Impact of solar heat pump system concepts on seasonal performance - Simulation studies

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Abstract

Solar and heat pump systems promise a significant efficiency improvement for heating systems. In this context three different system concepts are compared within TRNSYS simulations for solar heat pump systems with borehole heat exchangers and flat plate collectors. The concepts are examined with solar heat injection either to the hot side for domestic hot water preparation, to the cold side of the heat pump for thermal borehole support or in terms of a combination of both, hot and cold side injection. Connected to the hot side of the heat pump, the increase of the seasonal performance factor is 1.2. If connected to the cold side, the impact is typically below 0.2, but it significantly depends on the specific heat exchanger length and the collector area.

1. Introduction and system description

Solar and heat pump systems promise a significant improvement of system efficiency [1]. Nevertheless the combination of two systems, solar thermal and heat pump, results in an even more complex combined system that is sensitive to climate and temperature levels. Accordingly a comparison between different systems requires equal and clearly defined system conditions. A comprehensive set of reference conditions for system comparison is provided by IEA SHC Task 44/ HPP Annex 38 "Solar and heat pumps system" of the Internal Energy Agency [2]. System simulations are conducted according to these conditions with the simulation environment TRNSYS [3].

Table 1: Overview on the conditions for the system simulations

Description	Value	TRNSYS Type/ Model used
Location	Strasbourg (France)	Weather Meteonorm [4]
Building size	140 m²	Type 56 [5]
Heat demand for space heating	6.7 MWh = 47.8 kWh/m²a (Floor heating)	Type 362 [6]
Domestic hot water demand	2075 kWh/a	
Volume of domestic hot water storage	Without solar 150 l , with solar 300 l	Type 340 [7]
Flat plate collector performance	η_0= 0.8, a_1= 3.5 W $m^{-2}K^{-1}$, a_2 = 0.05 W $m^{-2}K^{-2}$	Type 301 [8]
Heat pump power	7.9 kW (35°C heat sink / 0°C heat source)	Type 401 [9]
COP	4.8 (35°C heat sink / 0°C heat source)	
Borehole heat exchanger		Type 557 [10]
Heat conductivity of ground	2.15 W m^{-1} K^{-1}	
Type of borehole heat exchanger	Double U- tube	

The heat pump is operated with a borehole heat exchanger (BHE) as heat source and supplies heat to the domestic hot water (DHW) storage or the floor heating system. The applied performance data for the heat pump characterization is provided from heat pump measurements at ISFH [11]. The range of the measurement data is extended compared to typically provided data from manufactures. On the cold side the data is applied in a temperature range for the evaporator inlet temperature from -5°C to 30°C and on the hot side for the condenser outlet temperature from 30°C to 60°C. All temperature level combinations are respected except the pair of 30°C on the hot and 30°C on the cold side.

In the system the heat pump is connected directly to the floor heating system, in the following called radiator. The flow and return temperature distribution for the concept is given in fig. 1 and compared to the distribution of the reference system of Task 44 [2]. The radiator temperatures and the supplied energy amounts are slightly higher than in the reference system. The reason for this is the direct interaction of the heat pump and radiator that leads in a discontinuous switching of the heat pump around the set point temperature and therefore to slightly higher flow and return line temperatures, room temperatures and accordingly building losses. The energetic weighted temperature is 0.9 K higher for the flow line and 0.6 K higher for the return line if compared to the reference system.

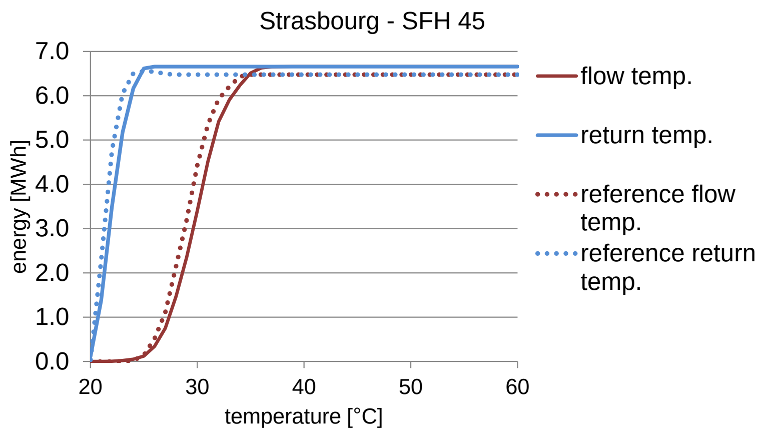

Figure 1. Temperature distribution of flow and return line of the radiator for the simulated system and the reference system in IEA Task 44 / Annex 38

This system is investigated in combination with a flat plate collector. The flat plate collector charges either the domestic hot water storage on the hot side of the heat pump (concept 1) or is connected in series to the borehole heat exchanger on the cold side of the heat pump (concept 2). Moreover, a combined system concept where solar heat could be either placed to the hot or the cold side of the heat pump is investigated (concept 3). A square view of all three systems concepts is presented in fig. 2.

