

SIMULATION BASED DESIGN AND VALIDATION OF HOME ENERGY SYSTEM

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ABSTRACT

The indoor thermal comfort and energy efficiency are the main design criteria for modern home energy systems (HES). In this work, simulation assisted development process of the home energy management system (HEMS) in a typical single-family house (SFH), equipped with a heat pump (HP) system, is depicted. By using the Software-in-the-Loop (SiL) approach, the controller is configured and optimized in connection with numerical simulation models, which are developed in Modelica language. The validation of the HES is carried out by adopting the Hardware-in-the-Loop (HiL) approach, where the complex numerical models such as the HP and the tank unit are replaced by real physical components, operating in an emulated environment through a multi-physics HiL test bed. Thus, more plausible validation results and further optimization potentials of the HEMS can be acquired.

INTRODUCTION

The research and development on HES technology gains more and more relevance especially focusing on the improvement of the domestic energy efficiency as well as the indoor climate quality. The energy components, which are interconnected with different energy carriers such as electricity, gas and heat, including a central control unit, are called HES. The main feature and trend of future HES is the incremental integration of renewable energy resource (RES) in order to achieve higher coefficient of performance (CoP). These kinds of decentralised energy units need a central control unit, called HEMS, so that different home energy components can be well coordinated to satisfy the domestic heating and hot water demand concerning better energy efficiency and lower overall consumption.

During the prototyping phase of the HEMS, the SiL approach is used, where the prototypes of HEMS algorithms (e.g. in C code) are embedded into the numerical simulation that contains the models of the physical system (OPAL-RT, 2012). By using SiL approach, many configurations and parameter settings can be tested prior to system design phase in order to reduce the time, cost, operating effort and complexity. However, a precise simulation always requires detailed models as well as validation

expenditures of the physical models, which are always difficult to be described analytically and leads to reduction of the validity of the results. On the other hand, field studies always have to compromise accuracy and generality because every study focuses on a very limited number of building types and system solutions. Additionally, it is very difficult to optimize a HES during a field study because of the continuously changing and non-reproducible boundary conditions. In order to mediate the trade-off between pure numerical simulations and field tests, the HiL approach can be applied as an intermediate step (Grosch, et al., 2008). Nowadays, the HiL approach is widely used for the rapid prototyping products in diverse industrial fields. The HiL testing applied in renewable energy technology, mainly focusing on wind turbines and fuel cells, has been reported in (Li, et al., 2006) and (Li, et al., 2010). The SiL/HiL based methodologies for the design, the optimization as well as the validation of the HES have not been proposed so far.

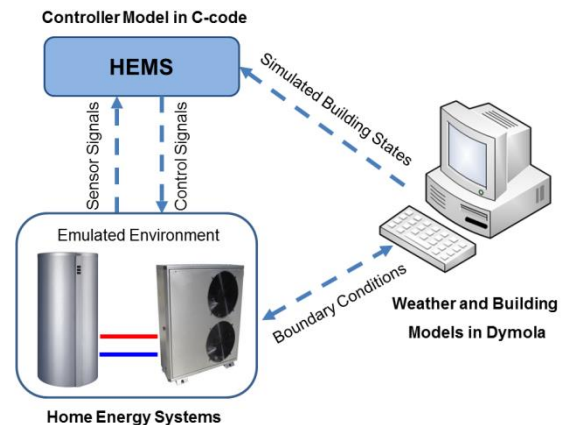


Figure 1 Principle of HiL approach for HEMS

The principle of the HiL approach adopted in this work is depicted in Figure 1. It provides an effective platform by adding the complexity of the plant under control (real home energy components) to the test platform instead of numerical models, so that modelling errors and uncertainties can be reduced dramatically. In order to keep the flexibility of the HiL simulation, the only numerical parts remaining in the loop are the weather and building models including the hydraulic systems in object-oriented

programming language Modelica, which can be modified and parameterized easily. Since the performance of the renewable energy components is dependent on the heat source/sink to great extent, the conventional emulation in signal level only by manipulating the sensor and actuator signals will not be feasible any more. Thus, a multi-physics test platform including thermal, hydraulic and electrical interfaces as well as the communication interfaces have been developed and elaborately described in (Chen, et al., 2012) and (Molitor, et al., 2012). The emulation of the operating environment of HES succeeds through the advanced weather and building simulation models and fast controllable facilities of the HiL test bed.

