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HEAT PUMP SYSTEMS WITH BOREHOLE HEAT EXCHANGER AND UNGLAZED PVT COLLECTOR

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1. Introduction

In the future energy supply both efficient heat pump systems for heat generation and photovoltaic (PV) electricity production will play an important role. Therefore, a heat pump system with a combined heat source consisting of a photovoltaic-thermal (PVT) collector and a borehole heat exchanger (BHE) is assumed to be a promising solution, because this particular combination provides a double benefit compared to conventional heat pump and PV-systems. First, the PV cells in the PVT collector are cooled, leading to lower cell temperatures and a higher PV efficiency. Second, the heat from the PVT collector raises the temperature level of the heat pump and the borehole heat exchanger. Consequently, the temperature increase of the heat source leads to a higher heat pump performance factor.

Within a research project, a pilot system has been built up and experimentally evaluated. Simulation studies allow analyzing the system behavior and extrapolating the results.

2. System configuration and measurement results

For the investigated system the PVT collector field is integrated in a heat pump system with borehole heat exchanger by a simple switching valve. This valve allows connecting the PVT collector in series to the borehole heat exchanger. Accordingly, the supplied heat from the collector is restricted to the heat source side of the heat pump. A hydraulic scheme of the system is given in Figure 1. The presented hydraulic concept is the starting point for all following investigations and system simulations. The formal classification according to an IEA SHC Task 44 proposal (Frank *et al.*, 2010) describes the system as ${}^{Sol,Air}_{G,HP}SHP^{G,S}_{SH,DHW}$. This means that the heat sources for the unglazed PVT collector are solar and during nighttime operation can also be heat from the ambient air (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).

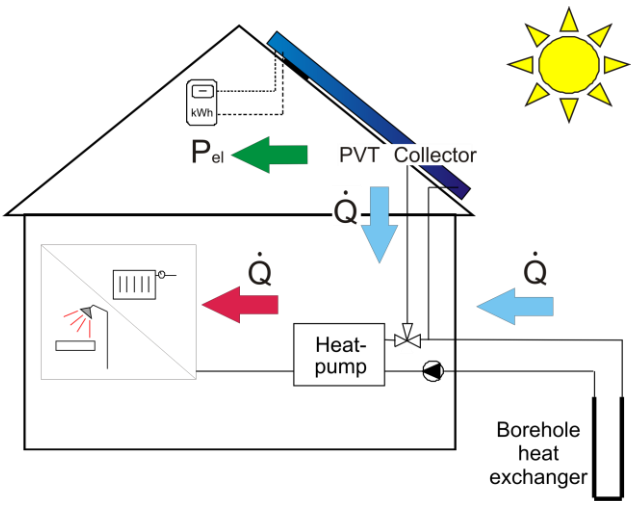

Fig. 1 Investigated system concept with the unglazed PVT collector integrated in a heat pump system with borehole heat exchanger

The pilot system near Frankfurt a. M., Germany, is 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 pump. The heat pump suppĺies heat to

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a floor heating system and a domestic hot water (DHW) storage. The DHW storage is charged by the integrated condenser of the heat pump. The system supplies heat to a large single-family dwelling. In addition to the cooled PVT collector field, identical but not cooled conventional PV-modules are installed in order to determine the additional PV yield Δpv. The additional PV yield Δpv generated by cooling effects is determined by the comparison of both cooled PVT collectors and not cooled PV-modules.

Over a period of two years of operation an additional electrical PV yield of 4% was measured. The standard deviation of the measurement is 1.5% points. Additionally the temperature T_{rear} on the PVT-module rear side was measured. This temperature is energy weighted with the produced electric energy E_{el} for all measured time steps 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.

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

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 including solar and BHE pump energy and 4.5 without pump energy. The respected usable heat for the SPF is the measured energy consumption of the user for space heating and domestic hot water. The SPF related 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 around 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 COP, 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 they are 34°C for the hot sides running line temperature and 5.7°C for the brine inlet temperature of the cold side of the heat pump.

The thermal system behaviour shows a significant seasonal influence that is well characterized by the heat flow rates of the heat source side (Fig. 2).

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 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 may be 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 extreme extraction from the heat pump and accordingly very low temperatures with clear decrease of the SPF or material damages in the BHE (compare Fig. 5).

