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Energy Procedia 30 (2012) 414 – 423

Energy Procedia

SHC 2012

Unglazed PVT collectors as additional heat source in heat pump systems with borehole heat exchanger

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Abstract

An unglazed photovoltaic-thermal (PVT) collector provides a double benefit in a heat pump system compared to a conventional heat pump system with PV and borehole heat exchanger. First, the PV cells in the PVT collector are cooled, leading to lower cell temperatures and a higher PV efficiency. Second, the PVT heat raises the temperature level of the heat pump and the borehole heat exchanger and consequently leads to a higher heat pump system performance. In this context a system was measured with a 39 m² unglazed PVT collector field. The impact of the solar heat to the heat pump is determined by TRNSYS simulations using energetic weighted temperatures for validation and to quantify the impact of the solar heat. The investigated system revealed a temperature increase of 3 K which equals 9% lower electricity consumption. The yearly additional PV yield was determined to 4% by reference measurement of uncooled conventional PV panels. Additionally, system simulations in TRNSYS are presented.

Keywords: Unglazed photvoltaic thermal collector; PVT; solar heat pump system; borehole heat exchanger

1. Introduction

Heat pump systems with PVT collectors and borehole heat exchanger as heat source achieve high efficiencies and can provide cooling for the PV cells [1]. Although recognized as a high potential system approach by the European PV catapult project [2], detailed investigations of such systems have only been performed as theoretical simulation studies, like presented by Bakker [3]. In this context a long-term measurement was conducted of a PVT and heat pump system over a period of two years starting in March

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doi:10.1016/j.egypro.2012.11.049

2009. In addition to the measurements simulations have been carried out in TRNSYS to assess the impact of the solar heat to the borehole heat exchanger.

Nomenclature

E_{el}	Produced electrical energy in kWh
i	Index for measured time step
P_{PV}	Nominal PV power in kW
p_{pv}	Specific photovoltaic yield in kWh per installed kW (kWh/kW)
Δpv	Relative Additional photovoltaic yield between PV and cooled PVT
$\dot{Q}$	Heat flow rate in kW
$Q_{HP,evaporator}$	Heat transferred via the evaporator of the heat pump in kWh or MWh
T_{rear}	Temperature on the rear side of PV or PVT- module in °C
T^*_{rear}	Energy weighted temperature on the rear side of PV or PVT- module in °C
ΔT_{HP}	Temperature difference at the heat pump source side in K
$T^*_{HP,inlet}$	Energy weighted temperature at the heat pump evaporator inlet in °C
u_{int}	Internal heat transfer of collector between fluid and absorber in W/m²K

1.1. Classification of system and seasonal performance factor

The investigated system can be classified according to the work of IEA SHC Task 44 / HPP Annex 38 solar and heat pump systems. The system is classified as a ${}^{Sol,Air}_{G,HP}SHP^{G,S}_{SH,DHW}$, system according to [4]. This means that the heat sources for the unglazed PVT collector are solar and ambient air during night-time (Sol, Air). Its heat sinks are the ground and the heat pump (G, HP). The heat sources of the heat pump in the system are the ground or the solar collector (G, S) while its sinks are the space heating or domestic hot water preparation (SH, DHW).

The PVT collector can be operated in series to the borehole heat exchanger on the evaporator side of the heat pump. Accordingly, the collector is operated with the coldest possible temperature.

The seasonal performance factor (SPF) of the heat pump system is the usable heat related to the electrical effort. The usable heat is defined as the supplied heat by the heat pump condenser. The necessary electrical energy input consists of the consumption of the compressor and the parasitic consumption for pumps and control units. The electrical consumption for the heat distribution system, the radiator pump, is not included. In the field measurement the heat for domestic hot water preparation was measured behind the domestic hot water storage. The storage is heated by the heat pump with an immersed condenser and could therefore not be measured directly.

2. Measurement results

The investigated system near Frankfurt a. M., Germany, has been measured since March 2009 and consists of an 39 m² unglazed PVT collector, 3 x 75 m pipe in pipe BHE and a 12 kW heat heat pump supplies heat to a floor heating system and a domestic hot water (DHW) storage. The DHW storage is charged by the immersed condenser of the heat pump. The system supplies heat to a large single-family dwelling. In addition to the cooled PVT collector field, not cooled conventional PV-modules are installed as reference in order to determine the additional PV yield Δpv. The additional PV yield Δpv generated by the cooling effect is determined by comparison of cooled PVT collectors and not cooled PV-modules.

