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Simulation and performance analysis of combined parallel solar thermal and ground or air source heat pump systems

Danny Jonas [a,*], Georg Frey [a], Danjana Theis [b]

[a] Chair of Automation and Energy Systems, Saarland University, 66123 Saarbrücken, Germany
[b] htw saar, University of Applied Sciences, 66117 Saarbrücken, Germany

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ABSTRACT

The combination of solar thermal (ST) systems and heat pumps (HP) is a promising hybrid heating system concept for efficient energy supply of buildings. In this work, a simulation study on the performance of combined ST and HP systems and a comparison with systems without ST collectors for different types of buildings and climates is presented. With regard to the dominating market-available systems, the evaluation is limited on systems with parallel integration of ST collectors. For a better transparency of the results, the simulation models and the main model parameterization are explained in detail. The results of the simulations show that the performance of HP systems can significantly be increased by adding a ST system. The relative increase of the performance decreases with increasing space heating demand of the building and is lower for climates with low ambient temperatures. In contrast, in most cases the absolute electricity savings increase with increasing space heating demand and are higher for systems with air source HPs. The seasonal performance factor (SPF) of parallel solar thermal and ground source heat pump (SGSHP-P) systems is between 0.5–1.1 (Strasbourg) and 1.0–2.0 (Helsinki) higher than the SPF of parallel solar thermal and air source heat pump (SASHP-P) systems with the same ST collector area. Hence, the difference between the performance of SASHP-P and SGSHP-P systems increases with increasing heat load and decreasing ambient temperatures of the location. However, in case of moderate climates like Strasbourg, SASHP-P systems can achieve the same or even higher values of SPF than ground source heat pump (GSHP) systems without ST collectors. Especially for buildings with low energy demand for space heating, the SPF is higher (up to 78.5% with a collector area of 25 m^2) and the systems can compete with each other. In a nutshell, in particular if the investment costs of a borehole heat exchanger and a ST system are similar or if there is no possibility to use a GSHP system with borehole heat exchanger, using a SASHP-P system may be a useful opportunity for a heating system concept with high energy performance and low electricity demand.

1. Introduction

The combination of solar systems, especially solar thermal (ST) systems, and heat pumps (HP) is a promising hybrid heating system concept for efficient energy supply for space heating (SH) and domestic hot water (DHW) preparation in buildings. The notion combined solar and heat pump (SHP) system comprises basically all combinations of these systems. Combined solar thermal and heat pump (STHP) systems can generally be classified in parallel, serial and regenerative system concepts by the interaction between ST and HP (Frank et al., 2010). The first research work with use of classification in series (serial) and parallel systems was carried out by Freeman et al. (1979). Parallel systems are systems with independent supply of useful energy for SH and/or DHW by ST system and HP, e.g. via a buffer storage tank. Serial systems are systems in which the ST system is used as heat source for the HP. In these concepts the ST system can either be used exclusively or as additional source and either directly or via a storage tank. Regenerative system concepts are systems in which the ST system is used for the regeneration of the main source of the HP, usually the ground. Furthermore, there is the possibility to combine these system concepts as individual concepts do not exclude each other (Frank et al., 2010; Hadorn, 2015). During the last years a wide range of combinations of these systems have entered the market. A statistical analysis on market-available STHP systems can be found in Ruschenburg et al. (2013) and Ruschenburg and Herkel (2013). As a main result, parallel systems were identified as the

* Corresponding author.
E-mail address: danny.jonas@aut.uni-saarland.de (D. Jonas).

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market-dominating system concepts (61% of the surveyed systems). Hence, the following investigations focus on parallel systems with ground or air source HP in combination with ST collectors.

Earlier overviews of simulation results of STHP systems within the International Energy Agency (IEA) Solar Heating and Cooling Programme (SHC) Task 44/Heat Pump Programme (HPP) Annex 38 were provided by Haller et al. (2014) and Hadorn (2015). The authors presented summaries of simulations which were performed by different authors and different simulation platforms. Although the boundary conditions of IEA SHC Task 44/HPP Annex 38 (see Section 3) were used, the simulation results are not comparable in detail as different simulation parameters and conditions were used for the STHP systems itself. Examples for different parameters and conditions in the performed simulations are different coefficients of performance (COP) of the HP or different assumptions on the hydraulic components (e.g. electricity consumption of pumps or hydraulic integration), ST collector performance, storage management and the control of the system. In Haller et al. (2014) simulation results for different concepts of STHP systems were compared, especially for the climate of Strasbourg and the SFH45 building (renovated building, see Section 3.2.2). The main benefits of parallel integration of ST collectors in HP systems were summarized in the increase of the seasonal performance factor (SPF, see Section 4) of the overall system and electric energy savings. For air source heat pump (ASHP) systems, the SPFs were in the range of 2.4 and 3.0 and were increased up to 4.2 by parallel integration of ST collectors with a collector area of 25 m^2. In case of ground source heat pump (GSHP) systems, the SPFs were in the range of 3.5 and 3.9 and up to 6.5 with parallel ST collector integration and a collector area of 25 m^2. According to the authors, the increase of SPF mainly depends on the type of HP, the type and area of ST collectors and the boundary conditions, especially climate and heat load. In Hadorn (2015) the reason for the significant increase of the SPF by adding ST collectors in parallel to HP systems was explained by the fact that ST collectors can cover a part of the heating demand with much higher ratio of heat delivered to electricity consumed (e.g. for pumps and controller) than the HP. The electricity savings related to the collector area of the investigated systems were in the range of 60 $kW\,h\,m^{-2}\,a^{-1}$ and 140 $kW\,h\,m^{-2}\,a^{-1}$. In heating systems with fuel burning devices the solar collector yield and also the fuel savings decreased with increasing temperatures of the heat demand. In contrast, in STHP systems the electricity savings compared with a HP system without ST increased with increasing temperatures of the heat demand. The reason for this is that the reduction of performance of the HP by increasing temperatures is higher than the reduction of solar yields.

