Performance of Heat Pump Systems with PVT Collectors with optimized Finned Heat Exchangers integrated as single Heat Source

Manuel Lämmle[1,2] and Gunther Munz[1]

[1] Fraunhofer Institute for Solar Energy Systems ISE, 79110 Freiburg (Germany)

[2] INATECH - Albert-Ludwigs Universität Freiburg, 79108 Freiburg (Germany)

Abstract

Novel photovoltaic-thermal PVT collectors with an optimized finned heat exchanger were designed, built and tested. The test results indicate an excellent convective heat transfer coefficient for the air-to-water heat exchange. The system performance is evaluated by simulation of a heat pump system, where PVT collectors are integrated as the only heat source to the evaporator. Due to the operating temperatures below ambient, the PVT collector harvests both ambient and solar heat and therefore can be considered as a solar air-to-water heat exchanger. The PVT heat pump system achieves a good overall system performance, depending on the PVT area and type of heat exchanger construction. The novel double-finned multichannel heat exchanger achieves a seasonal performance factor of SPF of 3.6 with a relatively small PVT collector area of 3 m^2/kW_{th} and thus consumes 9 % less electricity than a PV-coupled air source heat pump system.

Keywords: Photovoltaic-thermal collectors; heat pump systems; renewable heating; solar heating

1. Introduction

In recent years, photovoltaic-thermal PVT collectors received increasing interests, as these hybrid systems combine the solar generation of heat and electricity in a single component. Different design and types of PVT collectors emerged, which can be classified according to their suitable temperature range (Lämmle et al. 2020).

A promising system design concerns the combination of heat pumps, where PVT collectors comprise the only heat source. The operating conditions of solar thermal collectors integrated as heat source in heat pump systems differ substantially from the conventional operating conditions of solar collectors for hot water preparation. Fluid temperatures near and below ambient air temperatures occur frequently, particularly during the heating season in winter. As a consequence, collector and system must be ideally designed in such a way, that sufficient low temperature heat is supplied to the heat source also during cold winter days without sunlight.

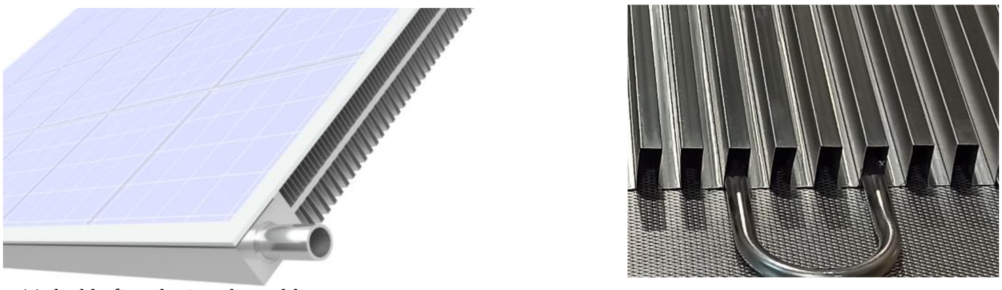
2. Design of optimized PVT collectors with finned heat exchanger

Two innovative PVT collectors were designed, built, and tested, which are optimized towards an enhanced air-to-water heat exchangers on the backside of the PV module (Figure 1). To increase the surface area usable for heat exchange, finned aluminum heat exchangers are used:

- Collector 1 uses a microchannel absorber with a double finned heat exchanger which is glued to a PV module with a gross area of 1.98 m² and a rated electrical efficiency of η_{STC} = 17 %. The fins on both sides of the microchannel absorber utilize solar heat from the PV module as well as heat from the environment.
- Collector 2 uses a finned sheet-and-tube absorber design. A perforated aluminum sheet is glued to the backside of a commercial glass-glass PV module with a gross area of 1.61 m² and a rated electrical efficiency of η_{STC} = 17 % ((Munz et al. 2022).

Both collector design differ in their specific construction, but both aim at making use of solar energy via a good conversion factor $\eta_{th,hem}$ and aim at increasing convective heat transfer of via an increased UA-value (a_1 and a_3). The latter comprises a considerable difference to conventional, insulated solar thermal collectors, which aim at reducing their convective heat loss coefficients.

doi:10.18086/eurosun.2022.07.06 Available at http://proceedings.ises.org



(a) double finned microchannel heat exchanger

(b) finned sheet and tube heat exchanger (SOLAB GmbH)

Figure 1: Design of the optimized PVT collectors

3. Performance of optimized PVT collectors with finned heat exchangers

The collectors underwent standardized performance characterization tests, carried out at the TestLab Solar Thermal Systems at Fraunhofer ISE (Figure 2).

