How does the thermal characteristics of PVT panels influence the performance of PVT heat pump systems

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Abstract

The effect of the thermal efficiency of hybrid photovoltaic – thermal (PVT) collectors was evaluated in system simulations where PVT collectors were used as source for a heat pump. The demand represented space heating and domestic hot water usage for a single-family house located in Denmark. With the presented system and demands it turned out that the value for the optical performance of the thermal absorber for the PVT collector had only marginal effect on the overall yearly system performance. An increase of the heat loss coefficient from 14.5 W m^{-2} K^{-1} to 58 W m^{-2} K^{-1} resulted in 1.7% higher electricity production of the solar cells due to lower PVT collector temperatures and 2% less electricity purchased from the grid due to higher COP in the heat pump caused by higher inlet temperatures to the heat pump in periods without solar radiation. The main effect of varying the different thermal characteristics was the minimum temperatures in the PVT collectors, which affect the heat pump performance and COP. The largest risk is that the brine temperature at the inlet to the heat pump will drop below the limits of the heat pump causing it to switch off and run only on direct electrical heating.

Keywords: : PVT assisted heat pump, system performance, thermal efficiency, Polysun simulation.

1. Introduction

Hybrid photovoltaic – thermal (PVT) collectors can be used as source for liquid/liquid heat pumps in heating systems in buildings (Dannemand et al., 2017). Benefits of using PVT collectors as the source for the heat pump include potential synergistic effect of combining PV and thermal collectors, better usage of limited roof space, potentially increased electrical output of solar cells due to cooling, avoiding noise from a ventilator in an air to water heat pump system, lower installation cost compared the ground sourced heat pumps, high heat pump efficiency without a soil based loop and better esthetics (Dannemand et al., 2020a).

The desired characteristics of the PVT collectors, when used as a source for the heat pump, will be different compared to the desired characteristics of traditional solar thermal (PVT) collectors where high efficiency and high temperatures are beneficial. When the PVT collector is the main source of the heat pump, it will operate in periods without solar radiation e.g. during night time to cover the heat demand (Dannemand et al., 2017). Therefore, insulation and front glass covers are no go in order to extract as much heat from the surrounding ambient air as possible when the sun does not shine. The mean collector temperature will be below the ambient air temperature during periods without significant solar irradiance e.g. at night. In this case the optical efficiency is less relevant and the "heat loss coefficient" from the collector efficiency expression will be the most influential parameter governing the heat gain to the collector.

As with all heating systems, low-cost components and systems are desired (Sifnaios et al., 2021). Potentially simple, less efficient collectors, produced at lower cost, can work well as source for heat pumps (Dannemand et al., 2020b)

Utilization of PVT panels in systems for heating with or without heat pumps has been the focus of the IEA SHC task 60 in the years 2018 to 2020 (Hadorn, n.d.).

2. Aim and scope

Current research aims to elucidate how the thermal characteristics, optical efficiency and heat loss coefficient,

10.18086/eurosun.2024.07.15 Available at http://proceedings.ises.org

of a PVT collector will affect the yearly performance of a PVT heat pump system. Further, the relation between the PVT collector area and the thermal performance is elucidated. Apart from the thermal performance, emphasis is placed on the temperatures in the PVT collectors because some liquid-liquid heat pumps have a relatively narrow allowed temperature span for inlet to the evaporator which may cause the heat pump to go to fail mode and run on direct electricity when the inlet temperature drops below a limit.

3. Method

The simulation software Polysun was used to perform parameter variations for optical efficiency and heat loss coefficient in a PVT assisted heat pump system. The performance evaluation was based on the yearly values of how much electricity was produced and how much was purchased from the grid. Besides the electrical consumption over the year, the temperature in the PVT collectors was evaluated in order to assess if the inlet temperature of the brine to the heat pump exceeded the limit of the heat pump.

The simulated demands of the building were 10.000 kWh per year for space heating, 2600 kWh for domestic hot water and 3500 kWh for electrical appliances. Weather data for Copenhagen, Denmark was used. The characteristics of a “Delta” heat pump from the manufacturer Metro Therm was applied. This heat pump has been developed with PVT collectors in mind to allow for a temperature range of the brine from -15 ºC to 50 ºC. The Delta heat pump has a nominal capacity of 4.7 kW and is suitable for smaller houses. Fig. 1 shows the schematics of the PVT heat pump system.