The seasonal performance factor (SPF) of the heat pump system is defined as the usable heat for domestic hot water and space heating related to the electricity input. The necessary electric energy consists of the compressor and the pumps' consumptions. Additional penalties are added to the electrical consumption in case the heating demand is not met.

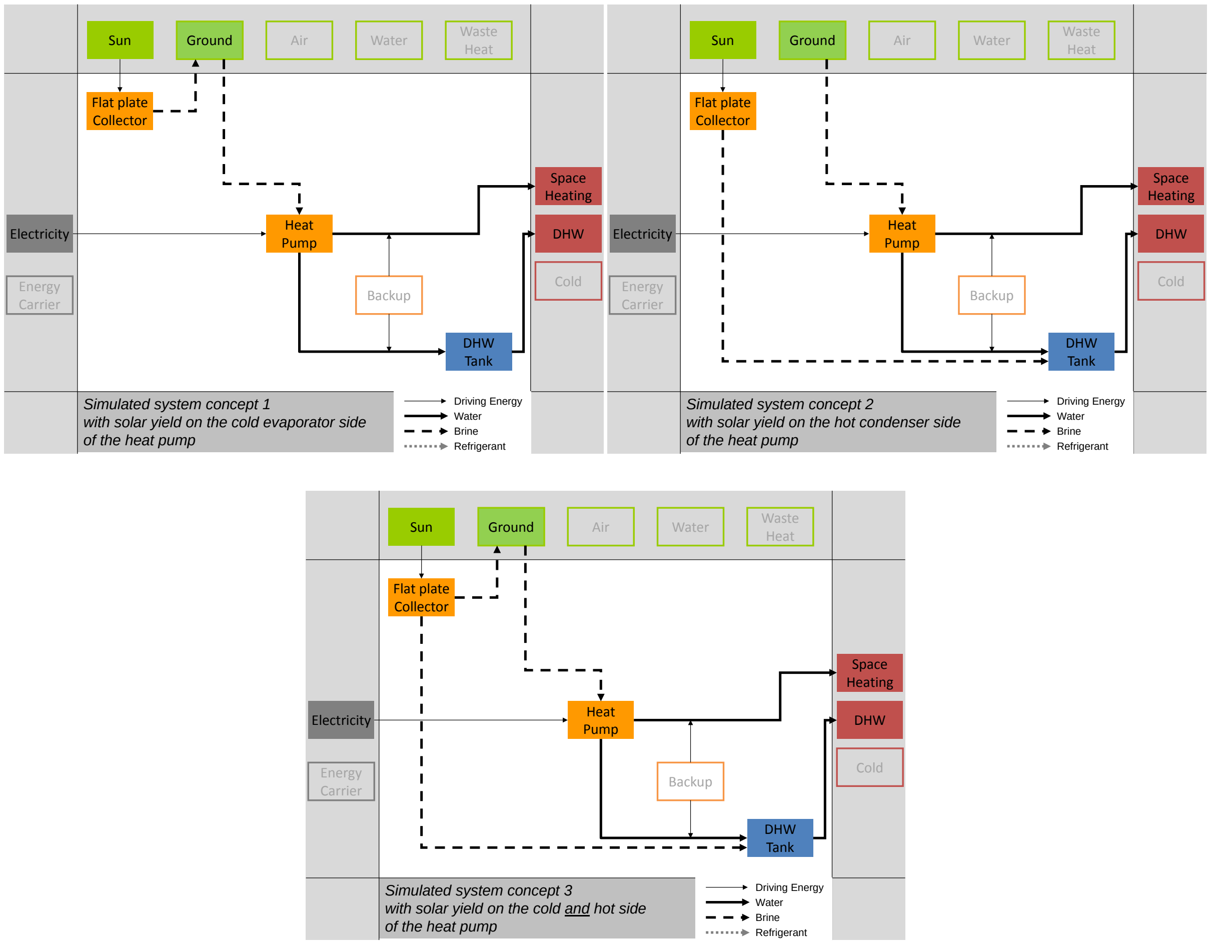

Figure 2. Square view of the investigated system concepts. Concept 1 (top, left): The solar collector is connected in series before the borehole heat exchanger on the cold heat source side only. Concept 2 (top, right): The collector is connected to the hot heat sink side only and charges the domestic hot water via an immersed heat exchanger. Concept 3 (bottom): The collector is connected to the cold heat and hot side of the heat pump. The backup heat is only used to protect the borehole heat exchanger from too cold temperatures.

