
700<G<800	15.6	207.4	0.62
800<G<900	14.9	222.5	0.61

3.3. Volumetric flow rate of 50 to 55 $lh^{-1}m^{-2}$

Figure 7 shows the thermal performance of the PVT collector when the flow rate is further increased to the range between 50 and 55 $lh^{-1}m^{-2}$. In this case, the thermal output can reach values of around 450 W/m² for ΔTs as low as 8 K and high solar irradiance levels. Once again, if we look at a more likely 6 to 7 K temperature difference, we can see that the thermal power production is in the 150 – 350 W/m² range, or 3 to 7 kW for the full collector field.

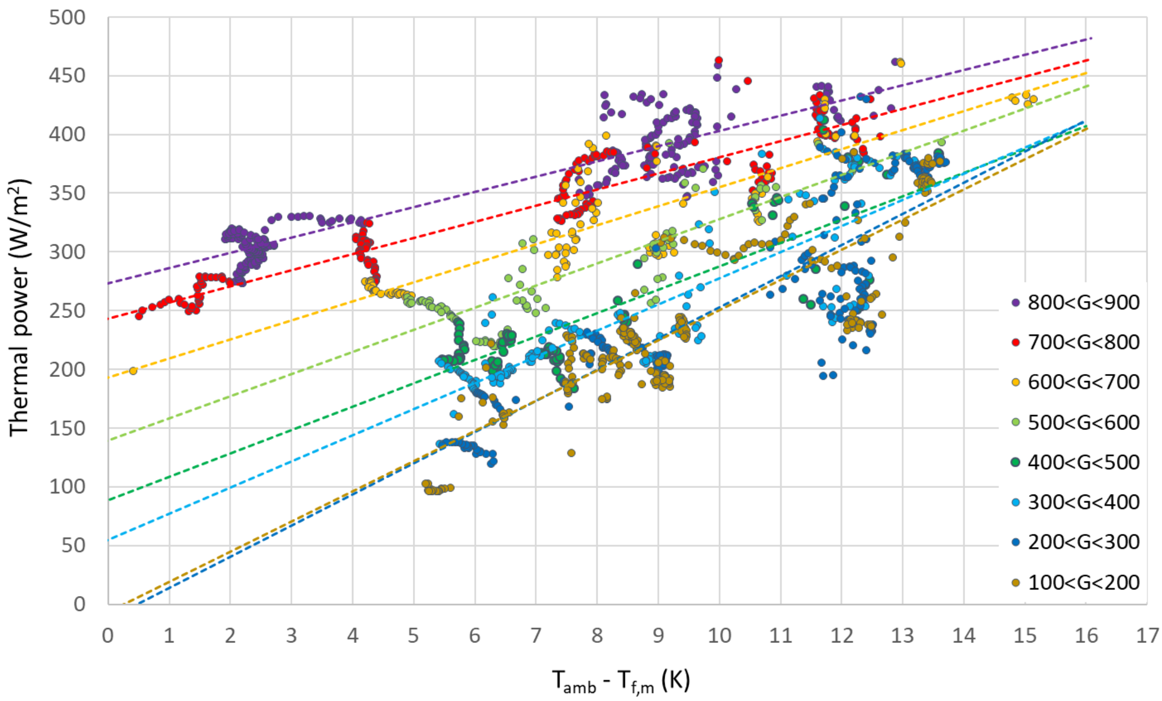

Figure 7. Specific thermal output of collector array as a function of $T_{amb} - T_{f,m}$ for different solar irradiance levels and flow rate of 50 to 55 $lh^{-1}m^{-2}$

An interesting observation when looking at the thermal performance curves is that they start to spread out for lower irradiance levels, but tend to converge as ΔT increases. This can be explained by the fact that the PVT collector has a limit on how much heat it can capture based on the flow rate and absorber geometry, so the curve tends to start flattening as we increase the temperature difference between ambient and mean fluid temperature. Another aspect to consider is that as the temperature difference increases, the relative importance of solar irradiance decreases within the overall heat transfer, meaning that convection will play a larger role. An important takeaway of this is that it seems to be convenient to work at higher flow rates at lower ΔTs, and lower flow rates at higher ΔTs.