Figure 2: Collectors during outdoor (microchannel heat exchanger) and indoor (finned sheet-and-tube heat exchanger) performance testing

Table 1 reports the test results of characterizing the thermal performance of the PVT collector following the collector equation of WISC collectors according to ISO 9806:2017:

$$\dot{Q} = A_G \left[\begin{array}{l} \eta_{0,\mathrm{hem}} G_{\mathrm{hem}} - a_1 (\vartheta_m - \vartheta_a) - a_2 (\vartheta_m - \vartheta_a)^2 - a_3 u' (\vartheta_m - \vartheta_a) + \\ a_4 \left(E_L - \sigma T_a^4 \right) - a_6 u' G_{\mathrm{hem}} - a_7 u' \left(E_L - \sigma T_a^4 \right) - a_8 (\vartheta_m - \vartheta_a)^4 \end{array} \right] \quad \text{(Eq. 1)}$$

Mind that the new standard ISO 9806:2017 reports the coefficients a_3 and a_6 as a function of the reduced wind speed u' = u-3m/s. Comparing performance parameters with measurements according to older standards therefore requires a conversion of the parameters from u to u'.

Performance tests of the PVT collector with double-finned microchannel HX were carried out under quasi-dynamic outdoor testing conditions in hybrid PVT mode of simultaneous thermal and electrical power conversion. The heat output strongly depends on convective heat transfer and wind speed u’ as can be seen at the high value of a_3. In general, a very high value of a_1=71.1 W/m²K is achieved, which indicates the high heat transfer capacity UA of the finned heat exchanger.

Performance tests of the PVT collector with finned sheet-and-tube HX were carried out under steady-state indoor testing conditions, also in hybrid PVT mode of simultaneous thermal and electrical power conversion. The solar conversion is improved considerably, compared to the double-finned microchannel HX due to a better thermal coupling of PV cells and fluid. Yet, the convective heat transfer, as indicated by a_1 and a_3 is smaller than in the double-finned microchannel HX.

The different test procedures were selected due to the different season during which the tests were carried out. Both test procedures can be applied interchangeably and achieve similar results. However, the steady-state indoor method does not provide performance values for the thermal capacity a_5 and the optical incidence angle modifiers.

	$\eta_{0,hem}$	a_1	a_2	a_3	a_4	a_5	a_6	b_0	K_d	A_G
	[-]	[W/m²K]	[W/m²K²]	[Ws/(m³K)]	[Ws/(m³K)]	[J/(m²K)]	[s/m]	[-]	[-]	[m²]
Double-finned microchannel HX	0.3747	71.1	0	16.7	0	41668	0.05	0.18	1.014	1.98
Finned sheet-and-tube HX	0.528	25.7	0	3.372	0.528	-	0.031	-	-	1.61
PVT products according to their Solar Keymark Data sheets										
Finned sheet-and-tube HX	0.137	84.35	0	22.03	0.44	41580	0.111	0	1	1.98
Non-insulated PVT collector	0.425	19.65	0	1.85	0	20800	0.018	0.2	0.88	1.88
Insulated PVT collector	0.543	8.95	0	0.783	0.45	47777	0.039	0.05	0.84	1.88

Table 1: Performance data of the optimized PVT collectors with finned heat exchangers compared to commercial PVT products according to their Solar Keymark Data sheets (CEN 2022).

The performance data of commercial PVT products, all unglazed WISC PVT collectors, are included for reference purposes. The commercial finned sheet-and-tube PVT collector (Leibfried et al. 2019) achieves excellent values of a_1 and a_3. The effect of fins to increase the overall UA-value can be assessed qualitatively by comparing the a_1 and a_3 values with the non-insulated and insulated PVT collectors without fins. Hereby, it is important to keep in mind that all performance coefficients a_1 – a_6 are obtained from multi-linear regression. Therefore, there is a high likelihood that these parameters are cross-corelated, which is why they should not be interpreted singularly.

