Soil regeneration by unglazed solar collectors in heat pump systems

E. Bertram[1], J. Glembin[1], J. Scheuren[1], G. Zienterra[2]

[1]Institut für Solarenergieforschung Hameln (ISFH)
Am Ohrberg 1, 31860 Emmerthal; Tel.: 05151/999-645; E-Mail: e.bertram@isfh.de

[2]RHEINZINK GmbH & Co. KG,
Bahnhofstraße 90, 45711 Datteln; Tel. 02363-605-706; gregor.zienterra@rheinzink.de

Abstract

Heat pump systems with borehole heat exchanger and unglazed solar thermal collector have been analysed in two pilot systems and assisting TRNSYS-Simulations. Measurements carried out and simulations demonstrate that the borehole heat exchanger is annually regenerated by the solar collector. This results in a different behaviour compared to systems without a solar collector. As one effect of the changed system behaviour, the results of one investigated system, e.g. a simulation reference system, become transferable to other buildings by normalization to the total heat demand. Furthermore the influence of significant parameters on the annual performance factor and a correction function to characterize the heat sink side of the heat pump is presented.

1. Introduction

An unglazed solar collector offers heat at low costs on a low temperature level. For this reason its application is especially suited in combination with a borehole heat exchanger (BHE) supplied heat pump system (HP-system) (Tepe et al., 2003). The low temperatures of the heat source side, of about -5°C to +10°C, result in very high solar yields of over 500 kWh/(m²a). The major part of the solar yield however, is provided during periods of small heat demand during the summer. Nevertheless the high solar collector yield affects the system in two aspects. Firstly, it results in higher temperatures on the heat source side of the HP, which leads to a 0.3 to 0.5 increased annual performance factor (APF) and hence reduced electricity consumption. Additionally, the balance between the heat extracted in winter and solar energy supplied in summer, the complete regeneration, changes the system behaviour significantly. These aspects of a solar regenerated BHE and their impact on the system are discussed in this paper.

2. Long-time temperature development in BHE

The soil in conventional HP-systems cools down by the continuous heat extraction. In several systems a quasi stationary state is only reached after years. This applies in particular to large systems with many BHE or comparatively close adjacent BHEs in residential areas. BHE affect each other particularly in such arrangements. After some years of operation, a temperature field forms around such BHE arrangements, which usually reaches over the border of the estate and reduces the thermal efficiency of the BHE (Kübert et al., 2008).
Both simulation and measurement demonstrate that the long-term cooling of the soil is avoided by solar regeneration. As an example the temperatures measured in the BHE field of the pilot system Limburg are displayed in figure 1. The 14 (2 x 7) rectangularly arranged BHE are 17 m deep and constructed at a distance of 4 m. The extracted and rejected heat from the BHE is balanced on a yearly basis (Bertram et al., 2008). Although the temperature influence of the surface and of the BHE interfere with each other in the comparatively shallow BHE field, it nevertheless shows clearly that despite the HP operation the soil temperatures show no long-term decrease. Hence, long-term cooling of the soil is avoided by solar regeneration. These measurement results confirm the simulations conducted.

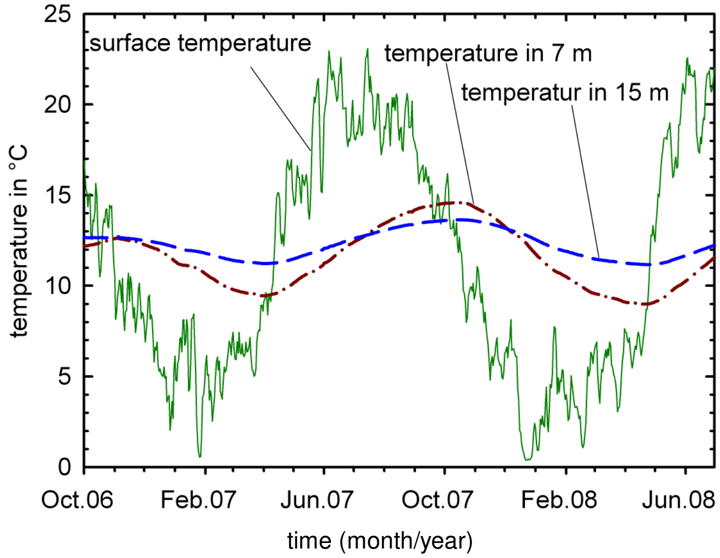

Figure 1. Temperatures measured in the middle of the BHE field in the pilot system Limburg. Distance of BHE is 4 m with an arrangement of 2 x 7 and a depth of 17 m

3. Minimum distance for BHE

A further impact of the soil regeneration BHE is that they can be realized with significantly smaller distance to each other than in conventional HP-systems. This is demonstrated by the simulation results of figure 2, in which the BHE are situated with a distance of 3 m and 15 m. Without collector, the BHE distance has a significant influence on the APF of about 0.5. On the contrary, with collector the APF becomes nearly independent of the BHE distance. Thus it is inferred, that the interference of multiple BHE even at very low distances is extensively neutralized by solar regeneration.