The main parameters of the linear regression curves are presented in Table 4. As happened with the previous two cases, it can be seen that as the solar irradiance increases, the U-value decreases and the thermal output value for ΔT=0 increases. If compared with the 40 to 45 $lh^{-1}m^{-2}$ case, the slope of the curves are higher for lower solar irradiance levels and lower for higher solar irradiance levels. The same occurs with the specific thermal output at ΔT=0. Opposite to what happened with lower flow rates, the value of R^2 increase as solar irradiance increases and is higher than 70% for all cases.

Table 4. Main parameters of thermal performance curve for a flow rate of 50 to 55 $lh^{-1}m^{-2}$

	W/K	W@ΔT=0	R^2
100<G<200	25.7	-6.8	0.75
200<G<300	26.5	-12.5	0.73
300<G<400	22.3	55.0	0.72
400<G<500	19.9	89.0	0.72
500<G<600	18.8	139.4	0.75
600<G<700	16.1	193.5	0.77
700<G<800	13.7	243.5	0.89
800<G<900	13.0	273.1	0.87

3.4. No solar irradiance

Figure 8 shows the performance of the PVT collector for a solar irradiance level of 0 W/m^2, for different ΔTs and volumetric flow rates. It can be seen in the chart that when working exclusively as an air to water heat exchanger, the PVT collector can generate up to 250 W/m^2 for a ΔT of 10 K, and as high as 150 W/m^2 when ΔT is in the 6-7 K range. The latter means a total thermal energy production for the collector field of more than 3 kW.

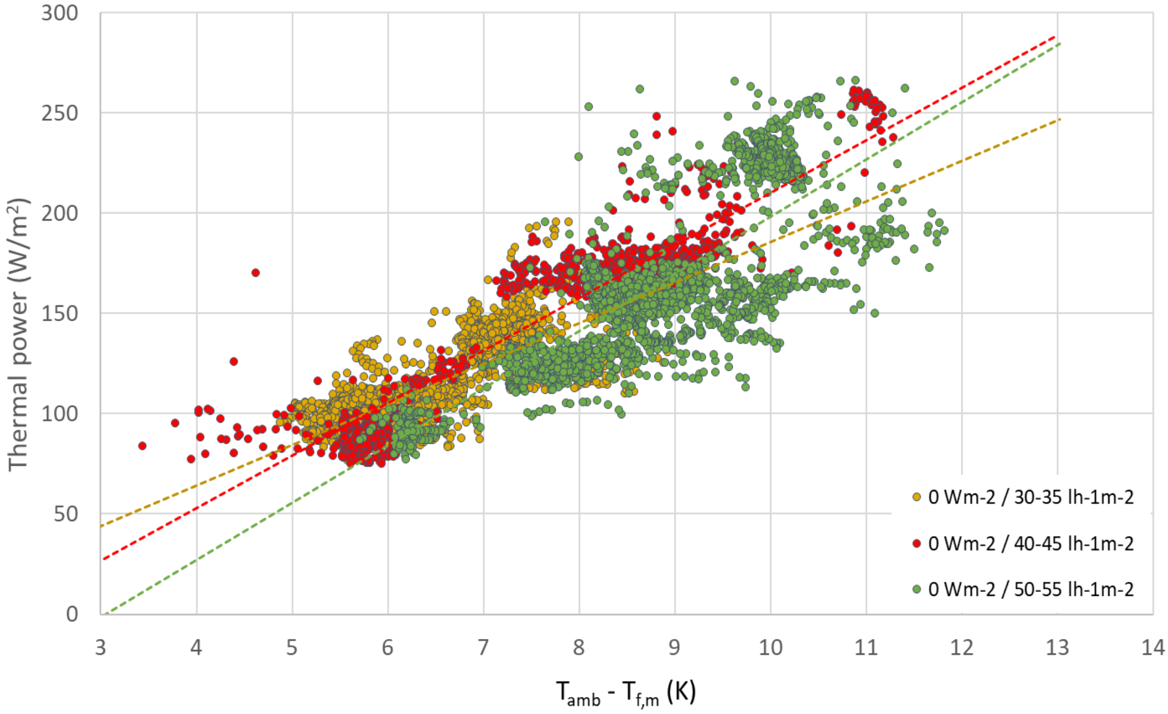

Figure 8. Specific thermal output of collector array as a function of $T_{amb} – T_{f,m}$ for solar irradiance levels of 0, 400 and 800 W/m^2 and varying flow rates

The main parameters of the thermal performance curves are presented in Table 5. It can be observed that the slope of the curve increases together with the flow rate. When looking at the thermal output at ΔT=0, it decreases with increasing flow rate. Finally, the coefficient of determination is higher than 60% for all cases, meaning that the linear regression curves are a good fit for the empirical data.