4. Performance of single-source PVT heat pump systems

To assess the performance of PVT collectors integrated as single low temperature heat source to the heat pump's evaporator, we modelled a thermo-hydraulic system in Dymola/Modelica, including PVT collector, heat pump, electrical back-up heater, hot water storage and corresponding system control. Figure 2 shows a simplified hydraulic sketch of the PVT heat pump system. The considered building with its demand profiles and supply temperatures represents an existing multi-family building with a retrofitted PVT heat pump system. The heat pump and building model are described in Lämmle et al. 2022, yet nominal supply and return temperatures for space heating of 40/35°C, corresponding to a radiant floor heating system are used.

The thermal output of the PVT collectors are calculated based on the standardized, dynamic performance model in (ISO 9806 2017). Field tests of collector 2 showed, however, that the performance model is only partially applicable for sub-ambient temperatures (Munz et al. 2022). Chhugani et al. 2020 found a similar deviation between solar keymark test parameters and parameters identified from field tests. Therefore, the performance model is mostly valid for the solar operation mode with fluid temperatures above ambient, and the simulation results should be primarily used for comparing the different PVT technologies.

To ensure a resilient operation of the PVT system throughout the year, an electrical resistance heater is integrated in the primary heat pump loop. It supports the PVT collector when brine temperature drops below the minimum evaporator temperature of -10°C.

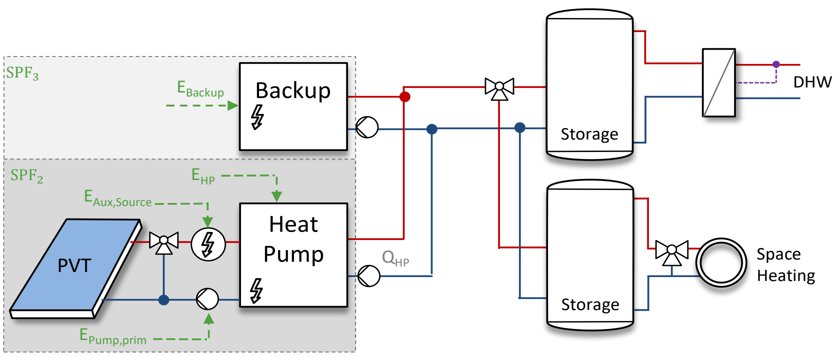


Figure 3: Hydraulic layout of thermo-hydraulic heat pump system model

The seasonal performance factor of the heat pump system SPF_2 is evaluated as the key performance indicator to consistently compare different types of heat pump systems (PVT-source, air-source and ground-sources). The following definition for SPF_2 based on Zottl et al. 2012 considers the system boundaries as shown in Figure 3 and includes the electricity consumption of the heat pump E_{HP}, auxiliary heater in the brine loop $E_{Aux,Source}$ and primary pump $E_{Pump,prim}$:

$$SPF_2 = \frac{Q_{HP}}{E_{HP} + E_{AuxSource} + E_{Pump,prim}} \quad \text{(Eq. 2)}$$

The seasonal performance factor of the heat pump system SPF_3 additionally considers the electricity and heat supplied by the backup heater. In our case, the backup heat is supplied by an electrical resistance heater with an assumed ideal efficiency of 100%.

$$SPF_3 = \frac{Q_{HP} + Q_{Backup}}{E_{HP} + E_{AuxSource} + E_{Pump,prim} + E_{Backup}} \quad \text{(Eq. 2)}$$

The total heat gain and the system performance depends significantly on the size of the PVT collector array: the larger the area of the PVT collectors, the higher are the evaporator temperatures and the higher is the efficiency. Therefore, the size of the PVT collector array is varied, with relative values of 1 – 5 m² of collector area per kW_{th} of the nominal heat output of the heat pump.

Figure 3 also includes the evaluated SPF of a reference air-source ($SPF_2 = 3.3$) and a ground-source heat pump system ($SPF_2 = 4.2$). The PVT heat pump system with double-finned microchannel HX achieves the SPF of an air-source heat pump at a relative area below 2 m² per kW_{th} of nominal heat pump power. With a larger area of the PVT collector, the SPF increases further with a maximum $SPF_2 = 3.7$. At a relative area of 3m²/kW_{th} the PVT heat pump system achieves an $SPF_2 = 3.6$ and thus consumes 9 % less electricity than the air-source heat pump system.

