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Abstract—In general, the modeling and simulation of 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 example of a complex energy system, this paper considers a combined solar and heat pump (SHP) system for the efficient energy supply of buildings. The challenges in designing new models within the simulation environment TRNSYS are described. As an alternative to the complex and lengthy general modeling process, a TRNSYS-based stand-alone tool (SHP-SimFRAME) is presented which enables users to analyze different predefined SHP concepts with hardly any knowledge in modeling and simulation itself.

Keywords—modeling; simulation; solar thermal; heat pumps; TRNSYS

I. INTRODUCTION

The combination of solar systems and heat pumps (HP) is a promising hybrid heating system concept for 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 and can generally be classified in parallel, serial and regenerative system concepts by the interaction between ST system and HP [1]. Parallel systems 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 are systems in which the ST system is used as heat source for the HP. 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 [1], [2]. The following investigations will focus on HP systems without ST collectors and parallel STHP systems with ground or air source HP.

The variety of possible investigations on STHP 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 aim of this work is the development of a user-friendly simulation tool (SHP-SimFRAME) which can be used for the simulation of STHP systems without any knowledge in modeling or programming. In the following sections, the model design in TRNSYS (section II) and the system concepts (section III), which are integrated in SHP-SimFRAME, will be explained in detail. This is followed by the description of the tool itself (section IV). Section V goes on to show an example of possible investigations with the tool. Finally, section VI provides the main conclusions and an outlook to further work.

II. MODEL DESIGN IN TRNSYS

A. TRNSYS Simulation Environment and Architecture

TRNSYS [3] is a simulation environment with a modular structure for the simulation of transient systems, especially thermal and electrical energy systems. Typical TRNSYS applications are simulations of energy systems with renewable energy sources (RES), like solar systems (ST and PV) or HPs, multi-zone buildings including heating, ventilation and air conditioning (HVAC) systems or combined heat and power (CHP) systems. TRNSYS consists of the following main programs:

- TRNSYS Simulation Studio (visual interface for model design, parametrization and simulation)
- TRNDll (simulation engine) and TRNExe (executable)
- TRNBuild (visual interface for the building simulation input data)
- TRNEdit (editor to create redistributable applications, known as TRNSED applications).

The source code of the kernel as well as the source code of the component models are delivered with the software which simplifies the modification of existing models and building individual models in order to fit the user-specific needs. The DLL-based structure of the program allows model developers to add component models using different common programming languages like C++ or Fortran. In addition,
TRNSYS can be connected to other applications, for pre- or post-processing or through interactive calls during the simulation, e.g. Microsoft Excel, Matlab/Simulink [4, 5] or Modelica tools via Functional Mockup Interface (FMI) [6, 7] (e.g. for multi-domain modeling of distributed energy systems [8] or modeling of systems with distributed control [9]).

B. Model Design and Simulation in TRNSYS

The general model design and simulation procedure in TRNSYS is shown in Fig. 1. First, the user starts on an engineering knowledge level with the detailed description of the real system (1). Afterwards, the user has to decide whether the available component models fulfill the user-specific needs or not (2). Due to the variety of available component models, the user must be a TRNSYS expert to decide which components fulfill the specific requirements for the later simulation of the system. If the real system can be designed by available models, the user can proceed with the system model design in TRNSYS (4). If not, the user has to take a detour via designing detailed models of the missing components and write his own TRNSYS components (types) in a programming language like Fortran (common language in TRNSYS) or, for example, C++ (3). Consequently, the user needs to have expert knowledge in developing TRNSYS types (TRNSYS expert) and a usable programming language (programming expert).

TRNSYS types typically consist of inputs (variable, e.g. input temperature or mass flow), parameters (fixed, e.g. solar collector area, storage volume) and outputs (e.g. output temperature or mass flow). Depending on the model, the type can also include external files, like data sheets (e.g. weather data), or derivatives as initial values for the numerical solution of differential equations (see Fig. 2).