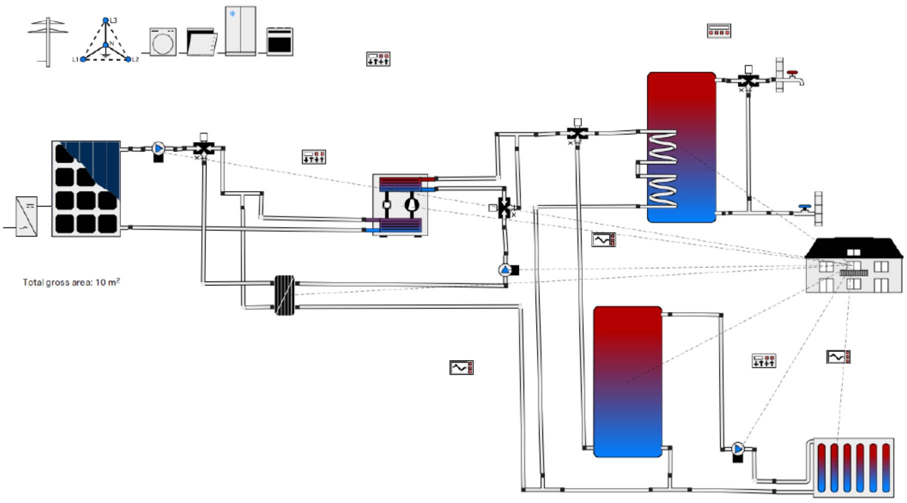

Fig. 1: Schematic of PVT heat pump system in Polysun.

The system had buffer tanks of 100 liters for domestic hot water and in the space heating loop. A 10 m^2 PVT collector area was used for the simulation in the reference model. The panels are facing south with a tilt of 45°.

The PVT collector model in Polysun does not account for condensation on the collector surface and possible ice formation on the collector when brine fluid is below 0 ºC, therefore this effect is not considered in the analysis. Eq.1 shows the collector efficiency expression based on the ISO 9806 standard terminology where only the coefficients that are used in Polysun are included.

$$\dot{Q} = A_G \left[\eta_{0,b} K_b(\Theta_L, \Theta_T) G_b - a_1(\vartheta_m - \vartheta_a) - a_3 u\,(\vartheta_m - \vartheta_a) + a_4(E_L - \sigma T_m^4) - a_5\left(\frac{d\vartheta_m}{dt}\right) - a_6 u G - a_7 u (E_L - \sigma T_m^4)\right] \quad \text{(eq. 1)}$$

In Polysun other terminology for the coefficients is used as shows in Tab. 1.

Tab. 1 shows the applied characteristics of the PVT panel in the reference model and for the variations. The characteristic of the reference panel represents an uninsulated PVT collector or PVT WISC. The effects of the optical efficiency Eta0 and the heat loss coefficient b1/b3 were evaluated separately in the parameter analysis.

Tab. 1: Reference and variations for PVT collector characteristics for parameter variation.

Thermal efficiency coefficient		Unit	Reference value	Variation 1	Variation 2	Variation 3
ISO 9806	**Polysun**					
$\eta 0$	Eta0 (turbulent)	-	0.55	0.33	0.77	-
a1	b1	$W\ m^{-2}\ K^{-1}$	14.5	7.25	29	58
a3	b2	$W\ s\ m^{-3}\ K^{-1}$	4.5	2.25	9	18

The PV STC nominal efficiency was 0.21.

PVT collector area variations between 5 m^2 and 40 m^2 were used.

4. Results

4.1. Optical efficiency

Increasing Eta0 from 0.55 to 0.77 resulted in 2.2 % (45 kWh) less electricity production; 0.5 % (50 kWh) higher thermal energy to the system and 0.5% (26 kWh) more electricity purchased from the grid.
Reducing Eta0 from 0.55 to 0.33 resulted in 1.1% (21 kWh) higher electricity production; 0.5% (48 kWh) less thermal energy to the system and 0.1 % (7 kWh) less electricity purchased from the grid. Fig 2 shows the energy amounts as functions of Eta0.

