Model-based Analysis of Solar Thermal and Heat Pump Systems using TRNSYS

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Abstract

The combination of solar thermal and heat pump (STHP) systems is a promising hybrid concept for the efficient and sustainable energy supply of buildings. In general, the modeling and simulation of such complex energy systems is a challenging task as it requires expert knowledge in modeling as well as in the behavior of the real systems. As an alternative to the complex and lengthy general modeling process, a TRNSYS-based stand-alone tool is presented which enables users to analyze different predefined SHP concepts with hardly any knowledge in modeling and simulation itself. The predefined STHP concepts are explained in detail and the simulation results for a comparison of the performance of different system concepts are presented. The predefined systems are ground or air source heat pump systems with or without parallel integration of solar thermal collectors. In addition to earlier work, these system concepts are extended by solar thermal and ice storage heat pump systems. On the one hand, the simulation results show that in case of moderate climate and new as well as renovated buildings, solar thermal and air source heat pump systems can compete with ground source heat pump systems without solar integration and can achieve the same or even higher values of seasonal performance factors. On the other hand, the results show that solar thermal and ice storage systems are efficient solar thermal heat pump systems, which can achieve higher SPFs than air source heat pump systems and for new buildings even SPFs in the range of ground source heat pump systems. Furthermore, this contribution shows the advantages and the possible performance improvements by parallel integration of solar collectors in different system concepts.

Keywords: modeling, simulation, solar thermal, heat pumps, combined systems, performance, TRNSYS

1. Introduction

The combination of solar systems and heat pumps (HP) is a promising hybrid concept for the efficient energy supply of buildings. The notion combined solar and heat pump (SHP) system comprises basically all combinations of these systems, including photovoltaic (PV) and solar thermal (ST) systems. Combined solar thermal and heat pump (STHP) systems only comprise combinations with ST integration. Depending on the heat source of the HP, STHP systems can be divided in systems with ground source (SGSHP), air source (SASHP), ice storage (SISHP) and others, like combined solar and water source or waste heat source HP systems. Independently of the heat source of the HP, the systems can be classified in parallel, serial and regenerative system concepts by the interaction between ST system and HP (Frank et al., 2010). Parallel systems (fig. 1a) are systems with independent supply of useful energy for space heating (SH) and/or domestic hot water (DHW) preparation by the ST system and the HP. Serial systems (fig. 1b) are systems in which the ST system is used as heat source of the HP. Regenerative system concepts (fig. 1c) 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; Ruschenburg and Herkel, 2015). The classification in parallel, serial and regenerative system concepts (or combinations) can be indicated with -P, -S and -R at the end of the abbreviation of the general STHP concept, e.g., SGSHP-P means parallel combined solar thermal and ground source heat pump systems.

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During the past decade, a wide range of combinations of these systems entered the market. A statistical analysis on market-available STHP systems can be found in Ruschenburg et al. (2013) and Ruschenburg and Herkel (2013, 2015). As a main result, parallel systems were identified as the market-dominating system concepts with a proportion of 61% of the surveyed systems (Ruschenburg et al., 2013). Hence, the following investigations will focus mainly on parallel STHP systems with ground or air source HP and on HP systems without ST collectors. As addition, (serial and serial plus parallel) concepts with ice storage systems will be considered as solar only concept without additional heat source.

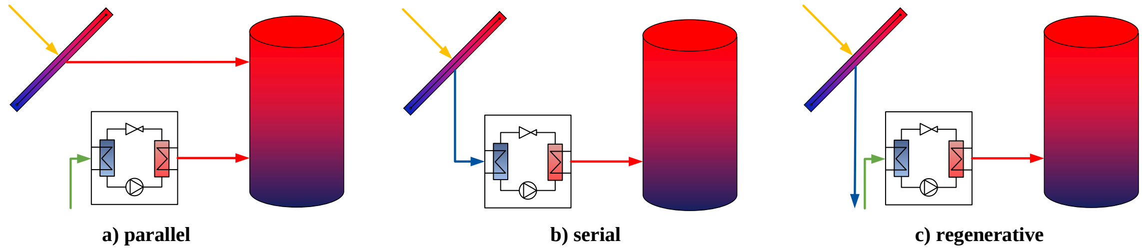


Fig. 1: Classification of solar thermal and heat pump systems in parallel, serial and regenerative system concepts