Now, the user is ready for the design of the system model in the visual interface TRNSYS Simulation Studio (4). The types are placed by drag & drop and connected to each other. Afterwards, the simulation parameters are defined (usually by parameter identification or common values). After first test simulations, the user has to check whether the simulation results are valid or not, e.g. by comparison with measured data from the real system (quantitative validation) or by plausibility checks, e.g. comparison of the system behavior or energy balances (qualitative validation). Finally, the desired TRNSYS simulation can be performed (5). The simulation project information is saved in a TRNSYS project file and, via starting the simulation, TRNSYS Simulation Studio creates a TRNSYS input file, known as deck file. TRNDisplay reads all information in the deck file; it is called by TRNExe for the execution of the simulation. In case of building simulations, TRNBuild is used to create different files like a building description file which will be read for the simulation of multi-zone buildings (Type 56). The results can be printed in external files or visualized in an online plotter. Alternatively, TRNSYS users have the possibility to create a stand-alone application (TRNSED application, see section II.C) with limited possibilities for the parameterization of the models and the simulation itself as a user-friendly framework for end-users like engineers. In this case, the end-user can bypass steps (2) to (4) and start with the parameterization of the simulation model based on engineering knowledge of the real system (1). Here, the user may perform TRNSYS simulations without any knowledge of modeling or programming in TRNSYS itself.

C. TRNSED Applications

TRNSED applications are redistributable stand-alone applications based on TRNSYS which can be run by an executable file without the installation of TRNSYS itself. TRNEdit is a specialized editor which can be used for modifying TRNSYS deck files and creating these simplified stand-alone applications as end-user simulation tools without TRNSYS knowledge and license. Within TRNEdit, the TRNSED developer has the possibility to create a graphical user interface (GUI) with multiple tabs, pictures for illustration, links, pull-down menus for parameters or data files, check boxes or radio buttons [3]. At this, the developer can choose which parameters, data sets or simulation options should be provided to the end-user of the simulation tool. Examples of such applications are the Solar Air Heat Analyzer or the SDHW tool which have been developed by TESS [10].

III. SOLAR THERMAL AND HEAT PUMP SYSTEMS

In the latest version, SHP-SimFRAME contains four different SHP system concepts which can be simulated:

- ground source heat pump (GSHP) systems
- air source heat pump (ASHP) systems
- parallel solar thermal and ground source heat pump (SGSHP-P) systems
- parallel solar thermal and air source heat pump (SASHP-P) systems.
The HP charges the buffer storage tank in two pre
iport.

Heat Source
parameters.
simulation environment itself (e.g. for different locations or buildings) or test their
students or manufacturers (e.g. of
The tool should be a user
create a tool wh
solar collectors. If the supply temperature of the solar
storage tank as heat sink of the HP and an additional solar loop. The buffer storage tank is used for the energy supply of the SH system and the heat exchanger for DHW preparation. In this example, 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 DHW preparation. The solar collectors supply the buffer storage with solar energy via two internal heat exchangers depending on the actual supply temperature of the solar collectors. If the supply temperature of the solar collectors is high enough, the upper heat exchanger is charged and the return of the upper heat exchanger is used for the supply of the lower heat exchanger. Otherwise, the solar collectors supply only the lower heat exchanger with solar energy. The SASHP-P system correspond to the SGSHP-P system with a replacement of the GSHP by an ASHP. The GSHP and the ASHP systems correspond to the SGSHP-P and the SASHP-P systems without additional solar loop.

IV. SHP-SIMFRAME

A. Background

The aim during the development of SHP-SIMFRAME was to create a tool which can be used for the simulation of SHP systems without any knowledge in modeling or programming. The tool should be a user-friendly framework for engineers, students or manufacturers (e.g. of solar collectors or HPs) to perform parameter studies and analyses of the SHP system itself (e.g. for different locations or buildings) or test their manufactured components for the use in SHP systems in a simulation environment by editing the component specific parameters. SHP-SIMFRAME can also be used for the validation of simplified SHP system models or, in general, for physically-abstracted models (PAM) [11] by modeling experts using other tools, e.g. Modelica or Matlab/Simulink.

B. TRNSYS models

The simulation models of the main system components in TRNSYS are summarized in TABLE I. For a better structure and a higher level of modularity and flexibility, the TRNSYS model is divided in the subsystems Reference System, 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 [17]. The subsystems Reference System and Storage (see Fig. 4) include the reference system of the International Energy Agency (IEA) Solar Heating and Cooling Programme (SHC) Task 44 / Heat Pump Programme (HPP) Annex 38 and the Multiport-Store Model Type 340. In general, the SHP subsystem includes the HP and the heat source models. In case of systems with GSHP, the subsystem contains the components for the heat source circuit, the GSHP, 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 [18], [19]. In case of systems with ASHP, the subsystem includes the ASHP, the pump for buffer storage charging and the pipes from the HP to the storage. Furthermore, in case of systems with ST integration, the subsystem contains the solar collectors, the solar circuit pump and the pipes from the solar collectors to the storage.