2. Solar heat on the cold evaporator side of the heat pump (Concept 1)

In system concept 1, a flat plate collector is connected in series to the borehole heat exchanger. This and similar system concepts with borehole regeneration have been broadly investigated for different sorts of collectors with contradictory results. Kjellson [12, p. 31] points out that a temperature increase of 2 K was found for regenerated boreholes in 14 measured systems. In Bertram [13] a temperature lift of 3 K was determined for the combination with an unglazed collector in a measured system. Contrary to that, Hube [14] even states an absolute increase of the electrical consumption caused by the solar thermal borehole regeneration and the necessary pump energy.

Borehole heat exchangers may be regenerated for several reasons. Apart from the obvious reason to increase the temperature level and improve the system efficiency another motivation is to achieve an even balance on a yearly basis suppressing long- term temperature decrease and possible interference with other BHE. Moreover, the shortening of the BHE is an attractive goal as this could significantly reduce the system investment costs. In this context solar regeneration is an important feature to avoid oversizing of the BHE in the planning process, because regeneration reduces the influence of uncertain parameters as the real heat demand and the real ground properties. In the simulation the heat pump is supported by a direct electric back-up heater which allows the operation with short dimensioned BHE. This back-up heater covers the complete energy demand instead of the heat pump in case the BHE inlet temperature falls below -5°C. Accordingly, the back-up heater dominates the system performance for very short boreholes.

The mass flow rate for BHE recharging must be set carefully to avoid high pump consumptions. The mass flow rate on the evaporator of the heat pump is usually very high (above 1 m³/ h), which results in high pressure drops. Therefore, the BHE is regenerated with a reduced mass flow rate of 30 kg h^{-1} per m² collector. The dynamic calculation of the pump consumption is carried out during the simulations for every time step. The calculation takes into account the temperature, viscosity and BHE length of the fluid loop on the heat source side. The pump consumption is calculated with an mean efficiency of 0.32 assuming a variable speed high efficiency pump [15]. This recharging method achieves very small annual pump energy consumptions for BHE recharging of less than 10 kWh per year. The simultaneous operation of heat pump, solar collector and borehole heat exchanger however requires high nominal mass flow rates, which is respected accordingly. In contrast to the presented recharging with reduced mass flow rates a recharging concept with high mass flow rates would lead to significantly higher pump consumptions. In the given example with 5 m² collector the borehole is recharged during 2700 h hours. Assuming a constant nominal pump power of 100 W a pump consumption of 270 kWh would result for the collector loop.

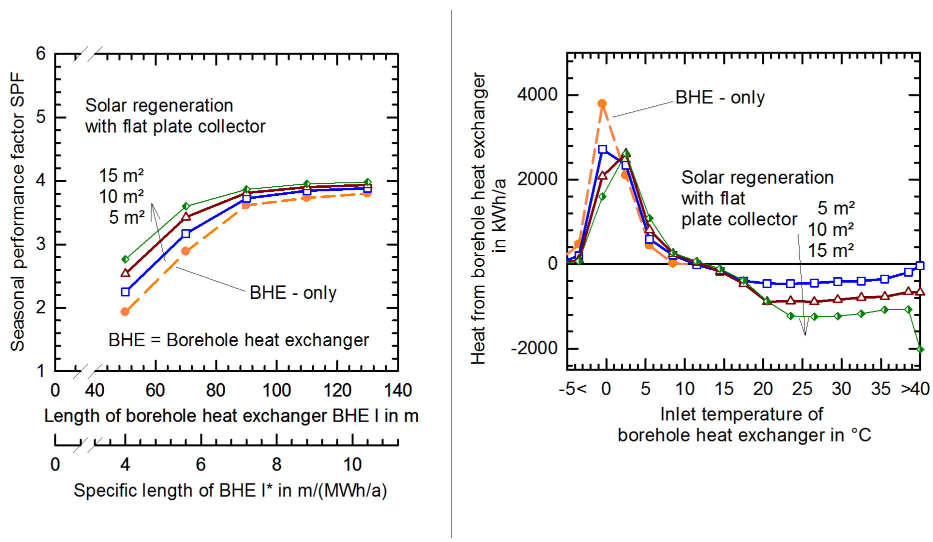

Figure 3. Impact of solar flat plate collector with 5, 10 and 15 m² on the seasonal performance factor SPF and the temperature distribution of the in system concept 1 the dashed line is without solar regeneration. The temperature distribution is given for a borehole heat exchanger length of 110 m.