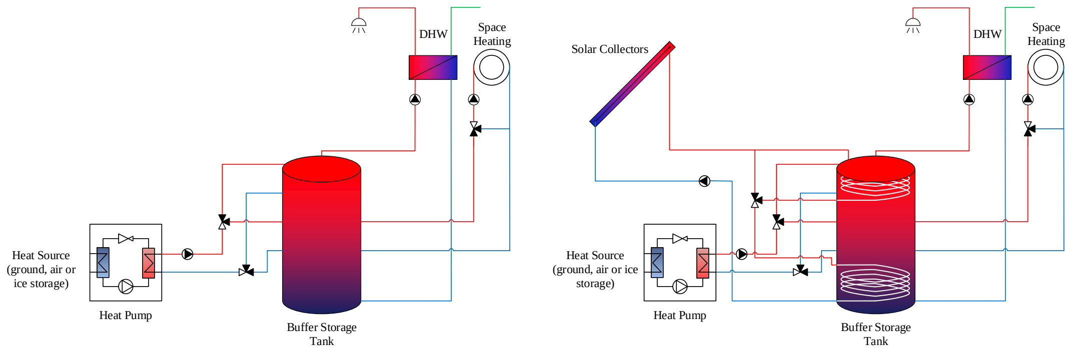
The variety of possible investigations on SHP systems requires well-validated simulation tools. One possibility to simulate these systems is the use of the simulation environment TRNSYS. Model design in TRNSYS is a complex task, which requires expert knowledge in different fields. The objective of this work, based on the former contributions published in Jonas et al. (2017a, 2017b, 2017c), is the development of a user-friendly TRNSYS-based simulation tool (SHP-SIMFRAME) which can be used for the simulation and the model-based analysis of different SHP concepts. In Dott et al. (2013) and Haller et al. (2013a), the International Energy Agency (IEA) Solar Heating and Cooling Programme (SHC) Task 44 / Heat Pump Programme (HPP) Annex 38 defined boundary conditions for a better comparability of results of STHP system simulations, which are also implemented in the simulation tool of this contribution (see section 3). At present, the tool contains four predefined STHP systems (GSHP, ASHP, SGSHP-P, SASHP-P). However, it will be expanded by SISHP systems and PV systems to analyze SHP concepts for heat and electricity supply of buildings. Overviews of simulation results of STHP systems within the IEA SHC Task 44 / HPP Annex 38 were provided by Haller et al. (2014, 2015). The authors presented summaries of simulations which were performed by different authors and different simulation platforms using the boundary conditions of IEA SHC Task 44 / HPP Annex 38. Investigations focused on SGSHP-P and SASHP-P systems can be found in Carbonell et al. (2014a, 2014b), Jonas et al. (2017a) and Poppi et al. (2016).

In the following sections, the system concepts (section 2) and the model design in TRNSYS as well as the developed TRNSED application (section 3) will be explained in detail. This is followed by a simulation study of the considered STHP concepts (section 4). Finally, section 5 provides the main conclusions and an outlook on further work.

2. System concepts

Fig. 2 shows the considered system concepts without ST collector integration (fig. 2a) and with parallel ST collector integration (fig. 2b) regardless of the heat source of the HP. The GSHP system consists essentially of a brine/water HP with borehole heat exchanger as heat source and a buffer storage tank as heat sink of the HP. 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 current demands, the heating by the HP is switching to the different zones with priority on DHW preparation. The SGSHP-P system corresponds to the GSHP system with additional solar loop. The solar collectors supply the buffer storage with solar energy via two internal heat exchangers depending on the current solar collector outlet temperature. If the temperature of the solar collectors is high enough, the upper heat exchanger is charged and the return of the upper heat exchanger is used as input for the lower heat exchanger. Otherwise, the solar collectors supply only the lower heat exchanger with solar energy. The advantage of this solution is to supply the upper

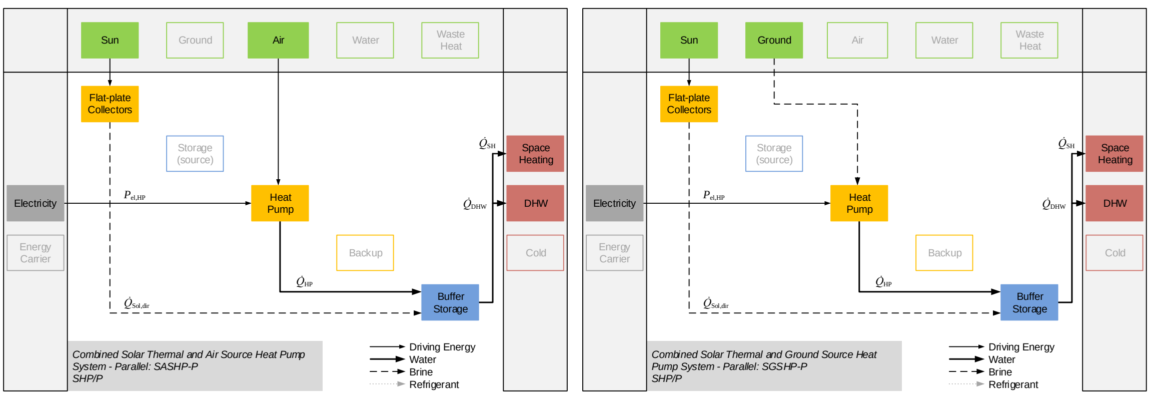
DHW zone of the storage with solar energy on a high temperature level, if possible, and thus avoid storage mixing and exergy losses and achieve better storage stratification. The ASHP system and the SASHP-P system correspond to the GSHP and SGSHP-P systems with a replacement of the GSHP by an ASHP. The SISHP-S systems correspond to the GSHP system with a replacement of the borehole heat exchanger by an ice storage, which is charged by solar absorbers, as heat source of the HP. The SISHP-S+P concept corresponds to the SISHP-S system with additional solar loop using solar collectors for the direct supply of the buffer storage tank (indicated by "-S+P" instead of "-S,P" which could be used for concepts with switching of solar absorbers from heat source to direct buffer storage (heat sink) charging).