Over a period of two years of operation an additional electrical PV yield of 4% has been measured. The standard deviation of the measurement uncertainty is 1.5% points. Additionally the temperature T_{rear} on the PVT-module rear side has been measured, too. This temperature is energy weighted with the produced electric energy E_{el} for all measured time steps i according to equation (1). This weighted temperature T^*_{rear} is 25°C for the PVT collector and 33°C for the not cooled PV- module. To conclude, the cooling effect was measured and found to be approx. 8 K, which leads to about a 3 to 4% higher yield, taking into account a PV cell temperature coefficient of 4 to 5% per 10 K. Thus, this indirect method is in good accordance with the more accurate direct electrical measurement of the additional PV yield Δpv.

This comparison measurement is conducted for two different PVT collector designs, one with and the second without rear side insulation. The difference for the additional PV yield Δpv between the two designs lies within the range of measurement uncertainty.

pump. The

$$T^*_{rear} = \frac{\sum_i T_{rear,i} \cdot E_{el,i}}{\sum_i E_{el,i}} \quad (1)$$

The second focus of the measurements is the performance of the heat pump. In the second year of operation the seasonal performance factor (SPF) has been determined to 4.2. Neglecting the solar and BHE pump energy the SPF is 4.5. As mentioned above the usable heat for the SPF calculation is measured behind the DHW storage and at the inlet of the floor heating system. The SPF can be calculated from the incoming energy flow rates alternatively. This SPF derived from to the energy flow rates measured directly at the heat pump source is 4.6 including and 4.8 not including the pump energy. All SPF values for the first year of operation are about 0.2 lower.

The SPF improvement in the second year can be explained by the replacement with a heat pump, that has a 0.1 better coefficient of performance, and small modifications in the system (improved piping and DHW tank insulation, control strategy). The temperature levels of the system stay unchanged for the investigated period. In their energetic average, 34°C have been determined for the sink (hot) side outlet temperature and 5.7°C for the brine inlet temperature of the source (cold) side of the heat pump.

The thermal system behavior shows a significant seasonal influence that is well characterized by the heat flow rates of the heat source side (Fig. 1).

In winter, during the highest heating demand of the heat pump, the unglazed PVT collector provides only small thermal yields. In contrast, it is the dominating heat source during the summer, when it regenerates the BHE with nearly the same amount of heat that is extracted in winter. During the transition periods, especially in spring, the PVT collector provides a significant fraction of the evaporator heat. Here, the PVT collector is warmer than the BHE, accordingly it improves the efficiency of the heat pump and it relieves the BHE.

In addition to the increase in efficiency the provided solar heat significantly stabilizes the BHE heat source. The measured system presents an unintended example for this case. Here in the first year of real operation 35 MWh/a have been consumed instead of the planned 27.8 MWh/a. In the second year of operation this value lies even higher and reaches a value of 41 MWh/a. It is assumed that the main reason for this immense increase is mostly due to the user specific high consumption. The most obvious indications are the room temperatures of app. 22-23°C instead of the planned 20°C and the 50% higher domestic hot water consumption. Corresponding to the far higher heat demand the BHE is undersized. Without solar regeneration this would consequently lead to an extremely high heat extraction from the heat pump and accordingly very low temperatures with clear decrease of the SPF or even material damages in the BHE (compare Fig. 4). On the other hand, the high fraction of space heating surely has a positive influence on the SPF and therefore highlights the necessity to give absolute values of end energy consumption in addition to the SPF as main indicators.