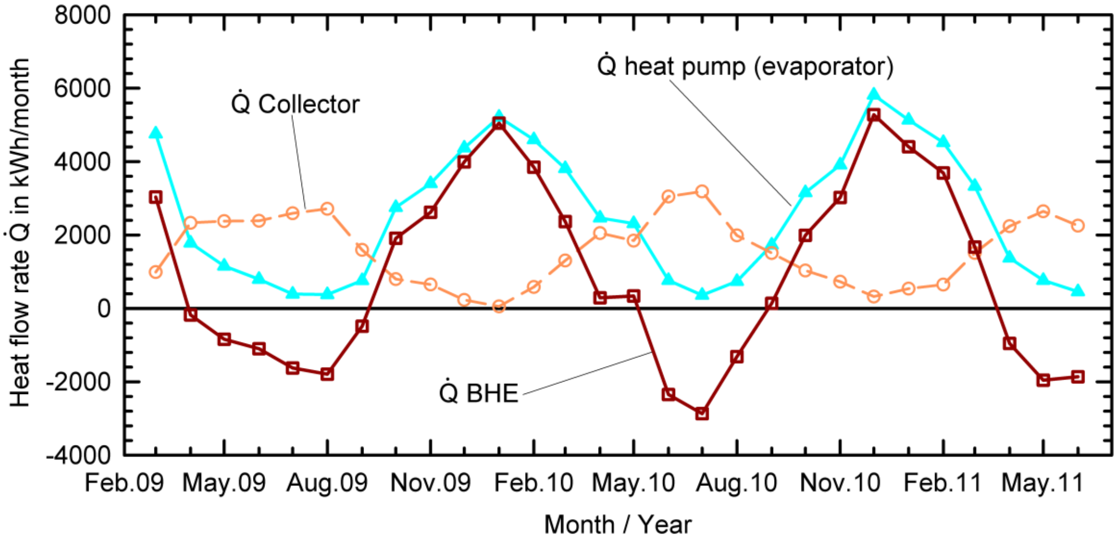

Fig. 2 Measured monthly heat flow rates on the heat source side over a period of 28 months of operation:. Solar collector yield, BHE heat transfer (positive: removal, negative: charging) and evaporator heat

3. Solar support of borehole heat exchanger – calculation

In contrast to the additional PV yield 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 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 source demand data.

The simulation with PVT collector, the first step, models the borehole heat exchanger, the PVT collector and the complete pipe system. For this purpose, a model of an unglazed PVT- collector, that requires only conventional and commonly used performance data as parameters, was developed at ISFH (Stegmann *et al.*, 2011). 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, the same time step like the measured data. The accordance between simulation and measurement is discussed by means of the energetic weighted fluid temperature $T^*_{HP,inlet}$ according to (eq. 2).

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

The simulation of a complete year results in a $T^*_{HP,inlet}$ of 5.7°C. For the whole year the summarized average difference between measurement and simulation of $T^*_{HP,inlet}$ is 0.02 K. The differences are higher for single days, the standard deviation for the simulated daily values of $T^*_{HP,inlet}$ results in 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.

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In the second step, the simulation is conducted 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 heat support $T^*_{HP,inlet}$ reduces and results in 2.7°C. Accordingly, for the investigated year the PVT collector could increase the temperature level by 3.0 K.

The simulation is repeated for a period of several years. The simulations for 20 years are elongated based on the measurement data from one year and are elongated to a time period of 20 years. The simulated temperatures of $T^*_{HP,inlet}$ for the system with and without PVT collector are displayed in Fig. 3. The longer operation period leads to an increase of ΔT_{HP} for the systems with and without support of solar heat. For the complete period results an energetic weighted temperature benefit for $T^*_{HP,inlet.}$ of 4.3 K. At the end of the 20 years period $T^*_{HP,inlet.}$ is 4.7 K lower if not supported by the collector.