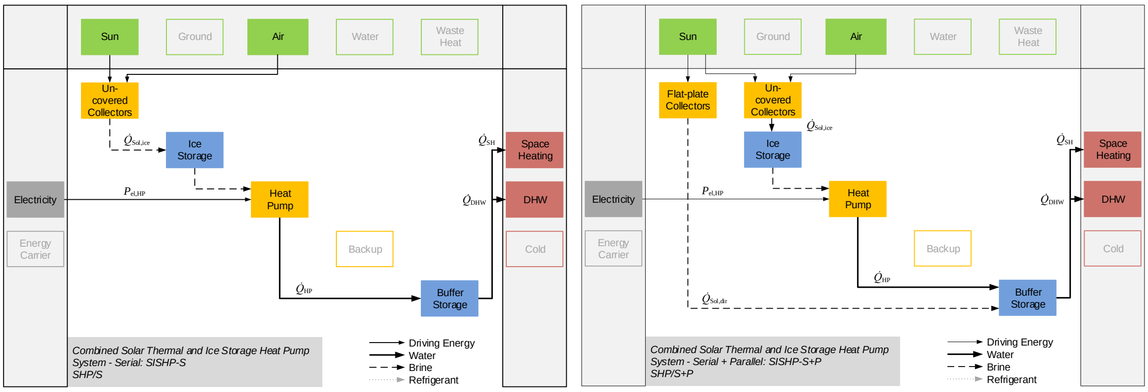
a) GSHP, ASHP and SISHP-S **b) SGSHP-P, SASHP-P and SISHP-S+P**

Fig. 2: STHP system concepts

According to the approaches in Frank et al. (2010) and Ruschenburg and Herkel (2015), visualizations of the energy flows of the considered STHP system concepts are shown in fig. 3. At this, flows of final energies, which are obtained externally (like electricity as driving energy for the HP), are shown on the left boundaries of the flow charts. The environmental energy sources (like sun, ground or ambient air) of the HP and the ST systems are shown on the upper boundaries. The useable energy output of the system (e.g. for SH or DHW preparation) is placed on the right boundaries. The system components (like HP, ST collectors or absorbers, thermal storages on the source or sink side of the HP and backup heating systems) have fixed positions and are highlighted if existing in the respective concepts. In case of the considered system concepts, the ST collectors (flat-plate collectors), the solar absorbers (uncovered collectors), the source side storage (ice storage), the HP and the sink side storage (buffer storage) are highlighted as well as the used environmental energy sources (sun and ambient air or ground). In addition, the electricity used as driving energy for the HP is highlighted as well. The energy flows between the components are shown as connections in the flow chart. The distinction between various carrier media is indicated by different types of lines.



a) SASHP-P **b) SGSHP-P**



c) SISHP-S d) SISHP-S+P

Fig. 3: Visualization of energy flows in the considered solar thermal and heat pump system concepts

3. Model design and simulation framework

3.1 Background

The aim during the development of the TRNSED application SHP-SIMFRAME was to create a tool, which can be used for the simulation of SHP systems with hardly any knowledge in modeling or programming. The tool should be a user-friendly framework which can be used to perform parameter studies and analyses of SHP systems (e.g. for different locations and/or buildings) or test individual components (e.g. ST collectors or HPs) for the use in SHP systems by editing the component specific parameters and data sets. In its latest version, SHP-SIMFRAME contains GSHP, ASHP, SGSHP-P and SASHP-P system models. In future work, the tool will be expanded by SISHP systems including the TRNSYS models used for the simulation study of this contribution. Furthermore, as the name “SHP”-SIMFRAME implies, it will be extended by electrical solar energy (PV and PV thermal) systems to analyze SHP concepts for the heat and the electricity supply of buildings.

3.2 TRNSYS models

The simulation models of the main system components, especially the SHP system components, in TRNSYS are summarized in tab. 1. For a better structure and a higher level of modularity and flexibility, the TRNSYS model is divided in the subsystems *Reference System and Storage*, *SHP* and *SHP Control*. The subsystems include TRNSYS equation blocks, which are used as inputs and outputs of the subsystems for their connection via variables (see Kuethe et al., 2008). The subsystem *Reference System and Storage* include the reference system of the IEA SHC Task 44 / HPP Annex 38 (including boundary conditions and building model) and the Multiport-Store Model Type 340. General boundary conditions contain weather data for three different locations which represent warm (Athens), moderate (Strasbourg) and cold (Helsinki) climates (Meteonorm, 2009)[1] and ground properties for the simulation of ground coupling losses of the building and ground heat exchangers (Haller et al., 2013a). Within the reference framework, three different buildings are defined. The different buildings represent single-family houses (SFH) with heat loads for SH of 15 kWh/m²a (SFH15), 45 kWh/m²a (SFH45) and 100 kWh/m²a (SFH100) for the climate of Strasbourg. SFH15 represents a new building with very high energetic quality, SFH45 a renovated building with good thermal quality of the building envelope and SFH100 a non-renovated existing building. The boundary conditions also include the design supply and return temperatures of the heat distribution system for SH for the different locations and buildings (Dott et al., 2013) as well as the DHW draw off profiles. The DHW draw off profiles correspond to an average draw off of 140 l per day with a draw off temperature of 45 °C and are equivalent to an energy consumption for DHW preparation of 5.845 kWh/d with a cold water temperature of 10 °C. According to the boundary conditions of IEA SHC Task 44 / HPP Annex 38, the borehole heat exchangers are simulated as double-U pipes. The main properties of the borehole heat exchangers

[1] The permission of Meteotest for using Meteonorm climate data for simulations within the IEA SHC Task 44 / HPP Annex 38 is gratefully acknowledged.

are also defined within the framework (Haller et al., 2013a). The annual heat loads for SH (Q_{SH}) and DHW preparation (Q_{DHW}) for the climate of Strasbourg and the different buildings are summarized in tab. 2. Further information on the reference system, boundary conditions and building models can be found in Dott et al. (2013) and Haller et al. (2013a, 2015).