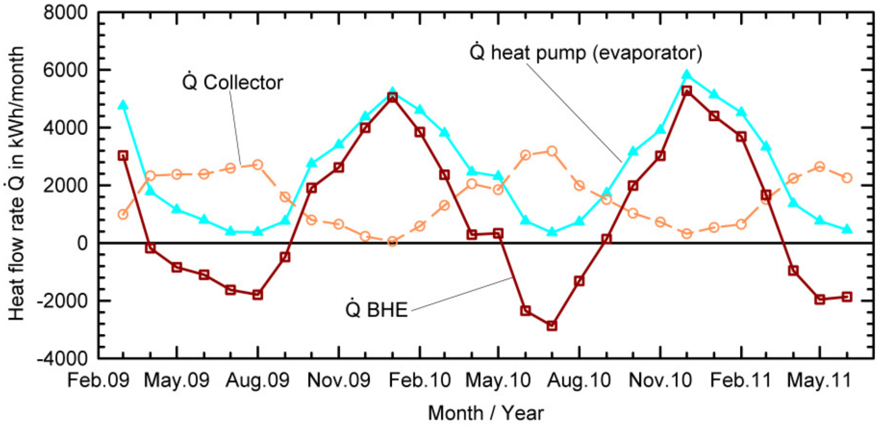

Fig. 1. Measured monthly heat flow rates on the heat source side over a period of 28 months of operation: Solar collector yield, BHE heat transfer (positive: removal, negative: charging) and evaporator heat.

3. Solar impact on the heat source

3.1. Determination of the solar impact on the heat source temperature level

In contrast to the PV yield improvement due to cooling it is not possible to measure the efficiency increase at the heat pump due to the heat injected to the borehole heat exchanger. Therefore, this improvement is determined with simulations based on measurement data. The solar heat from the PVT collector increases the temperature level of the heat source at the heat pump. Correspondingly the electrical consumption decreases. This temperature increase at the heat pump ΔT_{HP} can be determined from simulation and measurement data in two steps.

In the first step the heat source side is modeled as it is operated in the measured pilot system. This allows controlling the accuracy of the simulation. The second step consists of a rerun of the simulation with identical heat demand from the heat pump, but without the support of the PVT collector. Finally, the comparison of the temperatures with and without support of the PVT collector reveals the solar induced temperature increase for the heat pump inlet temperature ΔT_{HP}. The simulations are restricted to reproduce the heat source side of the system and are run with the measured meteorological and heat demand data of the heat pump source side.

The simulation with PVT collector, the first step, models the source system of the heat pump, consisting of the borehole heat exchanger, the PVT collector and the pipe system. For this purpose, a model of an unglazed PVT- collector, that requires only conventional and commonly used performance data as parameters, has been developed at ISFH [5]. Finally, the measured meteorological conditions, the mass flow rate of the heat source side and the evaporator heat $Q_{HP,evaporator}$ of the heat pump are applied to the developed model of the system. The simulation is conducted in one-minute time steps, like the measured data. The accordance between simulation and measurement is discussed by means of the energetic weighted fluid temperature $T^*_{HP,inlet}$ at the evaporator inlet according to (eq. 2).

$$T^*_{HP,inlet} = \frac{\sum_i T_{HP,inlet} \cdot Q_{HP,evaporator,i}}{\sum_i Q_{HP,evaporator,i}} \quad (2)$$

The simulation of a complete year results in a $T^*_{HP,inlet}$ of 5.70°C, while the difference between measurement and simulation of $T^*_{HP,inlet}$ is 0.02 K. The difference may be higher for single days, resulting in a standard deviation for the daily differences of $T^*_{HP,inlet}$ of 0.4 K. The maximum deviation between simulated and measured daily values reaches -1.7 K. In conclusion, the simulation reproduces the measurement without systematic error and a good accuracy.

In the second step, the heat pump source side is simulated again with the very same measurement data but without PVT- collector. In doing so, the simulation is repeated under identical dynamic heat demand of the heat pump and with the borehole heat exchanger as the only heat source. Due to the missing solar input $T^*_{HP,inlet}$ is reduced to 2.7°C. Accordingly, for the investigated year the PVT collector could increase the temperature level by 3.0 K.

In order to investigate long-term effects, the simulation is repeated for a period of 20 years, using the input data for weather and heat demand of the measured first year. The simulated temperatures of $T^*_{HP,inlet}$ for the system with and without PVT collector are displayed in Fig. 2. Long-term cooling effects of the BHE lead to an increase of ΔT_{HP} for the systems with solar support compared to the systems without solar. At the end of the 20 years period $T^*_{HP,inlet}$. is 4.7 K lower if not supported by the collector, the average over 20 years is 4.3 K.