Table 5. Main parameters of thermal performance curve for solar irradiance 0 W/m^2 and varying flow rates

$lh^{-1}m^{-2}$	No solar irradiance		
	W/K	W@ΔT=0	R^2
30-35	20.3	-16.8	0.60
40-45	23.8	-32.2	0.80
50-55	28.5	-86.8	0.61

3.5. Time-series performance between 15th and 18th of October

Figure 9 shows the time-series specific thermal and electrical output of the 14 PVT collector array for 4 days between the 15th and 18th of October. The temperature difference between ambient and mean fluid temperature is also plotted. It can be seen that the thermal and electrical output are the highest for the 17th of October, which coincides with day with highest solar irradiation and temperature difference between T_{amb} and $T_{f,m}$.

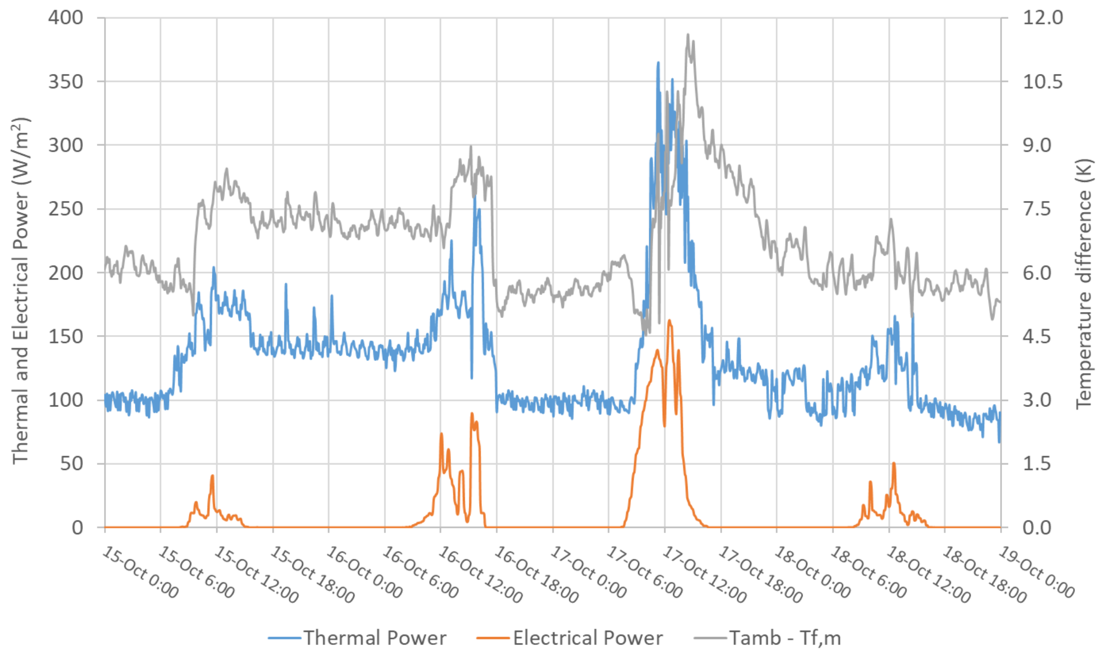

Figure 9. Time-series thermal and electrical performance of PVT collector field between 15th and 18th of October