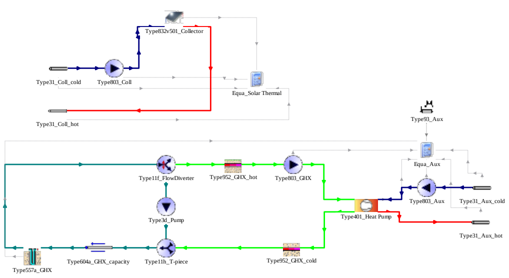
Tab. 1: TRNSYS models of the main system components

Component	TRNSYS Model
Building	Type 56 (TRNSYS, 2014)
Solar collector / absorber	Type 832 (Haller et al., 2013b)
Compressor HP	Type 401 (Wetter and Afjei, 1997)
Borehole heat exchanger	Type 557a (TESS, 2014)
Buried ice storage tank	Type 343 (Hornberger, 2006)
Multiport storage tank	Type 340 (Drück, 2006)
Single speed pump	Type 3d (TRNSYS, 2014)
Variable speed pump	Type 803 (Heimrath and Haller, 2007)
Pipe	Type 31 (TRNSYS, 2014)
Bi-directional noded pipe	Type 604a (TESS, 2014)
Buried noded pipe	Type 952 (TESS, 2014)
Flow diverter	Type 11f (TRNSYS, 2014)
Tee-piece	Type 11h (TRNSYS, 2014)

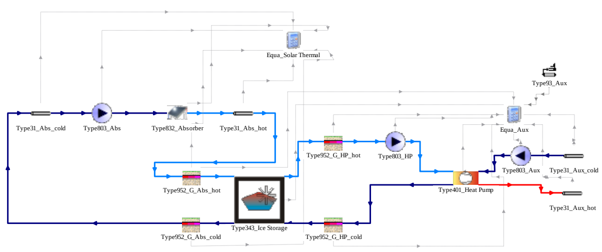
Tab. 2: Annual heat loads for SH and DHW preparation

Location	Building	Q_{SH}	Q_{DHW}
		[kWh/a]	[kWh/a]
Strasbourg	SFH15	2474	2076
	SFH45	6476	2076
	SFH100	14031	2076

In general, the *SHP* subsystem includes the HP and the heat source models. In case of *GSHP* systems, the subsystem contains the components for the heat source circuit, the brine/water HP, the pump for buffer storage charging and the pipes from the HP to the storage. The heat source circuit consists of the vertical borehole heat exchanger, the heat source pump, buried pipes and an additional circuit with adiabatic pre-pipe in front of the input of the borehole heat exchanger. The adiabatic pre-pipe is used for a better representation of the short-term behavior of the borehole heat exchanger in the simulation due to missing short-term heat capacity effects of Type 557. More information on the pre-pipe concept, the model validation and parameterization rules can be found in Bertram (2015) and Pärisch et al. (2015). In case of *ASHP* systems, the subsystem includes the air/water HP, the pump for buffer storage charging and the pipes from the HP to the storage. In case of *SISHP-S* systems, the subsystem contains the components for the heat source circuit, the brine/water HP, the pump for buffer storage charging and the pipes from the HP to the storage. The heat source circuit consists of the buried ice storage tank model, the heat source pump to the HP, buried pipes and an additional solar absorber circuit with solar absorber circuit pump and pipes from the solar absorber to the ice storage tank for ice storage charging. Furthermore, in case of systems with parallel ST (flat-plate collectors) integration (*SGSHP-P*, *SASHP-P* and *SISHP-S+P*), the subsystems contain an additional solar loop with ST collectors, solar circuit pump and pipes from the solar collectors to the buffer storage. Using the example of a SGSHP-P (fig. 4a) and a SISHP-S (fig. 4b) system, the subsystem SHP is shown graphically in fig. 4. The subsystem *SHP control* includes the control of the HP and ST system and consists of a combination of differential controllers (Type 2b) and equation blocks. Due to their simplicity, the subsystems of SHP control are not shown graphically. The used control strategies and parametrization possibilities are described in section 3.3.