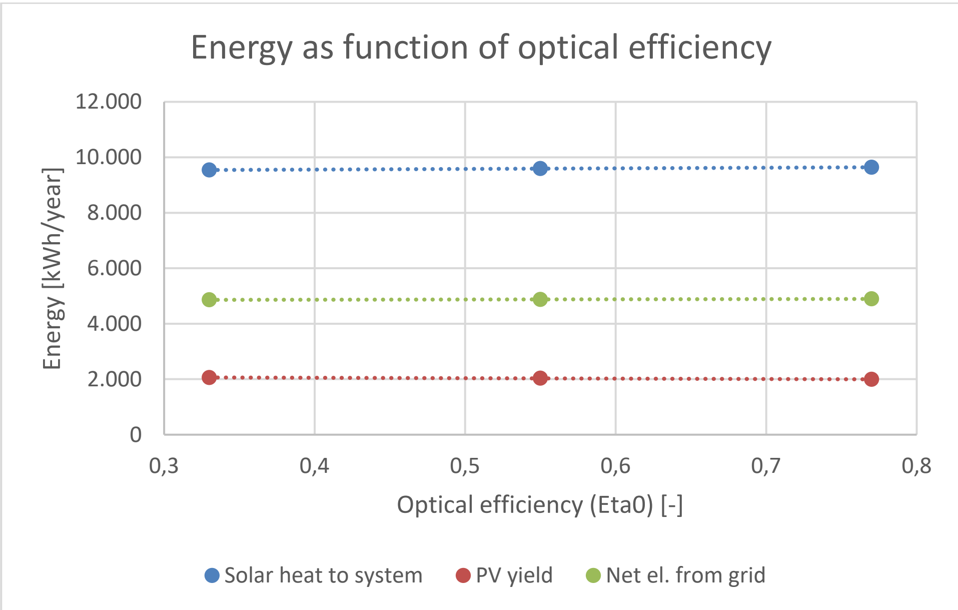

Fig. 2: Energy as a function of optical efficiency.

Fig **3** shows the simulated PVT collector temperatures. It can be seen that the minimum temperature is not affected by Eta0 but the maximum temperature is dependent on Eta0 especially in the summer months. Eta0 of 0.77 resulted in a maximum temperature in the PVT panel exceeding 50 ºC, which is the limit for the heat pump considered in these simulations.

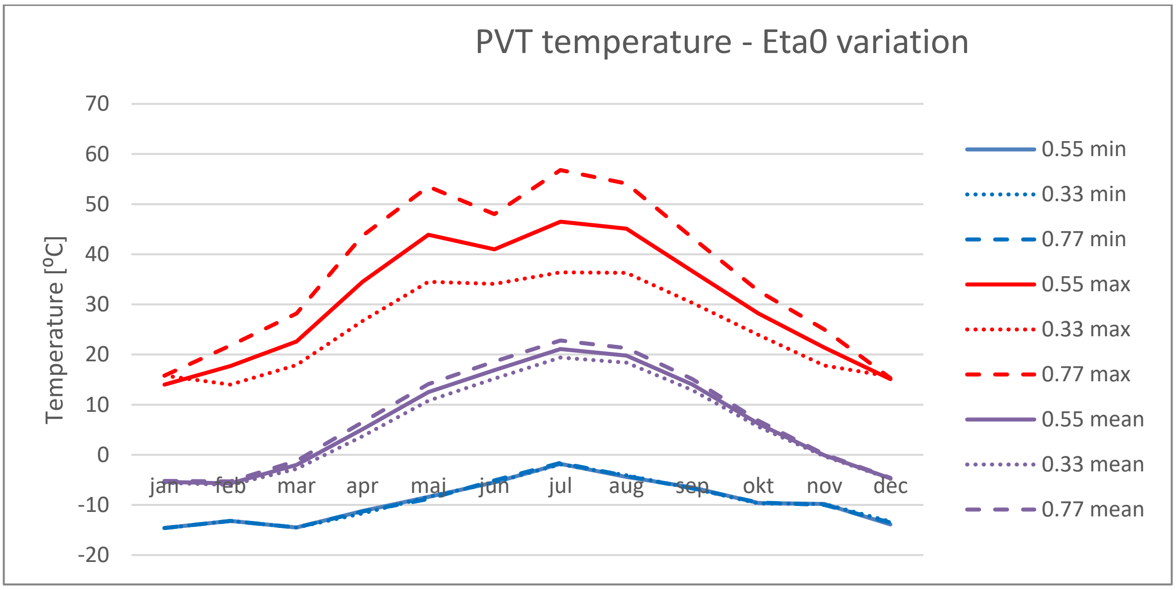

Fig. 3: Minimum and maximum temperatures in the PVT collector for different optical efficiencies.