SYSTEM COMPONENTS

The heating and domestic hot water (DHW) demands are responsible for the main energy consumption of a typical home. HP systems gain the focus because of the efficiency usage of renewable energy resources in comparison to a conventional heat generation system such as gas boilers or electro heaters. Compared to a brine-to-water (B/W) HP system, an equivalent air-to-water (A/W) HP has lower performance in sense of CoP. But the simple installation and considerably lower commissioning cost, lead to widely installation of this HP type. Therefore, a typical HES containing an A/W HP is considered in this work, but still providing flexibility to rearrange for testing of other HES configurations.

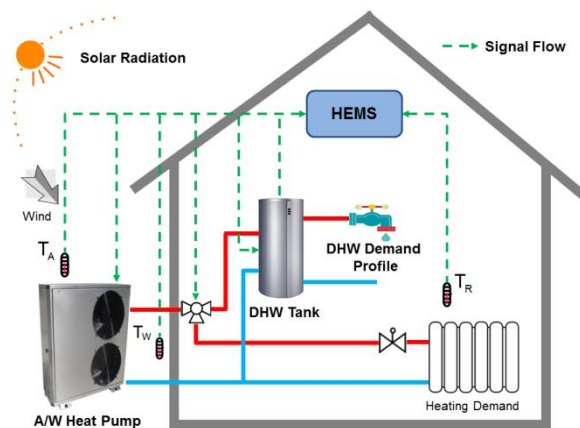


Figure 2 Connection scheme of the HES

Figure 2 shows the configuration of a HES, which is to be analyzed in this work, comprising a speed controlled A/W HP with a DHW tank unit, radiators with thermostatic valves and a HEMS. The house is heated by a speed controlled HP which regulates the compressor frequency according to heat demand. The direction of the outlet water from the HP is switched by a three-way valve (TWV), which decides if the room or the tank should be heated up. The DHW demands such as hand washing or showering, described by load profiles, are covered by the DHW tank. The HES components such as the HP, the tank

as well as the TWV are connected with the HEMS, that can read all the sensor signals from the HES and sends control commands back to the components according to the implemented algorithms.

The numeric simulation of the indoor climate needs detailed modelling of thermo-hydraulic systems in the building. The Modelica libraries (Modelica Association, 2012) developed at the Institute for Energy Efficient Buildings and Indoor Climate at the E.ON Energy Research Center, RWTH Aachen University, allow a detailed modelling of the thermo-hydraulic system. They are built modularly and parameterizable, considering the thermal building simulation with taking structural effects, user behaviour and weather data into account. The Modelica fluid library allows for modelling the thermo-fluid components such as pipes, thermostatic valves and radiators.

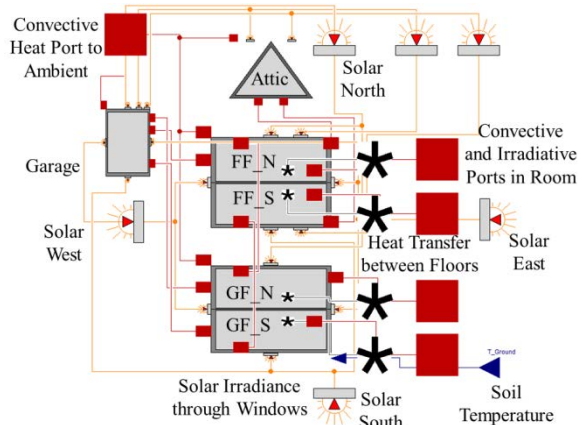


Figure 3 Building model in Dymola/Modelica

As presented in Figure 3, the schematic model of a signal-family house in Dymola (Dassault Systemes, 2013) is shown. The SFH model consists of four living rooms with different orientations distributed in two floors: ground floor south (GF_S), ground floor north (GF_N), first floor south (FF_S) and first floor north (FF_N). Besides that, one garage and one attic are also considered in the SFH model, which have thermal connections to the living rooms. In order to model the heat balance inside the building, two different kinds of heat ports are considered: convective and irradiative port. The heat ports (red squares) symbolize the heat conduction through walls and the convective heat transfer from radiator to indoor air; the irradiative ports (asterisks) describe the heat produced by direct solar irradiance through the window model and the irradiative heat emission by the radiator. The outside heat port of the building is connected with a weather model, generating the outdoor climate data such as ambient temperature, wind speed as well as the intensity of solar irradiance in different orientations. Each room (except garage and attic) is considered to be heated by a radiator, whose power is regulated by a thermostatic radiator valve (TRV). The insulation parameters such as U-

value, layers and thickness of the outside walls can be configured according to different kinds of norms. In this work, EnEV 2009 (Schoch, 2010) is chosen to be the isolation standard for the SFH modelling.