a) SGSHP-P

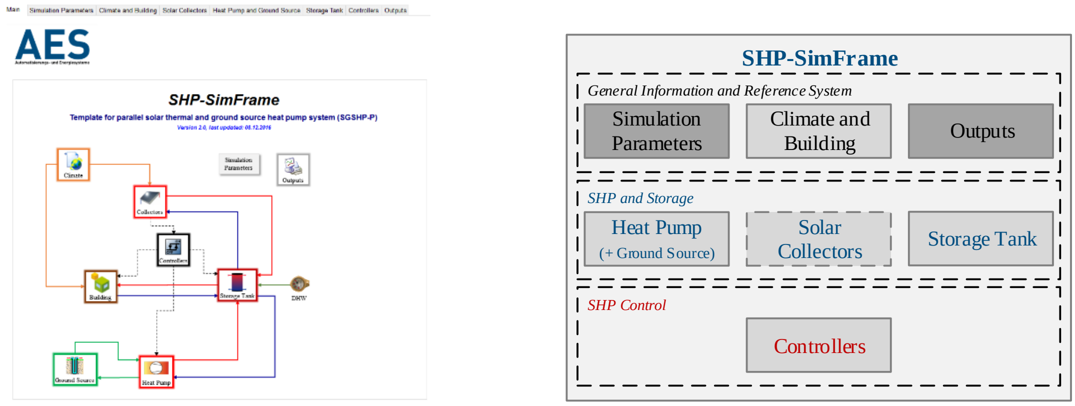


b) SISHP-S

Fig. 4: TRNSYS Subsystem SHP

3.3 TRNSED application

The developed TRNSED application for the simulation of SHP systems are based on the TRNSYS models illustrated in section 3.2. In addition to a navigation page (see fig. 5a) as initial interface, the tool consists of the submodules *Simulation Parameters*, *Climate and Building*, *Solar Collectors* (in case of ST integration), *Heat Pump* (*and Ground Source* in case of GSHP, SGSHP-P), *Storage Tank*, *Controllers* and *Outputs* for the parameterization of the simulation models. The submodules of the tool and the assignments to the TRNSYS subsystems mentioned before are illustrated in fig. 5b. In future work, an Ice Storage submodule will be added for the simulation of SISHP-S and SISHP-S+P systems.



a) Navigation page, example: SGSHP-P **b) Submodules**

Fig. 5: TRNSED application as stand-alone tool

The submodule *Simulation Parameters* can be used to set general simulation parameters like the simulation time step and length depending on the simulation requirements. The submodule *Climate and Building* allows the user to choose the pre-defined climate data (Helsinki, Strasbourg and Athens) and the building type (SFH15, SFH45, SFH100) from a pull-down menu. The *Outputs* submodule contains a selection of predefined outputs, which can be selected for the graphical (plotter) and data file (printer) based evaluation of the simulation results. The *Storage Tank* submodule is used to set the general thermal storage parameters (volume, initial tank temperature, insulation thickness and additional loss factors) and the relative heights of the temperature sensors for the control of the SHP system. This includes temperature sensors for storage protection, for collector loop control as well as for charging of the DHW zone and the SH zone. In addition, within this submodule, the user can specify the relative heights of the storage tank connections. This includes in general the relative heights of the HP connections (for reheating the SH zone and DHW zone) and the SH and the DHW supply connections. In case of ST integration, the submodule also includes the relative heights of the connections to the solar loop. In general, the *Heat Pump* submodule contains a pull-down menu to select data sets, which are used in Type 401 for the HP modeling, and the definition of HP parameters like power, heat exchanger temperature differences of the HP, mass flow rates, set points of low-pressure and high-pressure thermostat or heat-up and cool-down constants. In addition, within this submodule, the user can specify the piping between the HP and the storage tank. In case of ASHP systems, the user has the possibility to define additional parameters for a better consideration of icing and defrosting effects. Furthermore, in case of GSHP systems, this submodule allows the user to define ground properties and borehole properties like number and depth of the boreholes, space between boreholes or the length of buried pipes between ground heat exchanger and HP. In case of STHP systems, SHP-SIMFRAME includes the submodule *Solar Collectors*. This module allows the user to define the solar collector field (area, tilt, azimuth and specific mass flow) and the collector loop pipes properties as well as the solar collector efficiency parameters. The submodule *Controllers* can be used to set the control parameters for the solar loop and the reheating of the storage tank for SH and DHW preparation by the HP. The set point calculation of the supply temperature $T_{\mathrm{Set,SH}}$ for SH depends on different factors (e.g. the ambient temperature or the design heat load of the specific building and location) and is described in Dott et al. (2013). The HP buffer storage charging for SH is turned on if the difference between the storage temperature sensor for SH ($T_{\mathrm{S,SH,up}}$) and the set point for the supply temperature $T_{\mathrm{Set,SH}}$ for SH falls below $\Delta T_{\mathrm{SH,on}}$

(predefined: 0 K) until the temperature difference is higher than $\Delta T_{SH,off}$ (predefined: 3 K). The buffer storage charging for DHW depends on the value of the storage temperature sensor for DHW preparation ($T_{S,DHW}$) and is turned on if the temperature falls below $T_{DHW,on}$ (predefined: 53 °C) until it reaches $T_{DHW,off}$ (predefined: 55 °C). In SGSHP-P and SASHP-P systems, the solar loop is switched on if the difference between the supply temperature of the ST collectors (T_{Sol}) and the storage temperature sensor ($T_{S,c}$) is higher than $\Delta T_{Sol,on}$ (predefined: 5 K) and will remain on until the temperature difference falls below $\Delta T_{Sol,off}$ (predefined: 2 K). If the difference between T_{Sol} and $T_{S,DHW}$ is higher than $\Delta T_{Sol,DHW,on}$ (predefined: 5 K), the upper heat exchanger is additionally charged by the solar loop and the return of the upper heat exchanger is used for the supply of the lower heat exchanger (DHW mode) until the temperature difference falls below $\Delta T_{Sol,DHW,off}$ (predefined: 2 K). Otherwise, the ST collectors supply only the lower heat exchanger with solar energy (SH mode). In addition, for storage protection, a maximum storage temperature ($T_{Set,S,max}$, predefined: 80 °C) of the storage temperature sensor for storage protection ($T_{S,sp}$) is defined (storage protection mode). Furthermore, a high limit cut-out for the ST collector temperature is defined in the controller to avoid damage of the components in the solar circuit if the supply temperature of the ST collectors (T_{Sol}) reaches $T_{Set,Sol,max}$ (predefined: 130 °C). In this case (ST protection mode), the solar loop is turned off until T_{Sol} falls below a defined temperature $T_{Set,Sol,max,off}$ (predefined: 120 °C).