Table 6 shows a summary with the total heat and electricity production for each day per m^2 of collector, together with the daily solar irradiation, average ambient temperature and average temperature difference between ambient and fluid. One of the main observations here is that the performance of an unglazed-uninsulated PVT collector with fins is more dependent on temperature difference with ambient than solar irradiation. For example, the total solar irradiation for the 16th of October is three times more than that of the 15th of October; however, the total heat production from the PVT collectors only experiences a 3.7% increase. This is because the average ΔT is practically the same, with a value close to 9°C. On the other hand, electrical power production is highly dependent on solar irradiance levels and very little on ambient and/or fluid temperature. For the day with the highest solar irradiation levels, the electricity production of the full array is 12.9 kWh, with a peak power of 3.2 kW. For the considered study period, the 20-m^2 PVT collector array generated a daily average of 64 kWh of heat and 5.2 kWh of electricity. This translates into a daily average solar efficiency of 370% for heat and 17.1% for electricity, which is near the rated efficiency for the PV module.

Table 6. Daily performance of PVT collector field and weather data

Day	Heat *(kWh/m²-day)*	Electricity *(kWh/m²-day)*	Solar Irradiation *(kWh/m²-day)*	Solar efficiency Heat	Solar efficiency Electricity	Ambient Temperature *(°C)*	Average T_{amb}-$T_{f,m}$ *(°C)*
15-Oct	3.25	0.07	0.46	707%	15.2%	11.94	8.88
16-Oct	3.37	0.23	1.30	259%	17.7%	12.06	8.98
17-Oct	3.58	0.64	3.31	108%	19.3%	10.68	9.36
18-Oct	2.51	0.10	0.62	405%	16.1%	7.92	7.29

4. Discussion

For this study, the U-value calculated as the slope of the thermal performance curve, is in the range of 13 to 19 $Wm^{-2}K^{-1}$ for high solar irradiance levels, which is on the upper range of what a typical unglazed and uninsulated PVT collector would have (Brötje et al., 2018). However, it is 40 to 60% lower than other PVT collectors specifically designed for heat pump integration that were found in the literature.

Most residential heat pumps in villas are in the range of 10-15 kW, and likely to have a COP of 2 when operating at peak capacity. Assuming those operating conditions, the PVT field should be able to supply between 5 and 7.5 kW at the evaporator, meaning a minimum of 250 W/m^2 with the 20-m^2 array presented. The results in this study show that during sunny days, this could be achieved by the 20-m^2 collector array when temperature difference between ambient and mean fluid temperature is higher than 3 or 4 K. However, when looking at nighttime performance, it would be required to have a ΔT higher than 10 K, which is unlikely to happen during low ambient temperatures when the heat pump needs to operate at maximum capacity due to temperature limits at the evaporator. Under those circumstances, a PVT array of at least double the size would be required to meet the heating needs.

With regards to the seasonal performance factor (SPF) of a solar PVT sourced heat pump system, previous simulation research by the authors showed that an SPF of 1.6 can be achieved for a typical multi-family house in Stockholm with a PVT collector area of 4.5 m^2 per kW_{th} of nominal heat pump power (Sommerfeldt et al., 2020). Although this is on the lower end of what would be expected for an air source heat pump system, several design improvements to enhance heat capture with the air were also demonstrated that could bring the SPF up to 2.6, making it competitive with an air source heat pump in Stockholm. This performance is corroborated by studies carried out in Germany, where Chhugani et al., (2020) found that an SPF of 3.3 can be achieved during the winter period in Hamelin, using a sheet and tube collector with fins with an area of 2.5 m^2/kW_{th}. Lämmle and Munz, (2022) showed that an SPF of up to 3.6 can be achieved when using double-finned micro-channel PVT collector, with a collector area as little as 3 $m^2/kW_{th.}$

Although the effect of wind velocity or direction was not considered in this study, it has been proven significantly lower for a collector array than for a stand-alone collector. Chhugani et al. (2021) found that the overall heat transfer coefficient of a 20-m^2 PVT array is around 20% lower than that of a single PVT collector, and the wind dependence of the heat loss coefficient is reduced by half.

The effects of condensation and frost formation were not considered either, which could enhance the thermal performance of the collectors. However, once an ice layer is formed, it decreases the thermal output of the collector. Chhugani et al. (2021), found a 15% reduction in measured against simulated thermal output when frost formation occurs, showing that ice formation hinders the heat exchange with ambient air considerably.