Considering the living area, insulation standard and heat balancing in the coldest day, an A/W HP system with nominal heating power of 9 kW is selected in this SFH. The SiL simulation of the HES requires detailed modelling of dynamic behaviour of the HP system. Since the HP has a speed controlled compressor, the partial load behaviours of the HP should be considered. Thus, a dynamic heat pump model is required. Based on the medium package in Modelica, the thermo-dynamic properties of the standard refrigerant fluid R410a (Dupont Refrigerant, 2012), i.e. the interdependences between different thermal-dynamic states such as enthalpy-pressure, entropy-temperature diagrams and so on, have been modelled in a two-phase medium package. The operating point of the refrigerant fluid can be defined based on compressor frequency and heat source/sink temperatures. By measuring the performance data of the HP, a rated frequency table of the compressor model is parameterized in order to match the actual nominal thermal power of the HP in different operating conditions. The simulation of the different modulation points can be conducted by imposing the percentage of the rated compressor driving frequency from the look-up table.

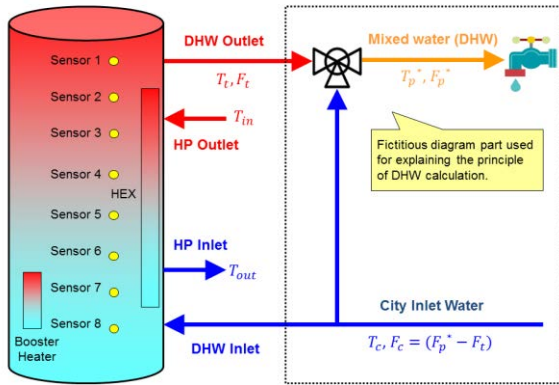


Figure 4 Configuration of the DHW tank unit

The connection scheme of the HP system with DHW tank unit is schematically described in Figure 2. A detailed overview of the tank configuration used in this work is illustrated in Figure 4. The DHW tank has a total volume of 200 L and is equipped with eight temperature sensors which are evenly spaced along the height of the tank in order to measure the tank temperature in different thermal layers. There are two kinds of heating energy supply in the DHW tank: a heat exchanger connected with the heat pump and an electrical booster heater (BH). The principle of DHW usage is illustrated in the area enclosed by dashed line. The outlet water from DHW tank is mixed with cold feed-in city water (about 10 °C) so

that the demand of different DHW temperatures for diverse household applications can be covered. For the SiL simulation, a tank model from the Modelica Libraries is selected and parameterized, where the total tank volume is discretized into 8 temperature layers and the heat transfers between the layers is considered. However the dynamic simulation of the temperature distribution during the charging by the heat exchanger is not respected in the model.

The user demand of DHW is described in a tabular profile with desired flow rate, total flow amount and target temperature and heat demand. Concerning the tank volume and the specification of the SFH, a standard DHW demand profile with size L is given according to norm EN 16147 (European Committee for Standardization, 2011), whose format is exemplarily depicted in Table 1.

Table 1
Format of DHW demand profile (Size L)

TIME	FLOW AMOUNT [L]	FLOW RATE [L/H]	TARGET TEMP [°C]	HEAT DEMAND [KWH]
7:00	6.02	4	25	0.105
7:15	40.13	10	40	1.400
⋮	⋮	⋮	⋮	⋮
21:00	103.34	10	40	3.605
21:30	6.02	4	25	0.105

The heat demand calculation in Table 1 is assumed to be based on the fact that the city water has a temperature of 10 °C. The simulation as well as the emulation of DHW heat demand in HiL approach should be adapted to the target profile (Table 1) in consideration of the flow rate limitation and the fluctuation in tank inlet and outlet temperatures. When a DHW demand begins, the adaption of the DHW load profile is realized in the following steps:

1. Considering the measuring range of the test bed, the minimal flow rate of tank outlet is set at 200 l/h. The tank outlet flow rate F_t can be adapted based on F_p as followed:

$$F_t = \begin{cases} \max\left(\frac{F_p(T_p - 10)}{(T_t - T_c)}, 200\right), & \text{if } T_t \geq T_p \\ \max(F_p, 200), & \text{if } T_t < T_p \end{cases} \quad (1)$$