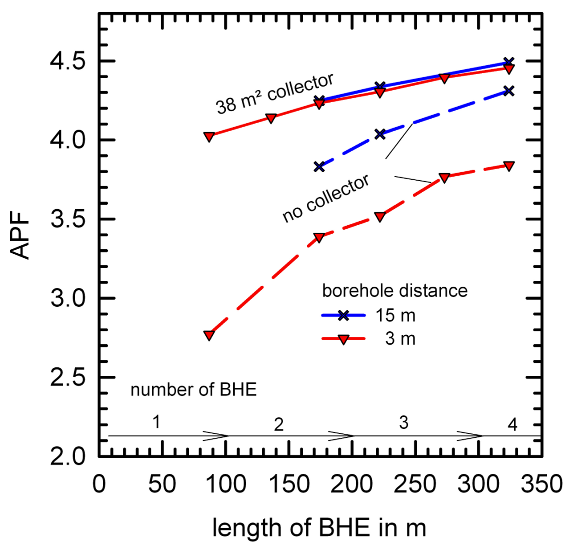

Figure 2. Annual Performance Factors without electrical parasitic consumption for borehole distances of 3 m and 15 m, an annual heat demand of 30 MWh/a and a simulation period of 10 years

On the basis of numerous TRNSYS-Simulations, solar supported HP-systems have been analyzed and the significant influences on the APF identified. The starting point is a reference system for a single family dwelling with an over-all heat demand of 12.7 MWh/a, a double U-pipe borehole heat exchanger and a unglazed collector from the Rheinzink company.

Within these simulations it is revealed that the correlation between APF, BHE and collector can be transferred from the reference system to different sized systems, if the length of the BHE and the collector array are normalized to the over-all heat demand.

The simulation results for the reference systems and two other heat loads with 20 and 30 MWh/a are displayed in figure 3 non-normalized (left) and normalized (right). While for absolute BHE-lengths and collector arrays (left) no obvious transferability is seen, the normalized representation (right) shows an extensively heat load independent APF behaviour.

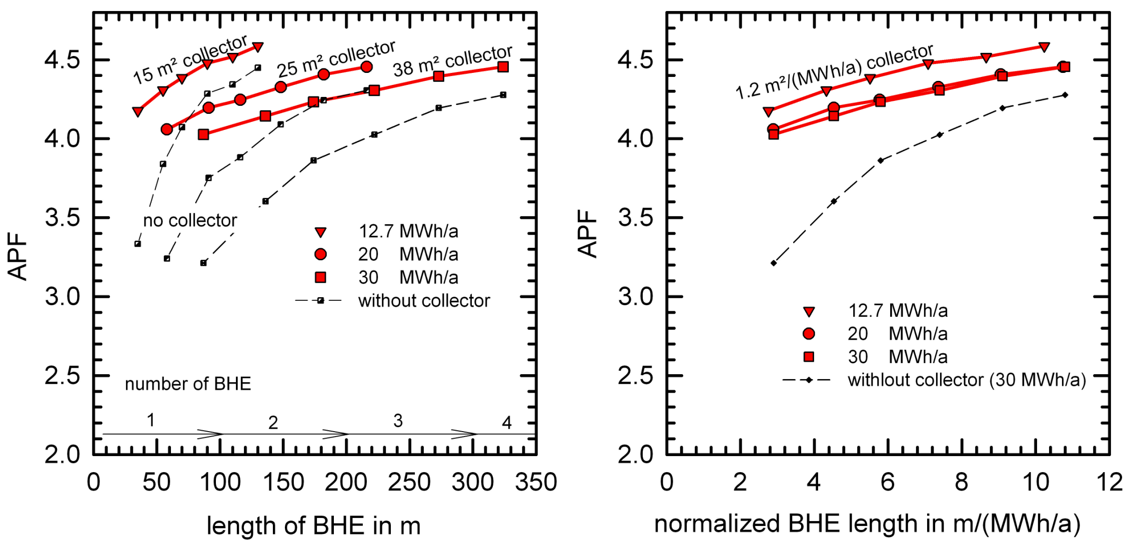

Figure 3. Annual Performance Factors without electrical parasitic consumption for different heat loads of systems with 30, 20 and 12.7 MWh/a in non normalized (left) and normalized form

In the normalized diagram the only difference occurring is a constant off-set of 0.15 in the APF between the two larger heat loads and the reference system (12.7 MWh/a). This difference is explained as the particular advantageous situation of operating a single BHE. Considering this constant deviation, an error for standardization of 0.06 in the APF results from the simulations. By normalizing the collector array and the BHE length to the over-all heat load, the simulated APF for the reference system can be transferred to other systems within a certain range. However, the following restrictions have to be considered:

- A normalization is only possible in systems with solar collector and complete regeneration. Systems without or very small specific collector arrays below 0.8 m²/(MWh/a) can not be normalized.
- In the simulations the BHE are designed as long as possible, but always smaller than 100 m. The maximum BHE length simulated has been 400 m corresponding to four BHE. Other designs of BHE fields have not been investigated.
- Systems up to a heat load of 35 MWh/a have been analyzed in the simulations. For larger systems or BHE fields it is assumed that due to long term storage effects and the interference of the BHE, the influence of the BHE field arrangement increases.
- The simulations are based on heat load distributions of residential buildings in Germany, which assumes a typical number of operation hours with maximum heating load below 2000 h/a. For very small BHE or longer annual operation periods high specific heat extraction

and correspondingly very low temperatures may occur. These effects are not considered within the normalization.