The simulation results for different collector sizes and BHE lengths are presented in fig. 3 (left). For conventionally dimensioned BHEs of 110 m the achieved SPF improvement through the collector is 0.11 for 5 m², 0.17 for 10 m² and 0.22 for 15 m². These results correspond to electricity savings of 70, 100 and 130 kWh/a, caused by an energetic weighted temperature increase of 1.7, 2.7 and 3.7 K at the evaporator inlet (+2°C without collector). A considerable higher impact of solar collectors is achieved in undersized systems with smaller BHEs, especially for large collector areas.

The distribution of the BHE inlet temperatures with and without regeneration for different collector sizes is presented in fig. 3 (right). With rising collector area very low temperatures are reduced by a slight shift to higher temperatures in case of heat extraction (positive values). In contrast to that the temperature level for heat injection (negative values) is more sensitive to the collector area. For a 5 m² collector all heat is injected below 40°C whereas for 15 m² 20% of the solar heat is injected above 40°C. Therefore, special attention should be paid on this effect for larger dimensioned collector areas as high temperatures can be critical for polymeric borehole heat exchangers.

To conclude, the temperature influence for solar regeneration found in the literature is clearly explained by simulation results. The results clearly indicate the dependency of borehole length and collector area on the impact on the system. Also, the importance of sensible mass flow adjustment for solar recharging is pointed out. Thus, the results give an explanation for the variety of outcomes found in the literature.

2. Solar heat on the hot condenser side of the heat pump (Concept 2)

In system concept 2 a flat plate collector of 5 and 10 m² for direct support of hot water preparation was simulated for differently sized BHE. In this case, the solar heat is used only on the hot side of the heat pump. The simulation results for a system with a BHE of 110 m and a collector of 5 m² are displayed in table 2. The performance development for differently sized boreholes and a distribution for the borehole inlet temperature are given in fig. 4 for a collector of 5 and 10 m².

Table 2: Simulation results for seasonal performance factor SPF and electric energy consumption with and without solar domestic hot water preparation

System	SPF	Electric energy in kWh
Without solar	3.73	2373
With 5 m² flat plate collector for DHW preparation	4.95	1790
Difference	1.22	583

As to be expected, the direct use of solar energy achieves significantly higher improvements compared to the heat injection on the cold side. For 5 m² collector the improvement is 1.2 in the SPF or 25% in electricity savings. The solar fraction for the pure domestic hot water preparation for the system reaches 65%. A larger collector area leads to small efficiency improvements. The SPF increases to 5.21 for a collector size of 10 m². The absolute electricity savings in the system are only connected to the collector size and are independent of the BHE length. Consequently, the impact by the direct collector use does not increase with smaller BHE (fig. 4) in contrast to the indirect collector use (fig. 3). On the contrary, the relative savings by the collector even decrease for inefficient systems, which correspond to smaller BHEs and high absolute electricity demands.

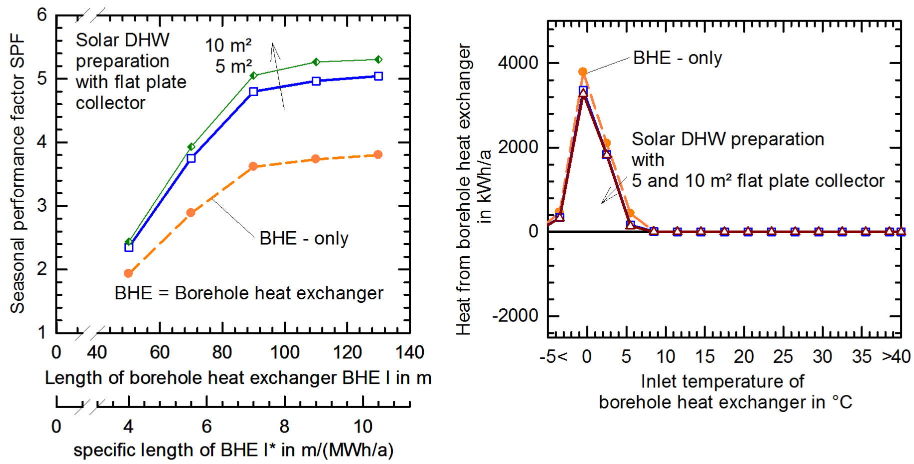

Figure 4. Impact of solar flat plate collector with 5 and 10 m² on the seasonal performance factor SPF (left) and the temperature distribution of the system concept 2 (right). The dashed line is without solar DHW preparation. The temperature distribution is given for a borehole heat exchanger length of 110 m.