2. Use the F_t from Equation (1) to be the set point of the pump control system. Measure the actual DHW tank flow rate $F_{t,m}$.
3. Calculate the heating power $P_{t,m}$ from tank supply T_t and feed-in temperatures T_c :

$$P_{t,m} = F_{t,m} \cdot (T_t - T_c) \cdot C_p \quad (2)$$

4. The remaining heat demand E_p^n to time step n is updated after each sampling period T_s :

$$E_p^n = E_p^{n-1} - P_{t,m} \cdot T_s \quad (3)$$

5. When $E_p \leq 0$, then turn off the flow rate of tank and wait for next DHW demand.

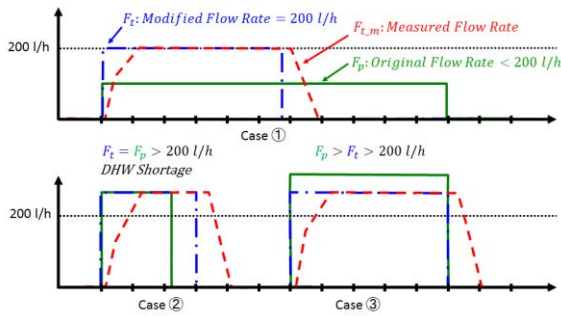


Figure 5 Principle of DHW demand adaption

According to the adaption algorithm of the DHW flow rate control, three possible cases of the DHW flow rate adaption can be classified in Figure 5. In case 1, the flow rate from the DHW profile is lower than the flow rate limitation ($F_p < 200$ l/h), then the actual flow rate is limited and the duration of the demand is reduced; In case 2, the DHW tank is in shortage mode ($T_t < T_p$) but the same heat amount is consumed by prolonging the demand duration; In case 3, the tank is in normal operation, the temperature and flow rate requirement of the profile can be satisfied ($T_t \geq T_p$).

SIL-ASSISTED DESIGN OF HEMS

The investigated HES has a typical configuration for a SFH, comprising an A/W HP and a DHW tank to cover the domestic heating and hot water demand. Considering the HES composition and its functional requirements, a modular design of HEMS is proposed and illustrated in Figure 6, which contains four different function modules.

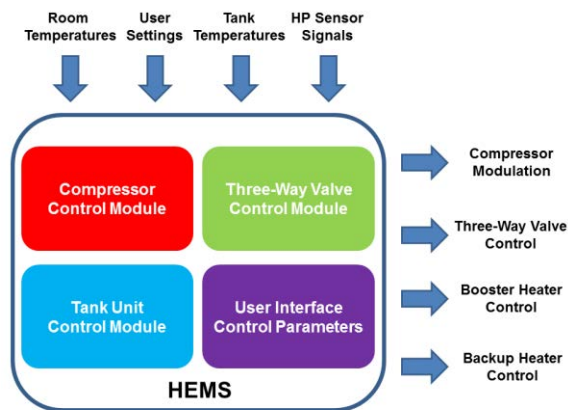


Figure 6 Structural design of HEMS

The compressor control module sends the modulation command to the HP so that the HP outlet temperature can be regulated; The tank unit control module decides when and how long the BH in the DHW should be activated; The TWV module controls the current heating mode of the HP (tank or room heating); The HEMS is also equipped with a user interface module that receives the control parameters and settings specified by the user, such as the heating curve, set temperature and so on. Moreover, the

HEMS is also equipped with a sophisticated I/O interface (see Figure 6), which is in charge of receiving the sensed signals from SFH and the HES components and meanwhile also in sending the control signals to different parts of HES. In SiL simulation, the HEMS is implemented in C-code and its I/O interface is coupled with the simulation models in Modelica, including the HP, the tank and the SFH models, so that the functionality and performance of the HEMS prototype can be tested and evaluated under virtual conditions.