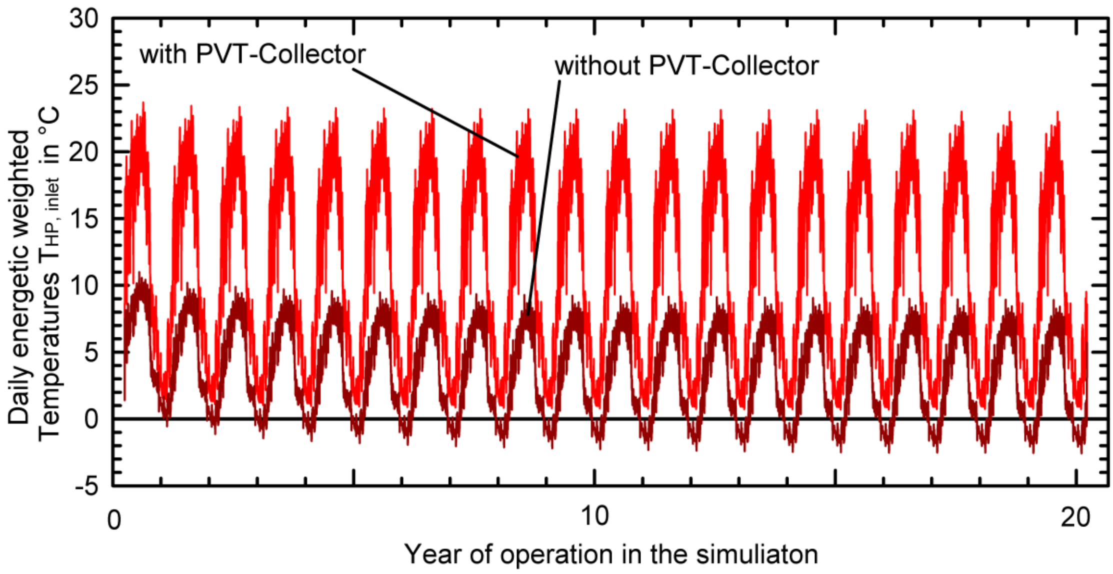

Fig. 3 Simulated heat pump inlet temperatures (heat source side, daily energetic weighted values) for the pilot system with and without solar heat support for 20 years. For all years the applied data of meteorological conditions and heat pump heat demand consist of the first year's measured data.

4. Solar support of borehole heat exchanger – assessment

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. Accordingly 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 electrical energy of 9% and accordingly 13%. The temperature increase in the 20th year of operation reaches even 4.7 K and therefore leads to an SPF improvement of 0.56 and 15% electricity savings.

The extrapolation from one year of operation to a period over 20 years implies a high inaccuracy for the simulations due to reasons like changed weather or heat demand conditions. Fig. 3 displays the long-term temperature development with and without solar regeneration. For this elongated time period of 20 years the temperature decrease without solar regeneration becomes very obvious. On the contrary, with solar regeneration the over seasonal temperature decrease can be neglected. Here, the BHE temperature reaches already a quasi-dynamic state in the second year of operation.

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.