Carbonell et al. (2014a) analyzed the influence of parallel integration of ST collectors in GSHP and ASHP systems for different types of buildings and climates by simulation. The SPF of the overall SHP system increased for both system concepts, ASHP and GSHP, by adding ST collectors. In GSHP systems, the SPF of the HP itself increased also by adding a ST system due to the covering of DHW loads with high temperatures and low HP performance by solar energy. In contrast, in most parallel solar thermal and air source heat pump (SASHP-P) systems, the SPF of the HP itself decreased in comparison with ASHP systems without solar collectors. On the one hand, the ST system covered a part of DHW loads and the HP worked less time with high heat sink temperatures. On the other hand, the performance of the HP decreased due to the covering of heat loads at times with moderately high ambient temperatures and best performance of the ASHP system, e.g. in spring, by solar energy. The decreasing effect for the HP performance in these periods usually dominated in comparison with the effect of increasing performance in periods with covering of high temperature demands for DHW preparation by solar energy (Carbonell et al., 2014b). In terms of absolute electricity savings, the benefit of adding ST collectors to a HP system increased with the electricity consumption of the reference system without ST system. Therefore, ASHP systems have sometimes higher potential of electricity savings by adding solar collectors compared to GSHP systems (Carbonell et al., 2014a). At this, it should be noted that the authors used different HPs with different COP at nominal conditions in case of resizing the systems for different locations and buildings.

Poppi et al. (2016) studied the influence of component size on electricity demand for STHP systems with air source and ground source for the climates of Zurich and Carcassonne by the use of scale factors. The results of the simulation studies showed that changes in collector area from 5 m^2 to 15 m^2 decreased the electricity demand between 305 $kW\,h\,a^{-1}$ and 552 $kW\,h\,a^{-1}$ depending on the type of HP and building. The smaller values in decreasing the electricity demand resulted for the SFH45 building with GSHP, the higher values for the SFH100 building (non-renovated existing building, see Section 3.2.2) with ASHP.

In the past, GSHP systems were classified as the most efficient standard HP system in moderate and cold climates. However, SASHP-P systems can be an efficient alternative to GSHP systems with no increase in investment costs. As mentioned in Poppi et al. (2016), a lot of research has been carried out for STHP systems, but there are no structured studies beside Poppi et al. (2016) that includes both, SASHP-P and parallel solar thermal and ground source heat pump (SGSHP-P) systems, for a wide range of boundary conditions with uniform efficiency parameters and assumptions on the main components of the STHP system. As Poppi et al. (2016) concentrated on STHP systems for SFH45 and SFH100 buildings without comparison with HP only systems, the main objective of this study is to figure out the influence of parallel ST integration on GSHP as well as on ASHP systems in consideration of new buildings with low heating energy demand (SFH15) and to analyze on which boundary conditions SASHP-P systems can compete with GSHP systems without ST collectors. Thus, this work presents a widely ranged simulation study on the performance of parallel STHP systems and a comparison with systems without ST collectors for three different types of buildings (SFH15, SFH45 and SFH100) and moderate as well as cold climates (Strasbourg, Helsinki).

In the following chapters, the system concepts (Section 2) and the simulation models with the main model parameterization (Section 3) will be explained in detail. This is followed by the description of the performance indicators and the methods of analysis (Section 4). Section 5 goes on to discuss the simulation results. Finally, Section 6 provides the main conclusions and an outlook to further work.

2. System description and concepts

As mentioned before, to analyze the impact of ST collectors on ground and air source HP systems it is necessary to compare the simulations of combined systems with systems without solar collectors. Therefore, the following investigations focus on four different system concepts which will be described in this section.

The GSHP system consists essentially of a ground source HP with borehole heat exchanger as heat source and a buffer storage tank as heat sink of the HP (see Fig. 1). The buffer storage tank is used for the energy supply of the SH system and the heat exchanger for DHW preparation. The HP charges the buffer storage tank in two different zones. The lower and middle zones of the storage are used for the SH circuit, the upper zone supplies the DHW circuit on a higher temperature level. Depending on the actual demands, the HP charging is switching to the different zones with priority on