4.2. Heat loss coefficient

Increasing the heat loss coefficient A1 from 14.5 W m^{-2} K^{-1} to 58 W m^{-2} K^{-1} resulted in 6 % (576 kWh) higher thermal energy to the system, due to better performance in periods without solar radiation; 1.7 % (35 kWh) higher electricity production of the solar cells due to lower panel temperature and 2 % (110 kWh) less electricity was purchased from the grid. Fig 4 shows the energy amounts for different heat loss coefficients.

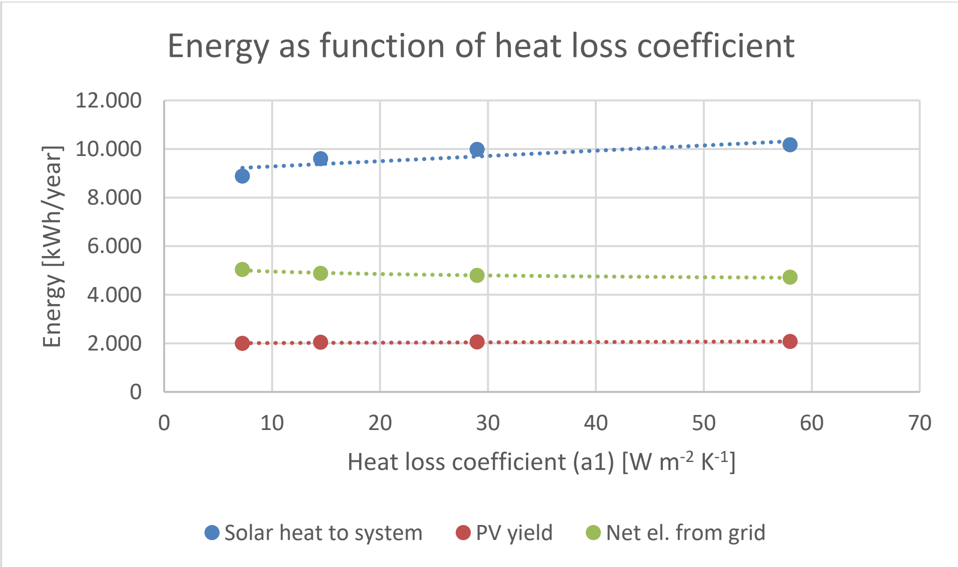

Fig. 4: Energy as function of heat loss coefficient.

Fig. 5 shows the minimum, mean and maximum temperatures in the PVT collector for various heat loss coefficients during operation over the year. It indicates that a low heat loss coefficient may increase maximum temperatures and reduce minimum temperatures exceeding the limits of the heat pump.