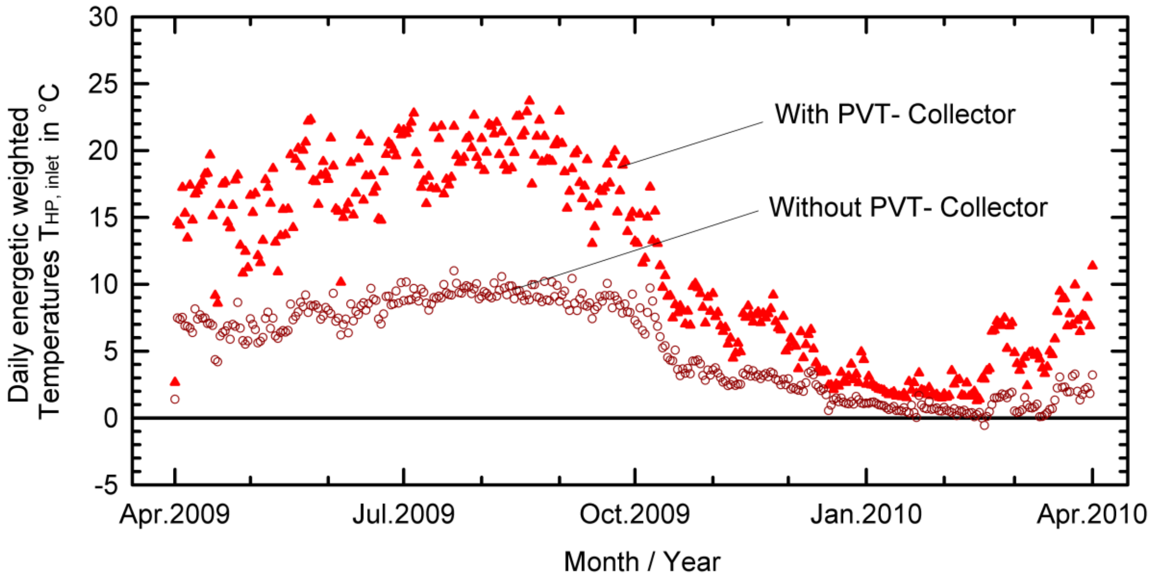

Fig. 4 Simulated daily average energetic weighted temperatures at the heat pump inlet $T^*_{HP,inlet}$ for the pilot system in the first year of operation

Fig. 4 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 especially big. 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 analog 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 this way a high heat source temperature level is provided for the heat pump even at very low ambient air temperatures. Anyway, the impact of the solar regeneration is not limited to the improvement of heat pump efficiency and its positive influence on the system should not be underestimated. Solar regeneration simplifies the required planning process, stabilizes the heat source side of the system and eliminates the over seasonal temperature drift especially in larger fields of borehole heat exchangers (Bertram *et al.*, 2009).

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5. System simulations and simplified dimensioning rules

The important influences for the described PVT system were investigated with TRNSYS simulations (Klein, 2007) 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 (Weiss, 2003). 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. 5 for the SPF and in Fig 6 for the additional PV yield. The displayed SPF includes both the consumption for a direct electric back-up heater and for 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.

Tab. 1: Parameters for the TRNSYS simulation of the reference system

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 W_p/m²
PVT- collector, thermal (OC) for open circuit operation and 1 m/s wind speed	$\eta_0 = 0.73$; b_1=15 W/m²K
Weather data	TRY 7, Kassel, central Germany

An attractive goal for the system dimensioning is an even balance between the yearly electric consumption and the PV yield. A first dimensioning approach is given by (eq. 3.) The required PV-power $P_{PV\text{-}Balance}$ always depends on the predicted yearly PV yield pv. Of course, this predicted yearly PV yield pv differs strongly with the location and specific system. Typical values for central Germany are around 1000 kWh per installed kW PV- power. The additional PV yield caused by the cooling effect is respected by Δpv.

$$P_{PV-Balance} = \frac{Q_{total}}{SPF} \cdot \frac{1}{pv \cdot (1 + \Delta pv)} \qquad \text{(eq. 3)}$$

Equation 3 delivers for an even balance a required $P_{PV\text{-}Balance}$ of 2.8 kW or 24 m² PVT collector array in the case of the described reference system with 90 m BHE and 20 m² PVT- Collector. When transferred in specific values this result equals an installed power of 0.23 kW/(MWh/a) or a collector array of 1.9 m²/(MWh/a). The specific values are related to the total heat demand Q_{total}. Of course, this specific number is not fix but changes with the expected PV yield pv, the additional PVT-yield Δpv and the SPF.

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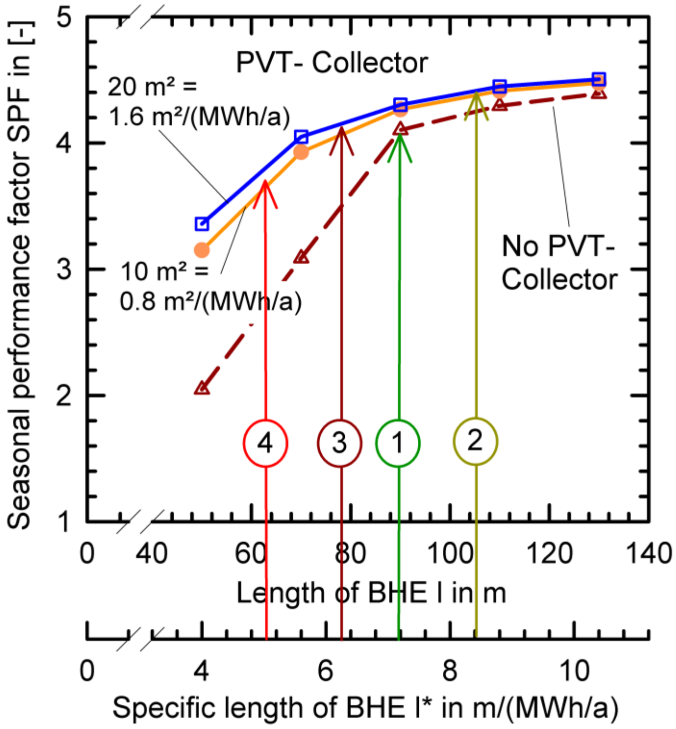