4. Simulation study

4.1 Parameter

An exemplary application of the model-based analysis of STHP systems is the investigation of the influence of system concepts on the seasonal performance factor (SPF, see section 4.2). The performed TRNSYS simulations consider GSHP, ASHP, SGSHP-P and SASHP-P (using SHP-SIMFRAME) as well as SISHP-S and SISHP-S+P systems. The simulations were performed for SFH15, SFH45 and SFH100 and the climate of Strasbourg with variations of the solar collector area (or absorber area in case of SISHP systems) with a maximum available roof area of 25 m². The main model parameters for the simulation of the HP, the solar collectors and the solar absorbers are summarized in tab. 3-6. In case of SFH100, characteristics of market available air/water HPs and brine/water HPs were used as data basis for the parameterization of the HP models. In case of SFH15 and SFH45, the power data was down-scaled to a nominal heating power of 6 kW due to a better fitting of the design heat loads.

Tab. 3: Key values of brine/water heat pump models, performance data based on data sheets of Viessmann BW301.B10 (Viessmann, 2017)

Parameter	Value
COP at B0/W35 [-]	5.01
condenser power at B0/W35 [kW]	
- nominal heating power for Strasbourg SFH100	10.36
- scaled heating power for Strasbourg SFH15 and SFH45	6.01

Tab. 4: Key values of solar collector models, flat-plate selective (Heimrath and Haller, 2007)

Parameter	Value
collector optical efficiency η_0 [-]	0.80
heat loss coefficient c_1 [W/m²K]	3.50
temperature dependence of heat loss coefficient c_2 [W/m²K²]	0.015
effective thermal capacity of the collector c_5 [J/m²K]	7000
first order IAM b_0 [-]	0.18
IAM for diffuse radiation K_d [-]	0.90

Tab. 5: Key values of air/water heat pump models, performance data based on data sheets of Viessmann Vitocal 350-A AWHI 351.A10 (Viessmann, 2013)

Parameter	Value
COP at A2/W35 [-]	3.66
condenser power at A2/W35 [kW]	
- nominal heating power for Strasbourg SFH100	10.60
- scaled heating power for Strasbourg SFH15 and SFH45	6.36

Tab. 6: Key values of solar absorber models, based on measured data and parameter identification of the TRNSYS model with GenOpt

Parameter	Value
collector optical efficiency η_0 [-]	0.699
heat loss coefficient c_1 [W/m²K]	32.79
wind speed dependence of the heat loss coefficient c_3 [J/m³K]	4.64
sky temperature dependence of the heat loss coefficient c_4 [-]	0.9338
effective thermal capacity of the absorber c_5 [J/m²K]	20000
wind speed dependence of the zero loss efficiency c_6 [s/m]	0.034
first order IAM b_0 [-]	0.0327
IAM for diffuse radiation K_d [-]	1.00

For the control of the systems, the predefined control parameters from section 3.3 were used. In case of SISHP systems, an additional controller for the charging of the ice storage is needed. In these system concepts, the solar absorber loop is switched on if the difference between the supply temperature of the solar absorbers ($T_{\text{Sol,abs}}$) and the ice storage temperature sensor ($T_{\text{S,ice,c}}$) is higher than $\Delta T_{\text{Sol,abs,on}}$ (predefined: 3 K). The solar absorbers loop will remain on until the temperature difference falls below $\Delta T_{\text{Sol,abs,off}}$ (predefined: 1 K). In addition, a maximum ice storage temperature ($T_{\text{Set,S,ice,max}}$, predefined: 15 °C) of the ice storage temperature sensor ($T_{\text{S,ice,c}}$) is defined. If the ice storage temperature reaches this value, the solar absorber loop is turned off until $T_{\text{S,ice,c}}$ falls below a defined temperature $T_{\text{Set,S,ice,max,off}}$ (predefined: 14 °C). In case of SISHP-S+P systems, the predefined control concept from section 3.3 was used for the control of the ST collector loop.