The heat pump system with finned sheet-and-tube PVT heat exchangers achieves a lower heat output and therefore a lower $SPF_2 = 3.1$ at a relative area of 3 m²/kW_{th}. Consequently, this system consumes 5 % more electricity than the air-source heat pump system.

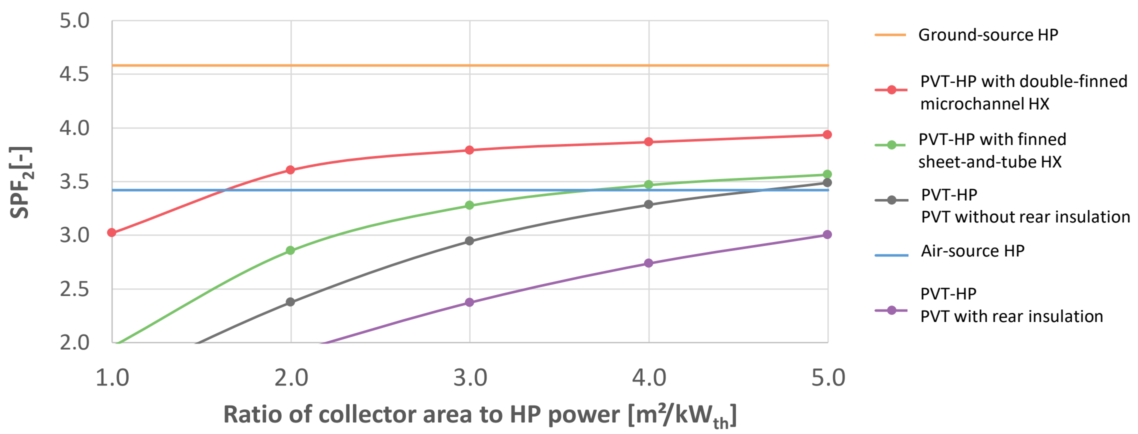


Figure 4: Seasonal performance factor SPF_2 of a PVT heat pump compared to reference air and ground source heat pumps.

The following figure plots the curves of the seasonal performance factor SPF_3 of the heat pump system, including the contribution from the backup unit. Due to the additional electricity requirement, the SPF_3 of all systems drop slightly by 0.1 – 0.2 points.

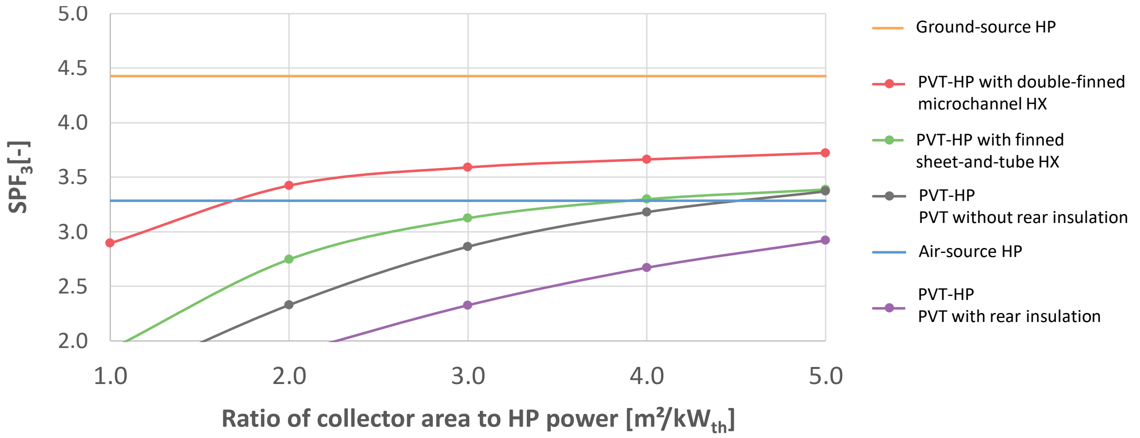


Figure 5: Seasonal performance factor SPF_3 of a PVT heat pump system compared to reference air and ground source systems.