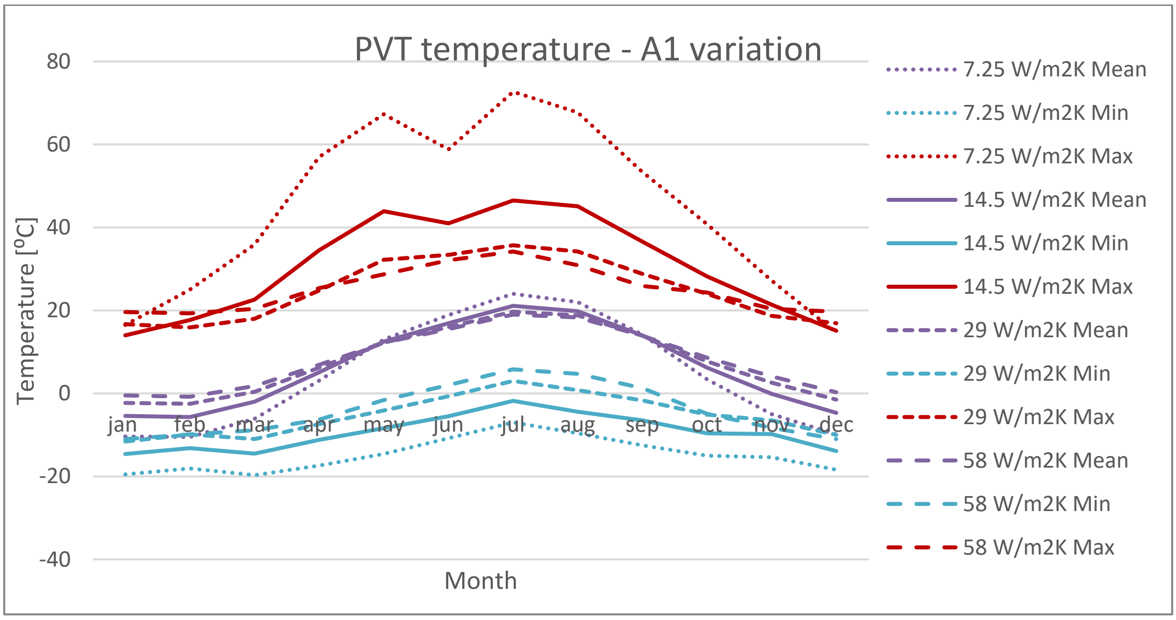

Fig. 5: Minimum and maximum temperatures in the PVT collector for different heat loss coefficients.

Considering the yearly thermal performance, it is desired to have a low optical efficiency and high heat loss coefficient, quite the opposite of what is desired for a traditional solar heating system.

4.3. Collector area

Fig. 6 shows the net purchased electricity from the grid over the year as a 2function of the PVT panel area. With approximately 29 m^2 PVT, the purchased and sold electricity to and from the grid balances out over the year, however, in this scenario, a majority of the needed electricity in the winter period is purchased from the grid and a large amount of PV generated electricity is sold to the grid in the summer period. The optimal PVT collector area depends on the electricity price and the feed in tariffs. With the current prices the economically optimal PVT area is likely a smaller PVT area due to very low feed in tariffs.

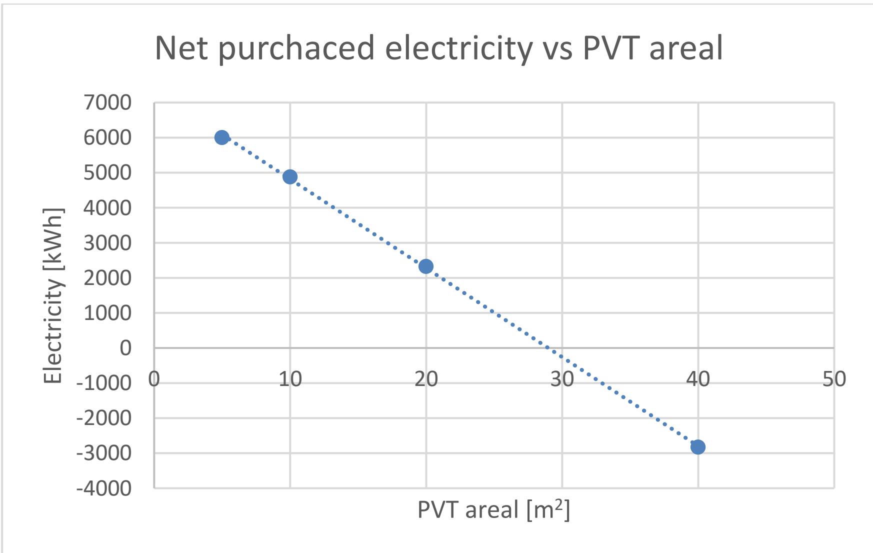

Fig. 6: Net purchased electricity from the grid as function of PVT collector area.

Comparing the PVT collector temperatures in systems with different PVT collector areas showed that the maximum temperature in the PVT array was not affected by the collector area. The mean and minimum temperatures were however highly affected by the PVT collector area. This indicates that for a given heat demand and a given heat pump there is a minimum collector area which is required to avoid that the minimum limit of the brine will be reached for the heat pump. Fig. 7 shows the minimum, mean and maximum temperatures in the PVT collectors for different collector areas.