**TABLE I. TRNSYS MODELS OF THE MAIN SYSTEM COMPONENTS**

<table>
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<tbody>
<tr>
<td>Building</td>
<td>Type 56 [3]</td>
</tr>
<tr>
<td>Solar collector</td>
<td>Type 832 [12]</td>
</tr>
<tr>
<td>Compressor HP</td>
<td>Type 401 [13]</td>
</tr>
<tr>
<td>Borehole heat exchanger</td>
<td>Type 557a [14]</td>
</tr>
<tr>
<td>Multiport storage tank</td>
<td>Type 340 [15]</td>
</tr>
<tr>
<td>Single speed pump</td>
<td>Type 3d [3]</td>
</tr>
<tr>
<td>Variable speed pump</td>
<td>Type 803 [16]</td>
</tr>
<tr>
<td>Pipe</td>
<td>Type 31 [3]</td>
</tr>
<tr>
<td>Bi-directional noded pipe</td>
<td>Type 604a [14]</td>
</tr>
<tr>
<td>Buried noded pipe</td>
<td>Type 952 [14]</td>
</tr>
<tr>
<td>Flow diverter</td>
<td>Type 11h [3]</td>
</tr>
<tr>
<td>Tee-piece</td>
<td>Type 11h [3]</td>
</tr>
</tbody>
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Fig. 3. Parallel solar thermal and heat pump system concept.

Fig. 4. TRNSYS subsystems Reference System and Storage.

### Fig. 3

**Fig. 3.** Parallel solar thermal and heat pump system concept.

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Using the example of a SGSHP-P system, the subsystem SHP is graphically shown in Fig. 5. The subsystem **SHP control** includes the control of the HP and ST system and consists of a combination of differential controllers (Type 2b). Due to their simplicity, the subsystems of SHP control are not shown here.

### C. Framework

**SHP-SimFRAME** is a TRNSED application for the simulation of SHP systems based on the TRNSYS models illustrated in section IV.B. In addition to a navigation page (see Fig. 6), **SHP-SimFRAME** consists of the following submodules (see section IV.E) for the parameterization of the simulation models:

- Simulation Parameters
- Climate and Building
- Solar Collectors (in case of ST integration)
- Heat Pump (and Ground Source in case of GSHP)
- Storage Tank
- Controllers
- Outputs.

#### D. Boundary Conditions

The boundary conditions of **SHP-SimFRAME** are based on the reference framework for system simulations of the IEA SHC Task 44 / Annex 38 [2, 20, 21]. General boundary conditions contain weather data for three different locations which represents warm (Athens), moderate (Strasbourg) and cold (Helsinki) climates [22] and ground properties for the simulation of ground coupling losses of the building and ground heat exchangers [20]. Within the reference framework, three different buildings representing single-family houses (SFH) with heat loads of 15 kWh/m²/a (SFH15), 45 kWh/m²/a (SFH45) and 100 kWh/m²/a (SFH100) for the climate of Strasbourg are defined. SFH15 represents a current building with very high energetic quality, SFH45 represents a renovated building with good thermal quality of the building envelope and SFH100 represents 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 [21]; the DHW draw off profiles correspond to an average draw off of 140 liters per day with a draw off temperature of 45 °C, which is 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 Task 44 / HPP Annex 38, the borehole heat exchangers are simulated as double-U pipes. The main properties of the borehole heat exchangers are also defined within the framework [20].

#### E. Submodules and Parameterization Possibilities

The submodule **Simulation Parameters** can be used to set general simulation parameters like the simulation time step and the length of the simulation. **Climate and Building** allows the user to choose the climate and the building type (SFH15, SFH45, SFH100) from a pull-down menu. The **Storage Tank** submodule is used to set the general thermal storage.

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1 The permission of Meteotest for using Meteonorm climate data for simulations within the IEA-SHC Task 44 / Annex 38 is gratefully acknowledged.
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. In addition, within this submodule, the user can specify the relative heights of the storage tank connections. This includes the relative heights of the HP, the SH and the DHW connections. In case of ST integration, the submodule also includes the relative heights of the connections to the solar loop. For a better understanding and visibility of the connections, the submodule includes a simplified schematic of the system including the allocations of the hydraulic connections and sensors of the storage tank (see Fig. 8). 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 the piping between the HP and the storage tank. Furthermore, in case of GSHP systems, this submodule allows the user to define ground properties (thermal ground conductivity) and borehole properties like borehole number and depth, 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 (aperture area, tilt, azimuth and specific mass flow) and the collector loop pipes properties as well as the solar collector efficiency parameters. The solar collector efficiency parameters include the collector optical efficiency $\eta_o$, linear heat loss coefficient $\alpha_1$, quadratic heat loss coefficient $\alpha_2$, first order Incidence Angle Modifier (IAM) $b_0$, IAM for diffuse radiation $K_{diff}$ and the effective heat capacity of the collector $C_p$. The submodule Controllers can be used to set the control parameters for the solar loop (e.g. hysterisis to switch on the solar pump or set temperatures for collector stagnation) and the reheating of the storage tank for SH and DHW preparation by the HP. The Outputs submodule contains a selection of predefined outputs, which can be selected for the graphical and data file based evaluation of the simulation results.