4.2 Performance figures

The SPF quantifies the final energy efficiency of a whole SHP system and is defined as the overall useful energy output to the overall driving final energy input for an adopted system boundary over a period of one year (Malenković et al., 2013). In some cases, the systems may not permanently provide the DHW tapping temperatures or the room temperature of the building. For a better comparison between simulation results, penalty functions are defined as direct electric heating for times in which the system does not reach the required comfort criteria (Heimrath and Haller, 2007; Jordan et al., 2003). The SPF of the overall SHP system with penalties ($SPF_{\text{SHP+,pen}}$) is defined as the amount of useful energy for SH (Q_{SH}) and DHW preparation (Q_{DHW}) divided by the amount of electric energy consumption ($W_{\text{el,SHP+,pen}}$) of the overall SHP system (including all electrical consumptions of the SHP system and penalties) (Haller, 2013):

$$SPF_{\text{SHP+,pen}} = (Q_{\text{SH}} + Q_{\text{DHW}}) \,/\, W_{\text{el,SHP+,pen}} \qquad \text{(eq. 1)}$$

For the comparison of simulation results of SHP systems with a defined reference system (e.g. without ST collectors) the relative increase $\Delta SPF_{\text{SHP+,pen}}$ is defined as:

$$\Delta SPF_{\text{SHP+,pen}} = (SPF_{\text{SHP+,pen}} - SPF_{\text{SHP+,pen,ref}}) \,/\, SPF_{\text{SHP+,pen,ref}} \qquad \text{(eq. 2)}$$

where $SPF_{\text{SHP+,pen}}$ is the SPF of the considered system and $SPF_{\text{SHP+,pen,ref}}$ is the SPF of the corresponding reference system. Another figure for the comparison of system concepts to a reference system are the absolute electricity savings $W_{\text{save,el}}$, defined as difference between the electric energy consumption of the defined reference system $W_{\text{el,SHP+,pen,ref}}$ and the considered system configuration $W_{\text{el,SHP+,pen}}$:

$$W_{\text{save,el}} = W_{\text{el,SHP+,pen,ref}} - W_{\text{el,SHP+,pen}} \qquad \text{(eq. 3)}$$

4.3 Results and discussion

The results of the evaluation of SPFs for the different STHP systems concepts and buildings are shown in fig. 6 and are summarized, with respect to the used collector / absorber areas and storage sizes, in tab. 7. In general, SGSHP-P systems achieve the highest SPFs for all types of building, which are in the range of 4.3 to 6.2 (SFH15), 4.9 to 6.7 (SFH45) and 4.5 to 5.4 (SFH100). For GSHP systems without ST integration, the SPFs are 3.1 (SFH15), 4.0 (SFH45) and 4.1 (SFH100). ASHP systems without ST collectors achieve the smallest SPFs, which are 2.6 (SFH15), 3.1 (SFH45) and 2.9 (SFH100). SISHP-S systems achieve higher values of SPF than ASHP systems for all types of building and in case of SFH15 even the same values as GSHP systems, which are in the range of 3.0 to 3.1 (SFH15), 3.6 to 3.7 (SFH45) and 3.4 (SFH100). The smaller values of SPF in case of SFH15 buildings with high fraction of DHW demand (46 %) show the impact of demand on high temperature level for DHW and as a result a lower performance of the HP in all system combinations without ST collectors. Additionally, the SH demand occurs predominantly in winter season with low ambient / source temperatures, especially in case of ASHP systems, and the HP runs with a lower performance. The simulation results show that the SPF can be increased for all system concepts by adding a parallel ST collector system. Due to the direct use of solar thermal energy, SASHP-P systems can even reach higher SPFs than GSHP systems without ST integration. In case of SFH15 with a minimum collector area of 5 m² (SPF: 3.4) and in case of SFH45 with a minimum collector area of 10 m² (SPF: 4.2). However, in case of SFH100 the simulated SASHP-P systems cannot reach the performance of GSHP systems.

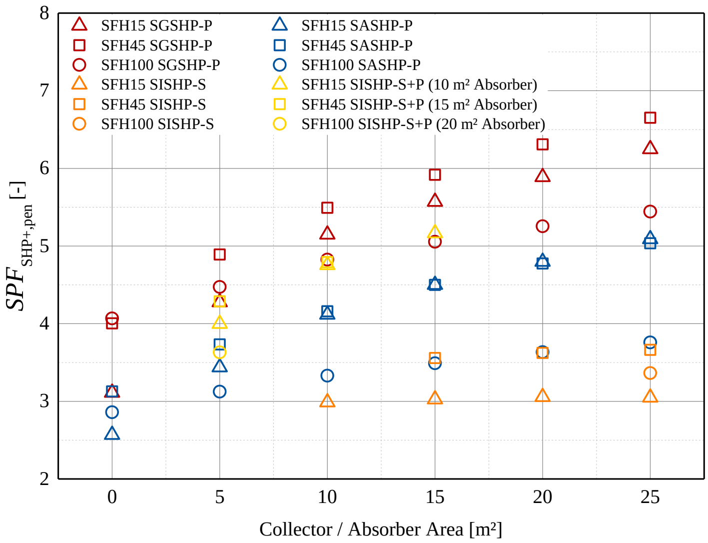


Fig. 6: SPF for Strasbourg depending on ST collector area (SGSHP-P, SASHP-P and SISHP-S+P) or absorber area (SISHP-S). SGSHP-P includes GSHP systems and SASHP-P includes ASHP systems (collector area = 0 m²).

The SPFs of SISHP-S systems can also be increased by adding small areas of ST collectors and can reach higher SPFs than GSHP systems without ST integration with a minimum collector area of 5 m² for SFH15 (SPF: 4.0) and SFH45 (SPF: 4.3). In case of SFH100, the simulated SISHP-S+P systems cannot reach the performance of GSHP systems. In case of SISHP systems, the benefit of adding flat-plate collectors to a SISHP-S system with design absorber area is higher than adding additional solar absorbers. If the roof area is limited to 25 m², this is shown by an increase of the SPF in the range of 33.8 % to 72.9 % in case of SFH15 and 20.5 % to 34.7 % in case of SFH45. In comparison, the maximum increase of SPF by adding additional solar absorbers is 2.0 % for SFH15 and 3.0 % for SFH45.