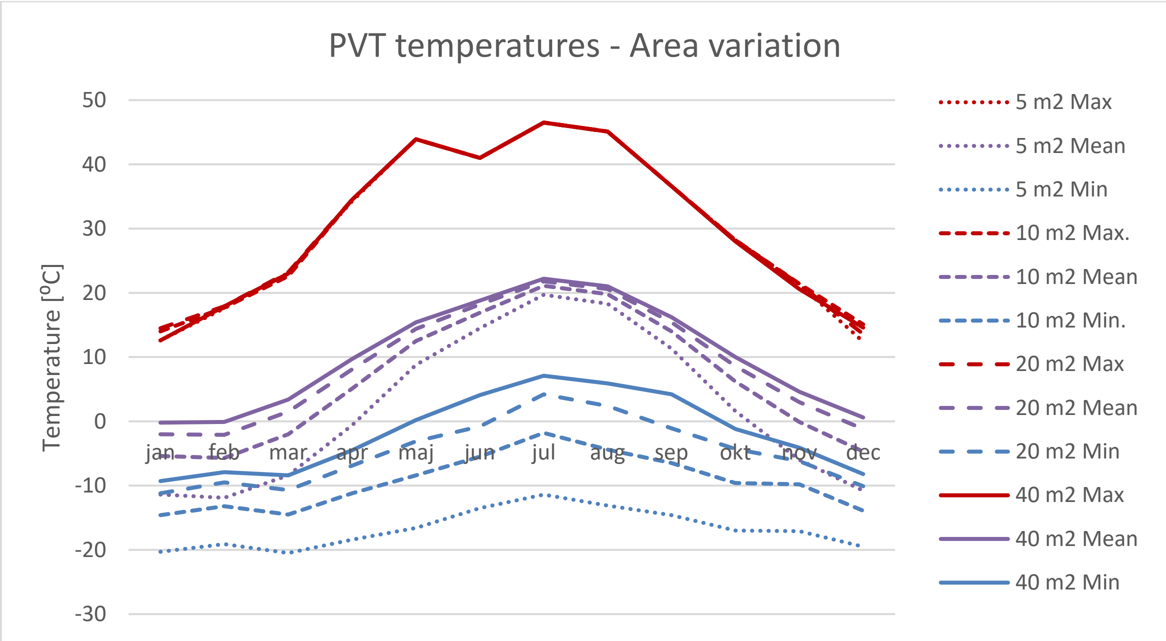

Fig. 7: Minimum, mean and maximum temperatures in the PVT collector for different collector areas.

Fig. 8 shows a comparison of PVT collector temperatures of the reference 10 m² PVT system compared to a 5 m^2 array with double heat loss coefficient. It shows that with a higher heat loss coefficient even a 5 m² PVT area may be sufficient as source for the heat pump and will not exceed the lower limit of the heat pump.