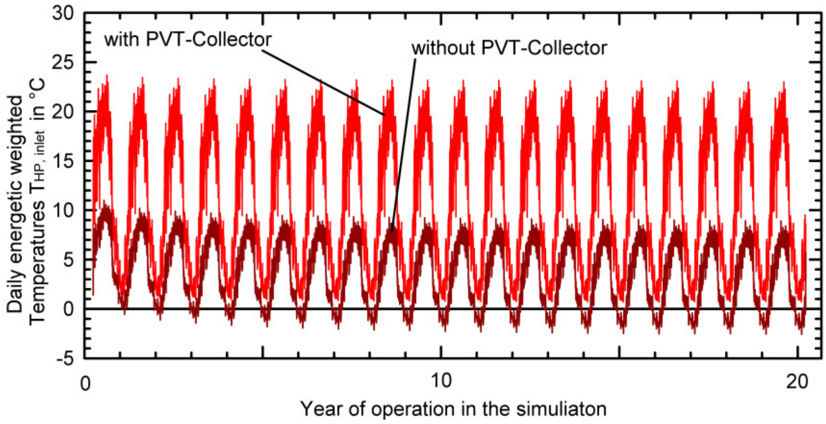

Fig. 2. Simulated heat pump inlet temperatures (heat source side, daily energetic weighted values) for the pilot system with and without solar heat support for 20 years. For all years the applied data of meteorological conditions and heat pump heat demand consist of the first year's measured data

3.2. Assessment of the solar improved temperature level at the heat source

The temperature increase at the heat pump ΔT_{HP} is calculated from the simulation and the measured data to 3 K for one year and to 4.3 K for a period of 20 years. The heat pump performance characteristic allows an assessment of the SPF improvement due to temperature difference. For the heat pump in the pilot system a seasonal performance factor improvement is deducted of 1.2 / 10 K. Correspondingly, the injected solar heat leads to a SPF improvement of 0.36 for the first year and 0.51 for a period of 20 years. This equals a saving of electric energy of 9% and 13%, respectively. In the 20th year of operation, the temperature increase of 4.7 K leads to an SPF improvement of 0.56 and 15% electricity savings.

Fig. 2 displays the long-term temperature development with and without solar regeneration. Without solar regeneration, the temperature decrease becomes very obvious. On the contrary, with solar regeneration the over seasonal temperature decrease can be neglected.

Of course, the reduced temperature level and a correspondingly lower SPF would lead to a reduced heat demand of the heat pump. This change is rather small. For the investigated year the difference of the evaporator heat flow rate lies at 3% for the first year and at 5% for a period over 20 years and therefore is not taken into account in the following.

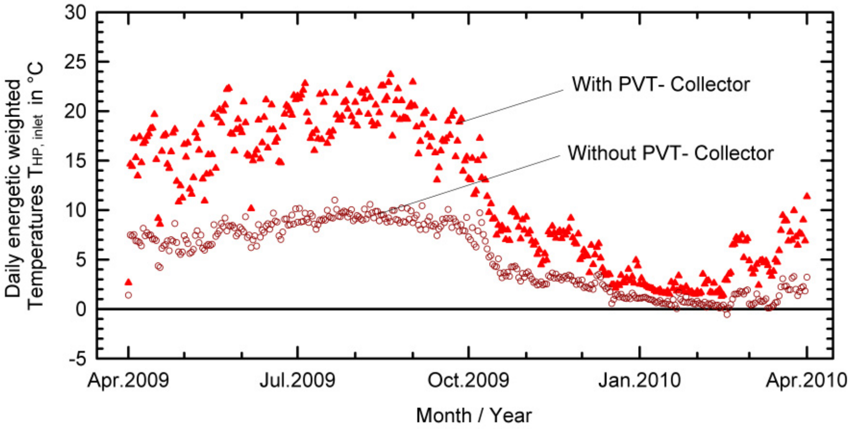

Fig. 3. Simulated daily average energetic weighted temperatures at the heat pump inlet $T^*_{HP,inlet}$ for the pilot system in the first year of operation

Fig. 3 displays the behavior of $T^*_{HP,inlet}$ for every day in the first year of operation. The diagram allows a qualitative discussion of the influence from solar heat on the BHE in the course of the year. In summer the influence of the injected heat is high. Here, typical temperature differences of around 10 K are reached with a slight rising tendency to the end of summer. However, the heat demand of the heat pump during the summer is small. In winter the benefit of the solar heat is significantly smaller and decreases to 1.5 K in January. Therefore, the temperature difference in the course of the year reveals a qualitative analogue behavior to the measured PVT collector heat flow rate.