Tab. 7: Simulation parameter and results for the climate of Strasbourg

Building	**System**	A_C [m²]	A_{Abs} [m²]	V_{Buffer} [l]	V_{Ice} [m³]	SPF [-]	ΔSPF [%]	$W_{save,el}$ [kWh]
SFH15	GSHP	-	-	1000	-	3.1	*Reference for SGSHP-P*	
	SGSHP-P	5	-	1000	-	4.3	37.5	397
		10	-	1000	-	5.1	65.5	576
		15	-	1500	-	5.6	79.0	643
		20	-	2000	-	5.9	89.3	686
		25	-	2000	-	6.2	100.8	731
	ASHP	-	-	1000	-	2.6	*Reference for SASHP-P*	
	SASHP-P	5	-	1000	-	3.4	33.9	446
		10	-	1000	-	4.1	60.2	663
		15	-	1500	-	4.5	75.2	757
		20	-	2000	-	4.8	86.7	819
		25	-	2000	-	5.1	98.1	873
	SISHP-S	-	10	1000	10	3.0	*Reference for SISHP*	
		-	15	1000	10	3.0	1.3	20
		-	20	1000	10	3.1	2.3	34
		-	25	1000	10	3.0	2.0	31

Building	**System**	A_{C} [m²]	A_{Abs} [m²]	V_{Buffer} [l]	V_{Ice} [m³]	SPF [-]	ΔSPF [%]	$W_{\mathrm{save,el}}$ [kWh]
SFH15	SISHP-S+P	5	10	1000	10	4.0	33.8	383
		10	10	1000	10	4.8	59.2	563
		15	10	1500	10	5.2	72.9	639
SFH45	GSHP	-	-	1000	-	4.0	*Reference for SGSHP-P*	
	SGSHP-P	5	-	1000	-	4.9	22.2	386
		10	-	1000	-	5.5	37.2	577
		15	-	1500	-	5.9	47.8	689
		20	-	2000	-	6.3	57.6	778
		25	-	2000	-	6.7	66.1	847
	ASHP	-	-	1000	-	3.1	*Reference for SASHP-P*	
	SASHP-P	5	-	1000	-	3.7	19.3	441
		10	-	1000	-	4.2	33.0	675
		15	-	1500	-	4.5	43.8	830
		20	-	2000	-	4.8	52.7	940
		25	-	2000	-	5.0	61.0	1032
	SISHP-S	-	15	1000	10	3.6	*Reference for SISHP*	
		-	20	1000	10	3.6	1.9	43
		-	25	1000	10	3.7	3.0	69
	SISHP-S+P	5	15	1000	10	4.3	20.5	407
		10	15	1000	10	4.8	34.7	617
SFH100	GSHP	-	-	1000	-	4.1	*Reference for SGSHP-P*	
	SGSHP-P	5	-	1000	-	4.5	10.0	357
		10	-	1000	-	4.8	18.6	617
		15	-	1500	-	5.1	24.2	767
		20	-	2000	-	5.3	29.2	888
		25	-	2000	-	5.4	33.8	994
	ASHP	-	-	1000	-	2.9	*Reference for SASHP-P*	
	SASHP-P	5	-	1000	-	3.1	9.3	476
		10	-	1000	-	3.3	16.4	792
		15	-	1500	-	3.5	22.0	1012
		20	-	2000	-	3.6	27.1	1195
		25	-	2000	-	3.8	31.5	1341
	SISHP-S	-	25	1000	20	3.4	*Reference for SISHP*	
	SISHP-S+P	5	20	1000	20	3.6	7.9	349

5. Conclusions and outlook

This contribution presented the TRNSYS-based stand-alone tool SHP-SIMFRAME for the simulation of STHP systems and a performance evaluation of different STHP system concepts. The main advantages of the tool for the end-users are the possibility to analyze different predefined SHP concepts without any knowledge in modeling and simulation itself as well as the related time saving and error prevention for model-based system design or system analysis by simulation. On the one hand, the performance evaluation shows that in case of moderate climate and new as well as renovated buildings, SASHP-P systems can compete with GSHP systems without solar integration and can achieve the same or even higher values of SPF. On the other hand, the results show that SISHP-S systems are efficient STHP systems, which can achieve higher SPFs than ASHP systems and for new buildings even SPFs in the range of GSHP systems. Furthermore, SISHP-S+P systems with parallel integration of solar collectors can achieve higher values of SPF for new as well as for renovated buildings than GSHP systems and even than SASHP-P systems with same ST collector area. However, the highest performance in the simulations can be reached by SGSHP-P systems for all type of buildings and in case of the considered non-renovated building, the SPFs of GSHP systems cannot be reached by the considered SASHP-P and SISHP-S+P systems with a limited available roof area of 25 m². In addition, the results illustrate the need of simulation tools to design SHP systems depending on the boundary conditions of the specific application and the comparison of different system concepts. In future work, SHP systems with electrical solar energy (PV and PV thermal) systems will be investigated and integrated in the simulation framework.

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