The principle of the compressor frequency control is exemplarily depicted in Figure 7, where the HP model is directly connected with the heating system in the SFH model. A heating curve is given which defines for the HP the target outlet temperature (blue) related to the current outdoor temperature. During the start-up phase of the HP, the compressor is fed with the rated frequency specified by the parameter table of the HP. When the HP outlet temperature accesses into the modulation band $\pm T_{hys_mod}$ (red), the frequency will be modulated to a lower proportion based on the rated frequency in order to keep the outlet temperature at the set point. The modulation points are discretized in 7 steps, which imply different proportions of the rated frequency. The modulation algorithm is implemented as a PI-controller with output limitation:

$$u = \min(\max(\text{floor}\left(k_p \Delta T + \frac{k_i}{\tau} \int \Delta T\right), 2), 7). \quad (4)$$

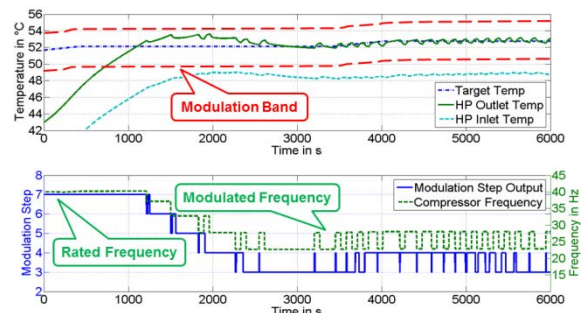


Figure 7 Compressor frequency Modulation

In the lower part of Figure 7, the controller output (blue) and simulated compressor frequency (green) are shown. In order to protect the compressor and inverter, the switch blocking time between modulation steps is set at 60 s. Under the dynamic heating load, the outlet temperature of HP can be controlled with an accuracy of ± 1 °C. Once the outlet temperature exceeds the modulation band for 3 minutes, the compressor remains off (1st step) with a blocking time until the temperature falls below the band.

The HEMS should coordinate different components of HES in order to meet the comfort requirement and also to achieve high energy efficiency. Besides the frequency modulation unit, the components such as the TWV, the tank BH and the HP back-up heater (BUH) are also controlled by the HEMS, with the difference that they are hysteresis controllers (Tan, et

al., 2005). The design of the rule-based control logic is illustrated by a sequence diagram in Figure 8.

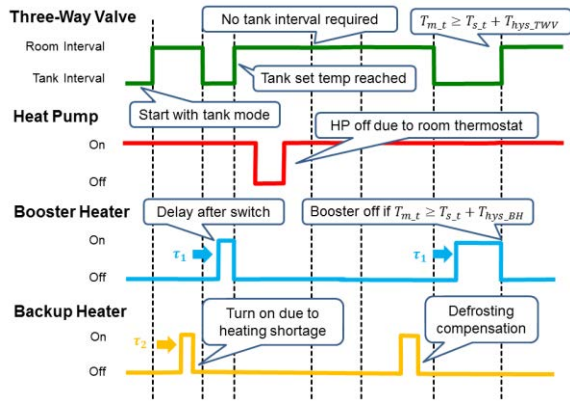


Figure 8 Rule-based control sequence

The switching logic of the TWV (green), which decides the operation mode of the HP, is based on specified time interval for room and tank operation modes. During tank charging interval, once the tank temperature exceeds the hysteresis ($T_{m,t} \geq T_{s,t} + T_{hys_TWV}$), the room interval will be activated. The target HP outlet temperature (input of the compressor module) is given by the heating curves according to current operation mode (Table 2). During tank interval the heating curve is set to maximum so as to accelerate the tank charging speed. The BH (blue) is an electric heating rod (3.2 kW) which can enhance the heating capacity inside the tank. However, this inefficient usage of electrical energy should be minimized in order to achieve higher CoP. The trade-off is to charge the tank only via HP during low-temperature phase and to postpone the activation of the BH with a delay time τ_1 . Simultaneously the hysteresis of the BH T_{hys_BH} is assigned with a smaller value than T_{hys_TWV} in order to restrict the domestic electricity consumption. The BUH (yellow curve) is a similar device as BH in the HP, which is only activated to recover the heating shortage during the defrosting interval of A/W HP.

Table 2
Control parameters of the HEMS

PARAMETER	VALUE
Set Temperature on TRV	20 °C
Heating Curve in Tank Interval	-7→65°C; 15→65°C
Heating Curve in Room Interval	-7→55°C; 15→35°C
Tank Set Temp $T_{t,s}$	48 °C
BH Hysteresis T_{hys_BH}	1 °C
Valve Hysteresis T_{hys_TWV}	5 °C
Modulation Band T_{hys_mod}	2 °C
Compressor Blocking Time	60 s
Room Heating Interval	1 h
Tank Charging Interval	1 h
BH Delay Time τ_1	20 min
Gain Factor k_n in Eq. 4	0.5
Time Constant τ in Eq. 4	200

The proposed control logic is compiled in real-time C-code with the I/O data interface to other system components. In order to test the functionalities and the performance of the proposed HEMS concept, the SiL simulation is executed. Due to the fast simulation time (about 80 times faster than real time), one of the suboptimal parameter set can be selected by iterative tuning method with help of the SiL simulation, which are listed in Table 2.