The seasonal course of the solar influence gives important information on the general behavior and the limit for the solar regeneration or charging of the BHE. During the transition months the PVT collector delivers a significant fraction of the required heat and in summer it offers enough heat to regenerate the borehole heat exchanger. In winter however, the borehole heat exchanger is the essential source: Only via BHE a high amount of heat at a rather high source temperature level is provided for the heat pump evaporator in case of low ambient air temperatures.

The stabilization of the heat source side of the system and the elimination of over seasonal temperature drifts are further advantages of solar regeneration. This especially applies in cases of larger fields of borehole heat exchangers and for undersized BHE (e.g. in case of higher heat extraction or lower thermal conductivity of the ground as it has been planned) [6].

4. Parameter variation in transient system simulations

The important influences for the described PVT system were investigated with TRNSYS simulations [7] for a typical reference system of a single-family dwelling. The reference system and its conditions are given in table 1 and were mostly taken from the reference system in IEA Task 26 of the Solar Heating and Cooling Program [8]. The simulations were conducted in one-minute time steps. The PVT collector size and the borehole heat exchanger are varied for the reference system. The simulation results are displayed in Fig. 4 for the SPF and in Fig. 5 for the additional PV yield.

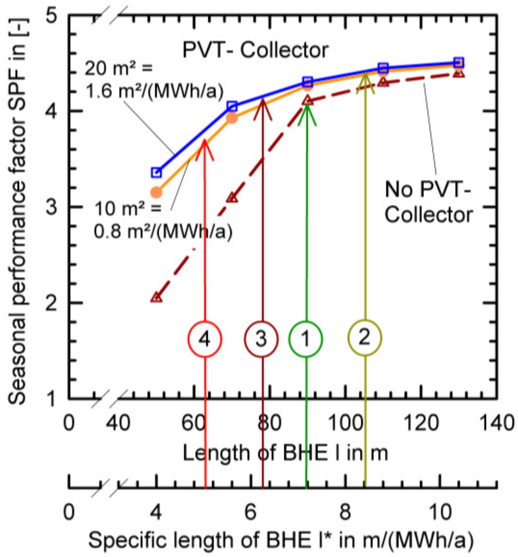

Fig. 4. The simulated SPF as a function of BHE length and PVT collector area for the reference system. The collector areas and BHE lengths are given in absolute values and in specific values related to the total heat demand. The arrows 1 to 4 mark operation points for the measured pilot system. 1 – recommended for solar assisted BHE system, 2 – design point according to planning of pilot system, 3- first year of operation, 4 – second year of operation

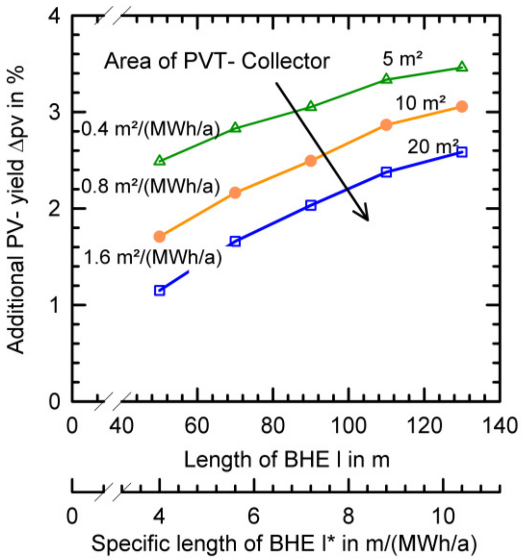

Fig. 5. Simulated additional PV yield as a function of BHE length and PVT collector area for the reference system. The collector areas and BHE lengths are given in absolute values and in specific values related to the total heat demand. The simulations have been carried out using the meteorological wind velocity values as ambient air speed over the collector

The displayed SPF includes both, the consumption for a direct electric back-up heater and for the circulating pumps.
For a conventionally dimensioned plant with 90 m borehole heat exchanger length and a PVT-field size of 1.6 m²/MWh/a (here 20 m²) lead to an SPF improvement of 0.2. The SPF in this point with PVT collector is 4.3.