Even though the coefficient of determination for the different thermal performance curves was within an acceptable range for certain data sets, there was a large variance of the data around the linear regression curve. This can be explained by the previous two limitations in the study: the effect of wind velocity (even if not as high as for a stand-alone collector) and the effect of condensation and frost. Usually tests on PVT collectors are performed at indoor testing facilities with fixed solar irradiance, wind velocity, ambient temperature and humidity. In this case it was tested outdoors, so there was no control on the weather conditions. Another limitation is that instead of using fixed values of solar irradiance or flow rates, ranges are used, which can bring differences in the measured values. Besides, as can be seen from the weather data, most of the days were partially cloudy which adds another layer of uncertainty.

The coefficient of determination for all curves was between 60 and 90%, which is relatively weak for a regression model. However, it was not the aim of this study to present a regression model for PVT collectors, rather use it to help in the description of the data that was gathered. A widely accepted empirical model of unglazed and uninsulated PVT collectors already exists, where factors such as wind speed, radiation to sky and thermal capacity of the collector are considered and will be part of future work.

5. Conclusion

The performance of a 20-m^2 PVT collector array specifically designed for heat pump integration was tested under outdoor weather conditions for 16 days in October 2022, in Stockholm, Sweden. The results show that the specific thermal output of such collectors varies primarily with the difference between ambient temperature and mean fluid temperature. With a specific thermal output in the range of 100 and 250 W/m^2 when there is no solar irradiance, a standard villa-sized PVT array can act as an air to water heat exchanger producing between 2 kW and 5 kW of heat to use as a source for a heat pump. Looking at peak heat capture capacity, the 20 m^2 PVT field is expected to provide 9 kW peak on a sunny day, and 5 kW peak during nighttime.

The U-values found for this collector at high solar irradiances are in the range of 13 to 19 Wm^{-2}K^{-1}, which compared to other collectors found in the literature, shows that there is room for improvement in the design. The addition of more and thinner fins can improve these values to a level with state-of-the-art heat pump PVT collectors. However, this could lead to an increase in collector weight and manufacturing costs, which need to be considered in a detailed techno-economic analysis.

The presented 20 m^2 PVT field is likely to meet the demand at the evaporator of the heat pump working at full capacity during cold and sunny winter days, but at least double the size would be required to meet the demand at night. Alternatively, more fins would increase the U-value, but even still it is likely that a larger area would be necessary. This study does not analyze how PVT and HP work together to meet building loads, but it gives some perspective on the required area and temperature difference that is needed.

The period of study produced a wide range of boundary conditions, which capture a wide range of possible operating conditions. It is observed that as solar irradiance, flow rate and temperature difference increase, so does the specific thermal output of the collector. A maximum value of 450 W/m^2 is registered throughout the experiments, suggesting that the thermal output may be limited at around that number for this particular design.

Finally, the time-series performance of the PVT collector array was studied, where it was found that the daily electricity production for four days in October was 7.5% of the daily heat production. However, the percentage of electricity production during the summer and spring should increase thanks to more hours of available sunshine. Looking at the solar efficiency of the collector, the daily average for heat is around 370%, meaning that around 75% of the energy captured by the PVT collector throughout a day in October comes from the ambient air. The daily average for electrical efficiency is 17.1%, which is around the rated electrical efficiency of the PV module.

6. Future work

This study looks exclusively at the thermal and electrical performance of an uninsulated/unglazed PVT collector with extruded fins. Future work should expand the system boundaries by examining the empirical performance of the heat pump when using PVT as the source, as a way to understand how PVT collectors can improve COP and SPF of the heat pump for real operating conditions under Nordic climate conditions. Moreover, different collector designs should be evaluated for benchmarking and better understanding of the characteristics that make a collector suitable for heat pump integration. Condensation and frost formation were not considered in this study, but these phenomena are going to be the focus of future work, particularly strategies for defrosting. Finally, it would be interesting to look at the benefits of having a cold water storage tank between heat pump and PVT array. The heat production fluctuations that are experienced by the PVT with changes in solar irradiance levels, can put a lot of stress on the compressor, which can affect its lifetime. The addition of a cold storage tank would act as a buffer tank with a certain thermal inertia, which would keep the heat flux to the evaporator at a constant rate.

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