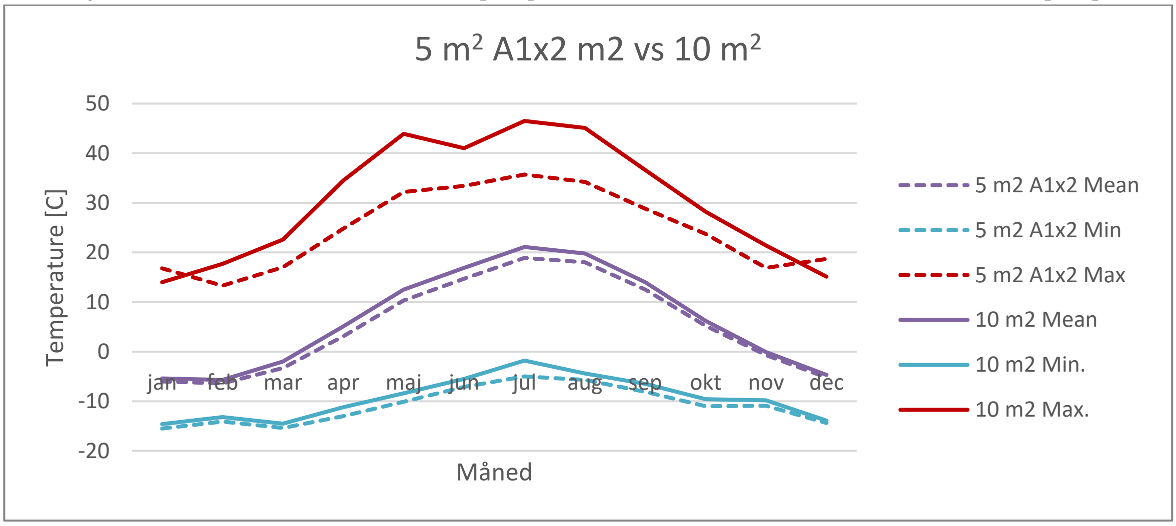

Fig. 8: Minimum, mean and maximum temperatures in the PVT collector for the reference 10 m2 array and 5 m2 with double heat loss coefficient.

5. Conclusions

The investigations showed that varying the optical efficiency of the thermal characteristics only had a minor effect on the yearly performance of the system. The heat loss coefficient had slightly more impact on the system performance. It turned out that the heat loss coefficient to some extent affected the temperature in the PVT panels and a large heat loss coefficient resulted in lower panel temperatures in summer, which improved electricity output slightly. During the winter period, large heat loss coefficients resulted in higher inlet temperatures to the heat pump. With a low heat loss coefficient, the collector outlet temperature reached -20 ºC in some periods, which was beyond the limits of the heat pump.

It can be concluded that for PVT heat pump systems, high heat loss coefficient will slightly improve the yearly performance and reduce the maximum temperature in the panel in summer and increase the minimum temperature in the panel in winter, which will give better operating conditions for the heat pump and potentially allow for heat pumps with a more narrow allowed temperature range to be integrated with PVT panels.

Ice formation and condensation on the PVT panels was not considered in this analysis. Investigations regarding the effect of condensation and ice formation on the thermal and electrical performance are recommended.

6. Acknowledgments

Thie research projects “integrated Triple energy Building elements”, “IEA Task 66 Subtask C ledelse” and “EUDP 2020-I IEA Solar Energy Buildings” were funded by the Danish Energy Agency through the EUDP program grant no: 64022-1036, 134-21020 and 64020-1071. We thank our partners in Racell for the collaboration.

7. Nomenclature and symbols

Quantity	Symbol	Unit
Gross area of collector	A_G	m^2
Heat loss coefficient	α_1	$W\ m^{-2}\ K^{-1}$
Wind speed dependence of heat loss coefficient	α_3	$J\ m^{-3}\ K^{-1}$
Sky temperature dependence of heat loss coefficient	α_4	-
Effective thermal capacity	α_5	$J\ m^{-2}\ K^{-1}$
Wind speed dependence of peak collector efficiency	α_6	$m^{-1}\ s$
Wind speed dependence of infrared radiation exchange	α_7	$W\ m^{-2}\ K^{-4}$
Heat loss coefficient (polysun)	b1	$W\ m^{-2}\ K^{-1}$
Wind speed dependence of heat loss coefficient (polysun)	b2	$J\ m^{-3}\ K^{-1}$
Stefan- Boltzmann constant	σ	$W\ m^{-2}\ K^{-4}$
Longwave irradiance	E_L	$W\ m^{-2}$
Hemispherical solar irradiance	G	$W\ m^{-2}$
Global solar irradiance at the collector plane	G_t	$W\ m^{-2}$
Beam irradiance	G_b	$W\ m^{-2}$
Diffuse irradiance	G_d	$W\ m^{-2}$
Incidence angle modifier for diffuse solar radiation	K_d	-
Incidence angle modifier for direct solar irradiance	K_b	-
Incidence angle modifier	K_ϑ	-
Incidence angle modifier coefficient	b_0	-
Air speed	u	$m\ s^{-1}$
Peak collector efficiency based on G_b	$\eta_{0,b}$	-
Mean temperature of heat transfer fluid	ϑ_m	ºC
Ambient air temperature	ϑ_α	ºC
Incidence angle	θ_i	°
Transversal angle of incidence	θ_T	°

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