Table 1. Parameters for the TRNSYS simulation parameter variations

Parameter	
Total heat demand Q_{total} incl. DHW, storage and distribution losses	12.5 MWh/a
Heat demand of domestic hot water	2.5 MWh/a
Length of Borehole heat exchanger (+ variations)	90 m
PVT- collecotor size (+variations)	20 m²
Heat conductivity of ground	2 W/mK
Type of borehole heat exchanger	Double U- tube
COP of the heat pump (35°C heat source side / 0°C heat sink side)	4.6
PVT- collector, electrical	0.12 Wp/m²
PVT- collector, thermal (OC)	η_0 = 0.73; b_1=15 W/m²K
for open circuit operation and 1 m/s wind speed	
Weather data	TRY 7, Kassel, central Germany

From a sensitivity analysis the main influencing parameters for the additional PV yield result as follows:

- The influence of the location of the system shows a variation of 1 to 5%, where locations with warmer summer, higher solar irradiation and lower wind velocity show a clear tendency for better cooling benefits, while locations with higher wind velocity show a lower benefit.
- The wind speed has a high influence. For the reference system with 20 m² PVT collector and 90 m BHE a reduced ambient air speed of 25% compared of the meteorological wind speed leads to a 2.2% point higher additional PV yield. In the measured system the ambient air speed has been measured to about one third of the given meteorological wind speed for the same location. Fig. 6 displays the additional PV yield for a gradually reduced meteorological wind speed.
- The type of installation on the roof of the PVT collectors or PV-modules influences the additional PV yield. The quality of the thermal contact between cells and collector heat exchanger, quantified by the internal conductivity U_{int}, has also an impact on the additional PV yield. Both effects can be seen in Fig. 6 for different air speed factors. In particular roof integrated and therefore rear side insulated PV-modules benefit more from the PV cooling, an additional PV yield of up to 10% may be expected.
- The control strategy has only a minor effect. The recommended control method is a simple 2-point on-off controller with temperature differences of 6 K and 3 K, respectively.
- The additional PV yield is increasing with longer BHE.

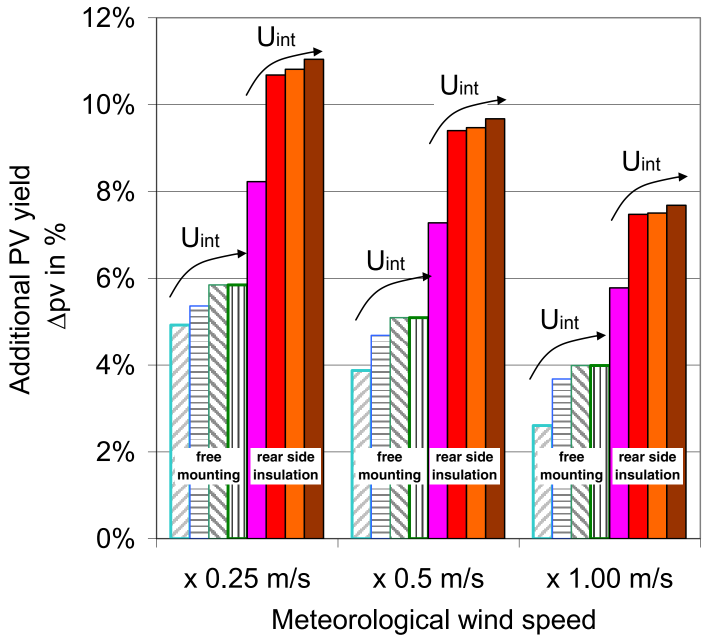

Fig. 6. Additional PV- yield in the reference system (90 m BHE length and 15 m² PVT- collector) for varying internal heat transfer coefficients U_{int}, ambient air speed factors and different types of installation. U_{int} is set to 25/60/80/95 W/m²K

5. Summary and conclusions

The additional PV yield for a PVT collector compared to a not cooled PV-system has been determined in measurement and simulation for a heat pump system with borehole heat exchanger. In the measured pilot system it has been determined to a value of 4%, which is confirmed in the simulation. In extreme cases the additional PV yield can reach values of 10%. Such a case would be a roof integrated (i.e. rear side insulated) PVT collector at a rather calm location with sunny summer in Germany. In most cases this benefit due to cooling alone does not justify the additional effort for the PVT collector and the connection to the pipe system.