Fig. 5: The simulated SPF as a function of BHE length and PVT collector area for the reference system. The collector areas and BHE lengths are given in absolute values and in specific values related to the total heat demand. The arrows 1 to 4 mark operation points for the measured pilot system. 1 – typical for conventional BHE system, 2 – Design point according to planning, 3- first year of operation, 4 – second year of operation

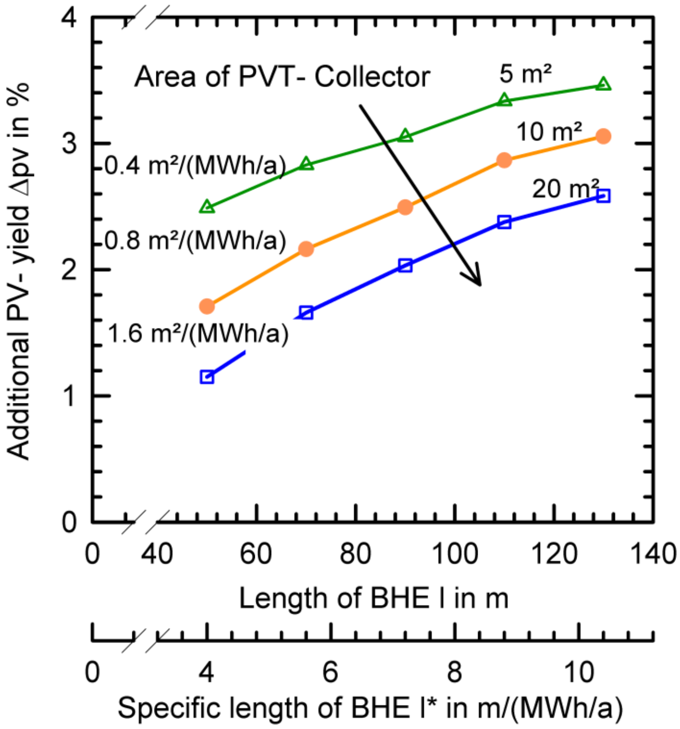

Fig. 6: Simulated additional PV yield as a function of BHE length and PVT collector area for the reference system. The collector areas and BHE lengths are given in absolute values and in specific values related to the total heat demand. The ambient air speed values in this figure are identical to the meteorological wind velocity values.

Starting from the reference system a sensitivity analysis was conducted to investigate the main influencing parameters for the additional PV yield. The most important results are presented in the following:

- The influence of the location of the system on the additional PV yield was investigated for different locations in Germany. This value increased or decreased up to 2.5% depending on the location compared to the reference system with around 2.5% additional PV yield at central Germany, Kassel (TRY 7). No clear correlation between yearly average weather data and additional PV yield could be found. Nevertheless, locations with hotter climate and higher solar irradiation 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 wind speed to 25% compared to the meteorological wind speed leads to a 2.2% point higher additional PV yield. In the measured system the wind speed is two thirds lower than the given meteorological wind speed from the reference weather data for the same location. Fig. 7 displays the additional PV yield for a gradually reduced meteorological wind speed.