5. Summary and conclusion

Due to the nature of integrating PVT collectors into heat pump systems, these collectors operate most frequently below ambient temperatures at $\Delta T = T_m - T_{amb} < 0$. As these collectors harvest both solar and ambient heat, this type of PVT collector should be considered as a solar air-to-water heat exchanger instead of a pure solar thermal collector. These considerations result in a new design options: the optimization of convective heat gains is of particular importance during nighttime operation or in winter when irradiation levels are low. Solar gains play a secondary role in integration as the single heat source.

Two novel types of PVT collectors were designed, built and tested. The first design features a double-finned multi-channel heat exchanger. The second design integrates a smaller fin construction added to an aluminum sheet-and-tube PVT absorber. Performance measurements indicate increased U-values for enhanced convective heat gains for both collectors.

System simulations of both PVT collectors integrated as the single source to a heat pump system demonstrate the capability of this system type. The finned heat exchanger achieves a seasonal performance factor in the order of magnitude between air and brine heat pumps. Next to the collector design, the area of the PVT collector array plays a central role. With a relative collector area of 3 m² per kW_{th} of heat pump power, the double-finned microchannel PVT collector achieves an SPF_2 of 3.6 and thus consumes 9 % less electricity than an air-source heat pump system. The finned sheet-and-tube PVT collector achieves slightly lower efficiency and requires 4 m^2/kW_{th} to achieve the same performance as an air-source heat pump system.

Condensation and frosting are not considered in the simulations yet. On the one hand, the condensation and frosting enthalpy is utilized thermally. On the other hand, icing of the surface of the PV module can reduce electrical power output of the PVT collector. Secondly, icing of the rear side heat exchanger may reduce the heat transfer capability temporarily, which may require defrosting of the PVT array. Both effects should be subject to further research.

6. Acknowledgements

We gratefully acknowledge financial support of the German Federal Ministry for Economic Affairs and Climate Action (BMWK) due to an enactment of the German Bundestag under grant number 03ETW011A. We would like to thank all project partners Solab GmbH and Solvis GmbH for the fruitful cooperation.

7. References

CEN (2022): Solar Keymark Database. The Solar Keymark CEN Keymark Scheme. https://solarkeymark.eu/database/. Brussels.

Chhugani, Bharat; Pärisch, Peter; Kirchner, M.; Littwin, Matthias; Lampe, Carsten; Giovannetti, F. (2020): Model Validation and Performance Assessment of Unglazed Photovoltaic-Thermal Collectors with Heat Pump Systems. In *EuroSun 2020: 13th International Conference on Solar Energy for Buildings and Industry - Proceedings*, pp. 1–12. DOI: 10.18086/eurosun.2020.05.13.

ISO 9806 (2017): ISO 9806:2017 Solar energy - Solar thermal collectors - Test methods, checked on 2017-09.

Lämmle, Manuel; Bongs, Constanze; Wapler, Jeannette; Günther, Danny; Hess, Stefan; Kropp, Michael; Herkel, Sebastian (2022): Performance of air and ground source heat pumps retrofitted to radiator heating systems and measures to reduce space heating temperatures in existing buildings. In *Energy* (242), Article 122952. DOI: 10.1016/j.energy.2021.122952.

Lämmle, Manuel; Herrando, María; Ryan, Glen (2020): Basic concepts of PVT collector technologies, applications and markets -. SHC Task 60/Report D5. IEA SHC Task 60. DOI: 10.18777/ieashc-task60-2020-0002

Leibfried, Ulrich; Fischer, Stephan; Asenbeck, Sebastian (2019): PVT-Wärmepumpensystem SOLINK - Systemvalidierung und zwei Jahre Praxiserfahrung. In *Symposium Thermische Solarenergie Bad Staffelstein*.

Munz, Gunther; Hesse, Gunther; Wartusch, Volker; Lämmle, Manuel; Helmling, Sebastian; Mehnert, Stefan (2022): PVT-Kollektoren als Luftwärmeübertrager - Leistungscharakterisierung und Performance in einem Wärmepumpensystem. In *Tagungsband 32. Symposium Solarthermie und innovative Wärmesysteme*.

Zottl, Andreas; Nordmann, Roger; Coevoet, Michel; Riviere, Philippe; Miara, Marek; Benou, Anastasia; Riederer, Peter (2012): Sepemo Report D4.2. /D 2.4. - Concept for evaluation of SPF Version 2.2. A defined methodology for calculation of the seasonal performance factor and a definition which devices of the system have to be included in this calculation. Heat pumps with hydronic heating systems.