Apart from the direct benefit through direct use the solar yield reduces the required heat from the heat pump. As a result, this decreases the extracted heat from the BHE and supports it passively. Without collector the BHE provides 6790 kWh on the evaporator side of the heat pump. This heat demand is reduced by the solar collector by 13.3% for the system with 5 m² collector and by 15.3% for 10 m². However, the effect of this passive support on the temperature of the BHE heat source is negligible.

3. Solar heat to both sides, hot and cold, of the heat pump (Concept 3)

In concept 3 solar heat can be injected either on the cold heat source side (Concept 1) or the hot heat sink side of the heat pump (Concept 2). Comparing both ways of heat injection obviously the injecting of the heat to the hot side is preferable. However, the combination of both, solar domestic hot water preparation and the solar BHE recharging, can be an attractive option with the intention to either avoid stagnation or to operate the collector at times of low solar radiation that do not meet the conditions for charging the domestic hot water storage. Times with low radiation levels might then offer a benefit switching the heat injection from the hot to the cold side [17].

In the case of system concept 3 a first simple system approach is realized that combines the heat injection on the cold and hot side. The system control has a clear priority for domestic hot water preparation. That means the solar collector is operated on the cold side of the heat pump only if the collector does not reach the necessary storage temperature of the domestic hot water storage. In fig. 5 the simulation results are presented comparing different system configurations of the concepts 1, 2 and 3.

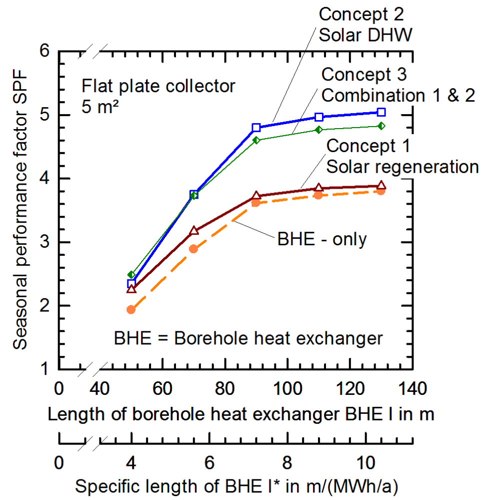

Figure 5. System performance of 5 m² flat plate collector for the system concepts one, two and three

The results reveal the simple concept 2 (domestic hot water preparation only) to perform best and the combined system concept 3 slightly lower. The reason for the decreased performance of the combined system is found in the lower solar heat delivered to the hot water storage. Despite the clear priority for DHW heating the solar DHW heat is decreased to 1.6 MWh/a instead of 1.9 MWh/a. In contrast to that the absolute collector yield is significantly increased from 2.2 MWh/a to 3.6 MWh/a with additionally recharging of the BHE. But, the achieved benefit caused by (partly) BHE regeneration in concept 1 is small and hence does not compensate the lack of solar heat in the DHW storage.

To conclude, small performance decreases could be expected when combining solar domestic hot water preparation and solar BHE regeneration concepts with simple control strategies. Nevertheless, the results are certainly not valid and transferable to all combined systems. It stands to reason that an intelligent control strategy could avoid a performance decrease and in the long-run combined systems should even lead to higher performances. Such intelligent control strategies might become more important especially for larger systems, where larger collector areas (longer stagnation periods) and larger BHE fields (higher advantage of regeneration) are combined.

4. Conclusion

The impact of solar thermal collectors on the heat pump systems was investigated in simulation studies. The direct use on the hot side for domestic hot water preparation was identified to be the best option. The comparatively small system with 5 m² collector area reached already a SPF of 5 (concept 2). In contrast, solar BHE recharging reaches smaller benefits of 0.1-0.2 and an absolute SPF of 3.85 for the same collector size (concept 1). The BHE regeneration necessarily demands a careful adjustment of the recharging mass flow rate. In the given example this method reduces the pump energy from 270 to 10 kWh. However, a first approach to combine these two systems in concept 3 results in a slightly reduced performance compared to concept 2. This clearly points out that the heat from flat plate collectors should preferably be used directly. Apart from the direct SPF benefit this relieves the BHE and therefore simplifies the natural regeneration of the ground. Nonetheless, the impact by passive support on the borehole temperatures for the investigated solar DHW application is negligible. Solar heat pump systems with heat injection on the hot and cold side of the heat pump on the other hand even bear the risk of a lower performance. More intelligent control strategies and further developments for combined system concepts would be necessary to make their theoretical advantage accessible.

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