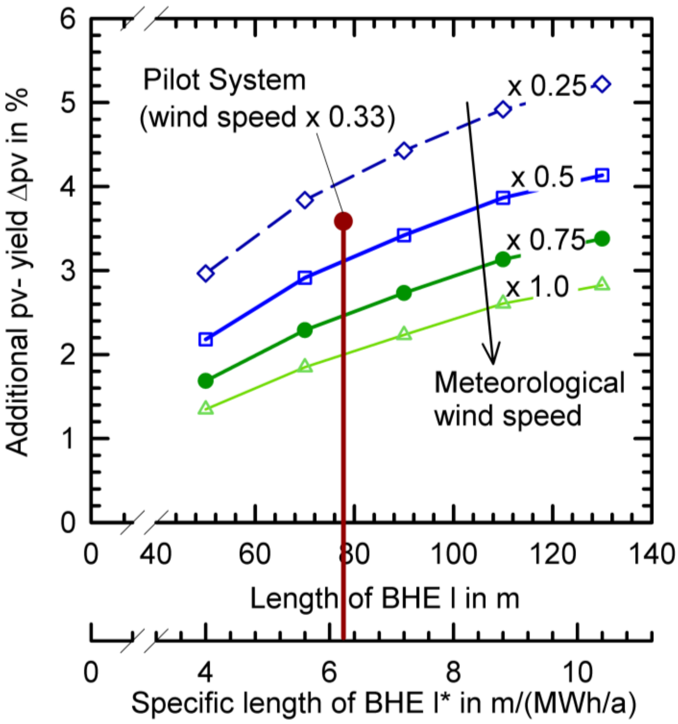

Fig. 7:Influence of the wind speed on the additional PV- yield in the reference system. The length of the BHE is varied while the PVT- collector is 15 m².

- 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. 8 for different wind speeds. In particular roof integrated and therefore rear side insulated PV-modules can lead to an additional PV yield of up to 10%.

- Several control strategies have been tested in the simulation. As a result, the recommended control strategy is a simple 2-point on-off controller with temperature values of 6 K and 3 K. The electricity consumption of pumps has been included in the investigation.

- The additional PV yield shows no dependency on the size of the system as long as systems with identical specific BHE length and PVT- collector area are compared.

- The heat conductivity of the ground only has a negligible effect on the additional PV yield.

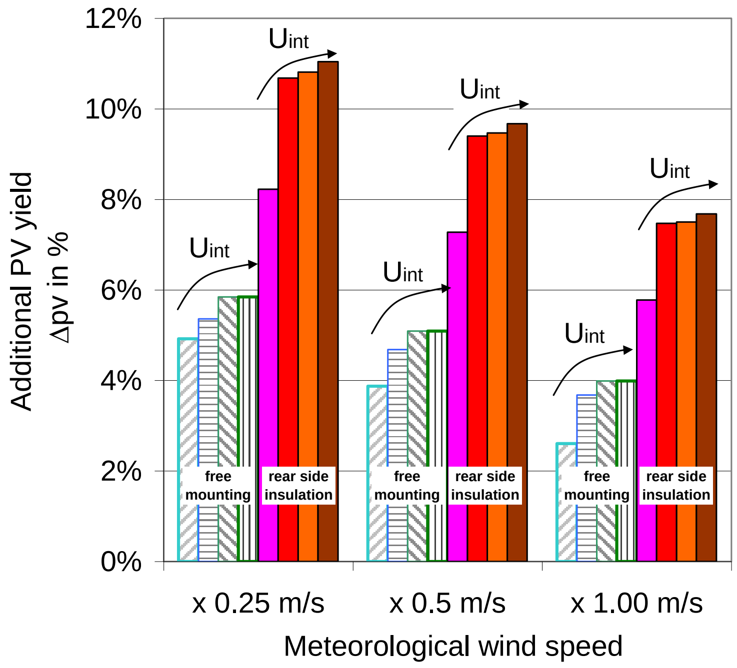

Fig. 8: Additional PV- yield in the reference system (90 m BHE length and 15 m² PVT- collector) for varying internal heat transfer u_{int} rates, wind speeds and different types of installation. The internal heat transfer is varied for values of 25/60/80/95 W/m²K.

6. Summary and deductions

The additional PV yield for a PVT collector compared to an uncooled PV-system was determined in measurement and simulation for a heat pump system with borehole heat exchanger. In the measured pilot system it is 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 hot, sunny and rather calm location 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 at the heat pump due to thermal yield of the PVT- collector for the measured system was determined for the SPF as 0.36 for the first year and 0.51 for the 20th year of operation. The much smaller simulation reference system shows an SPF improvement of 0.2. These results confirm earlier results (Bertram *et al.*, 2009), in which larger BHE- fields do not show an over-seasonal down -cooling with increasing heat demand, whereas systems without solar regeneration do, resulting in extreme cases in severe damages. 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, what 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 the user an easy way of track and control the integral process of planning, construction and the user behavior itself.

7. Acknowledgements

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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 (www.iea-shc.org/task44/index.html).

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