V. EXAMPLE

An exemplary application of SHP-SimFRAME is the investigation of the influence of the key values of flat-plate solar collectors (FPC) on the seasonal performance factor (SPF) of the overall SHP system $SPF_{SHP+}$. 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. The SPF 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 ($W_{elec,pen}$) of the overall SHP system (including all electrical consumptions of the SHP system and penalties) [16], [23], [24], [25]:

$$SPF_{SHP+pen} = \frac{Q_{SH} + Q_{DHW}}{W_{elec,pen}} \cdot (1)$$

The simulation with SHP-SimFRAME was performed for SGHSP-P and SASHP-P systems for the climate of Strasbourg with the building type SFH45. Each SHP system concept was simulated with a buffer storage size of 1000 L and collector areas of 5 m$^2$, 10 m$^2$, 15 m$^2$ and 20 m$^2$ for two different collector types. Collector A represents a FPC with selective absorber, collector B a FPC with non-selective absorber (see TABLE II). In the simulation, the GSHP has a coefficient of performance (COP) of 4.51 (B0/W35) and the ASHP has a COP of 3.66 (A2/W35). The nominal power of the condenser is 5,940 kW for the GSHP and 6,360 kW for the ASHP.

The simulation results are shown in Fig. 9. The SPFs of systems with selective FPCs in comparison with systems with non-selective FPCs with the same collector area increase up to 10 % in case of SGHSP-P systems and 9 % in case of SASHP-P systems. For both SHP system concepts, the SPFs

TABLE II. KEY VALUES OF FPC A AND B [16]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FPCA</th>
<th>FPCB</th>
</tr>
</thead>
<tbody>
<tr>
<td>collector optical efficiency, $\eta_o$ [-]</td>
<td>0.80</td>
<td>0.75</td>
</tr>
<tr>
<td>linear heat loss coefficient, $\alpha_1$ [W/m$^2$K]</td>
<td>3.50</td>
<td>5.46</td>
</tr>
<tr>
<td>quadratic heat loss coefficient, $\alpha_2$ [W/m$^2$K]</td>
<td>0.015</td>
<td>0.021</td>
</tr>
<tr>
<td>first order IAM, $b_0$ [-]</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>IAM for diffuse radiation, $K_{diff}$ [-]</td>
<td>0.90</td>
<td>0.88</td>
</tr>
<tr>
<td>effective heat capacity of the collector, $C_p$ [J/m$^2$K]</td>
<td>7000</td>
<td>7000</td>
</tr>
</tbody>
</table>

Fig. 8. Simplified schematic of the system including the allocation of the hydraulic connections and sensors of the storage tank.

Fig. 9. SPF for SASHP-P and SGHSP-P systems depending on the collector area of two solar collectors (FPC A and FPC B) for Strasbourg
of systems with selective FPCs and a minimum collector area of 10 m² are better than those for systems with non-selective FPCs and 5 m² higher collector area. The results illustrate that the collector efficiency parameters have a high impact on the SPF of SHP systems and that, depending on the amount of higher investment costs or for buildings with limited roof areas, selective FPCs are a worthwhile investment.

VI. CONCLUSIONS AND OUTLOOK

This contribution presented a TRNSYS-based, user-friendly stand-alone tool (SHP-SimFRAME) for the simulation of SHP systems for efficient energy supply of buildings. SHP-SimFRAME and its structure as well as the simulation possibilities of the tool were described in detail. SHP-SimFRAME is an alternative to the complex and lengthy general modeling process in TRNSYS. The main advantages 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.

In future work, SHP systems with latent heat storage as well as SHP systems with PV, especially systems with photovoltaic thermal (PVT) collectors, shall be integrated in SHP-SimFRAME. Furthermore, the flexibility of SHP-SimFRAME shall be extended related to locations, building types or HPs which can be simulated within the framework.

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