- The APF displayed in figure 3 does not include parasitic electrical consumption for the operation of pumps or a direct electric heater. But using the APF of the simulation reference system, these energies have to be taken into account.

4. Simplified Design

The normalization described above permits a prediction of the APF depending on the BHE length and size of collector array on the basis of the reference system introduced. In compliance with the fore mentioned restrictions, a design of a collector array of at least 1.2 m²/(MWh/a) and 7 m/(MWh/a) BHE length are recommended. This minimal design leads to an APF of 4.5 for a single BHE and 4.35 for multiple BHE (not taking electrical consumption for pumps and direct heater into account). As an example, for a building with a total heat load of 17 MWh/a the result is an unglazed collector array of 20.4 m² and a total BHE length of 120 m corresponding to two BHE each of 60 m in length.

5. Influences on the annual performance factor (APF)

Apart from collector array and BHE length, further influences on the APF have been determined in numerous simulation runs and correction functions have been developed. These correction functions allow an APF prediction, even in cases of conditions differing from the reference system. Furthermore, the influences on the heat pump heat source and on the heat sink side are independent and do not interact as the simulations indicate. Hence in the following, the heat sink side, heating system and domestic hot water is described first and then followed by a description of the heat source side, BHE and collector array.

All modifications on the heat sink side effect the APF by a constant value ΔAPF and can be characterized by the effective consuming temperature T_{eff} according to equation (1). Here T_{eff} consists of the most important temperature levels and associated heat loads. Both the heat load for the space heating Q_{heat} and the heat load for domestic hot water preparation Q_{DHW} include the heat losses in addition to the usable heat (e.g. for DHW storage losses).

$$T_{eff} = \frac{Q_{heat} \cdot T_{heat} + Q_{DHW} \cdot T_{DHW}}{Q_{total}} \tag{1}$$

The effective consuming temperature T_{eff} is determined by the energetic weighting of the heating- and domestic hot water temperatures T_{heat} and T_{DHW}. The determination of the heat loads for the demand and additional losses is calculated according to common design methods for buildings (e.g. in Germany “Energieeinsparverordung”). Further details are described in (Scheuren et al., 2008). System analysis revealed that for T_{DHW} the storage set-point temperature and for T_{heat} the design return temperature are good assumptions.

For different temperature levels and heat loads, ΔAPF, the difference to the reference system, is displayed in figure 4 and plotted against the effective consuming temperature T_{eff}. Here, the domestic hot water temperatures, heat loads and radiator size are varied simultaneously. From these results, a simple linear correlation is extracted in equation (2), which describes ΔAPF as a function of the effective consuming temperature T_{eff}.

$$\Delta APF = -0.097 \cdot T_{eff} + 3.733 \tag{2}$$

On the basis of equation (2) and the normalization in figure 3 (right), the results of the reference systems can be transferred to other cases of heat consumption with any combination of temperature level and heat load.

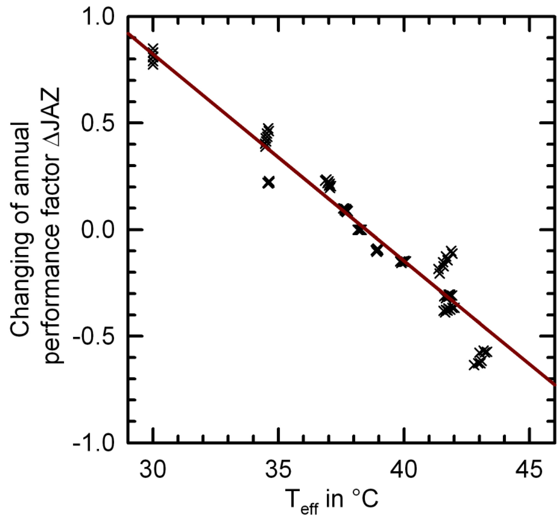

Figure 4. Changing ΔAPF for various effective consumer temperatures T_{eff} at different heat loads and temperature levels, simulation results and linear regression plot according to eq. 2

Finally, the characteristic influences on the heat source side have been identified and correction functions derived. These parameters are displayed in Table 1 and must be considered in the case that they differ from the settings in the reference system. The heat conductivity of the soil and the standard heat pump performance are revealed to be the most important and influencing parameters on the heat source side.
(Scheuren et al., 2008) contains a complete description of all correction functions.

Table 1. Parameters to consider in heat pump systems with unglazed collector

Influence to consider	**Value for reference system**	**Effect of correction function on…**
Heat conductivity of soil	2 W/mK	BHE length
Orientation of collector	45° tilted, south	Collector array
Climate location	Kassel, Germany	Collector array
Performance of heat pump 35°C running- and 0°C source temperature	4.6	APF
Electrical consumption of pump and direct heater	Not considered	APF

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