The efficiency gain, expressed as SPF improvement of the heat pump system due to the thermal yield of the PVT- collector has been measured in the pilot system to 0.36 in the first year and extrapolated to 0.51 for the 20th year of operation. The much smaller simulation reference system shows an SPF improvement of only 0.2, if designed properly. The higher SPF effect of the pilot system arises from a larger and additionally under dimensioned BHE, caused by a significantly increased energy demand compared to planning. These results confirm earlier results [6], in which larger BHE- fields with solar regeneration do not show an over-seasonal temperature decrease with increasing heat demand, in contrary to systems without solar regeneration. Accordingly, the obtained efficiency gain by solar heat regeneration depends on the size of the system, too.

Apart from efficiency aspects some attractive characteristics are connected with the presented PVT-system:

- The PVT collector can be integrated to the roof. Higher module temperatures, caused by the reduced rear side heat losses, are avoided.
- Furthermore, the solar regeneration stabilizes the heat source BHE especially against an increase in the total heat demand. This simplifies the dimensioning and improves the reliability of the planning and is demonstrated most impressively in the case of the measured system.
- Above all, the aim to reach an even electrical balance on a yearly basis offers to the user an easy way to control the steps of planning, construction and operation of the system.

Acknowledgements

The work presented in this paper was funded by the German Ministry for Environment, Nature Conservation and Nuclear Safety based on a decision of the German Federal Parliament. (Project: Solarthermie2000plus – Solar heat supply for buildings with unglazed photovoltaic-thermal collectors, borehole heat exchanger and heat pumps for 100% solar fraction– short name: BiSolar- WP, FKZ 0325952). The project partner has been GEFGA mbH (www.gefga.de). GEFGA was responsible for the planning, construction and commissioning of the pilot system and the PVT- collector.
The content of this publication is in the responsibility of the authors.
The project takes part in the framework of the joint Task 44/Annex 38 “Heat pump and solar” in the solar heating and cooling and heat pump program of the international energy agency [9].

References

[1] H. A. Zondag, D. W. de Vries, W. G. J. van Helden, R. J. C. van Zolingen, and A. A. van Steenhoven, “The yield of different combined PV-thermal collector designs,” *Solar Energy* **74**, 253–269 (2003) [doi:16/S0038-092X(03)00121-X].

[2] H. A. Zondag, W. Eisenmann, H. Fechner, P. Affolter, M. Rommel, A. Schaap, H. Sørensen, and Y. Tripanagnostopoulos, “PVT ROADMAP - A European guide for the development and market introduction of PV-Thermal technology,” EU-supported Coordination for PV-Catapult Project European Union contract no 502775 (SES6), Energy Research Centre of the Netherlands, p. 91 (2005).

[3] M. Bakker, H. A. Zondag, M. J. Elswijk, K. J. Strootman, and M. J. M. Jong, “Performance and costs of a roof-sized PV/thermal array combined with a ground coupled heat pump,” *Solar Energy* **78**, 331–339 (2005) [doi:10.1016/j.solener.2004.09.019].

[4] E. Frank, M. Haller, S. Herkel, and J. Ruschenberg, “Systematic Classification of combined solar thermal and heat pump systems,” presented at EuroSun 2010 International Conference on Solar Heating, Cooling and Buildings, Graz, Austria, 2010, Graz, Austria, IEA-SHC.

[5] M. Stegmann, E. Bertram, G. Rockendorf, and S. Janßen, “Model of an unglazed photovoltaic thermal collector based on standard test procedures,” in *Proceedings of ISES Solar World Congress*, Kassel, Germany (2011).

[6] E. Bertram, J. Glembin, J. Scheuren, and G. Zienterra, “Soil regeneration by unglazed solar collectors in heat pump systems,” presented at ISES Solar World Congress 2009 renewable energy shaping our future, 11 October 2009, Johannesburg, South Africa, International Solar Energy Society.

[7] S. A. Klein, W. A. Beckmann, J. W. Mitchell, J. A. Duffie, and T. A. Freeman, *TRNSYS 17, A Transient System Simulation Program, Solar Energy Laboratory University of Wisconsin, Madision*, Stuttgard, Germany (2009).

[8] W. Weiss, *Solar heating systems for houses : a design handbook for solar combisystems IEA SHC Programme - Task 26*, James & James, London (2003).

[9] IEA-Task 44, “IEA-SHC || Task 44,” 2010, <http://www.iea-shc.org/task44/> (17 April 2011).