For the SiL test a typical weather profile on 12th January in the region of Aachen according to DWD (Deutscher Wetterdienst, 2012) has been selected, which is shown in the upper diagram of Figure 9. The selected outdoor temperature ranges from 0 °C to -7 °C during the day. The simulated room temperatures are plotted in the lower part of Figure 9. Due to different room orientation and solar irradiation, southern rooms (GF_S and FF_S) have higher temperature than northern rooms (GF_N and FF_N) in general. In the room temperature profiles, several temperature drops can be found, which are caused by the tank charging mode of the HP system. However, according to the SiL simulation the thermal comfort requirement in the SFH can be satisfied, since the room temperature can be kept mostly between 20 °C and 22 °C.

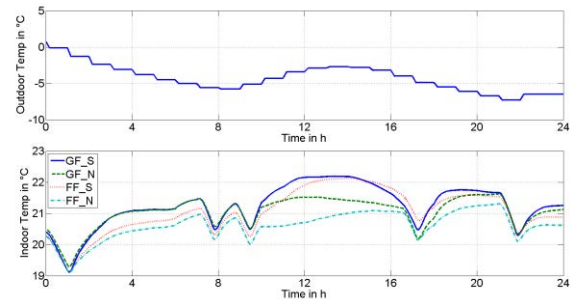


Figure 9 In- and outdoor temperatures in SiL

The simulated HP information is given in Figure 10. The in- and outlet temperature of HP are plotted with the target temperature profile, which is defined by the heating curve, in the upper part of Figure 10. In the tank charging mode, the target outlet temperature is set automatically at 65 °C by HEMS, so that the tank can be charged with full power.

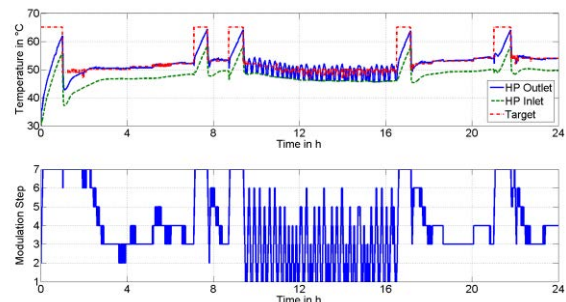


Figure 10 HP information in SiL

The compressor modulation step is visualized in the lower part. Since there is very little heating demand in the SFH during the solar irradiation, which is even less than what the smallest modulation step provides, the compressor starts to do the intermittent operation between 10:00 and 17:00. This can also be observed by the fluctuating HP outlet temperature in Figure 10.

The reference tank temperature in layer 3 (according to Figure 4) is plotted in Figure 11. By over-dimensioning the switching hysteresis T_{hys_TWV} of the TWV, the tank can be heated up to 53 °C, which may not only reduce the possibility of the DHW demand shortage (case 2 in Figure 5) to a great extent, but also maintain a higher energy efficiency of the HES in terms of CoP due to the usage of the RES. The simulated flow rate chart of the DHW usage F_t is visualized in Figure 5, which is calculated by the DHW profile adaption algorithm. According to the simulation results, those demand profiles with temperature requirements of 25 °C or 40 °C can be fully satisfied. The only DHW shortage occurs at 20:30, when the desired outlet temperature is 55 °C.

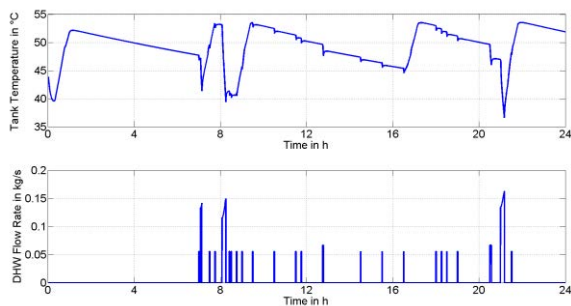


Figure 11 DHW tank information in SiL

The SiL simulation results of HP thermal power generation \dot{Q}_{th_HP} (blue), the electrical power consumption (green) of HP P_{el_HP} as well of the BH (red) P_{el_BH} are provided by Figure 12. Thanks to the small hysteresis of the BH, the T_{hys_BH} , this electrical heating rod has been activated for only short intervals to accelerate the tank charging to the set point.

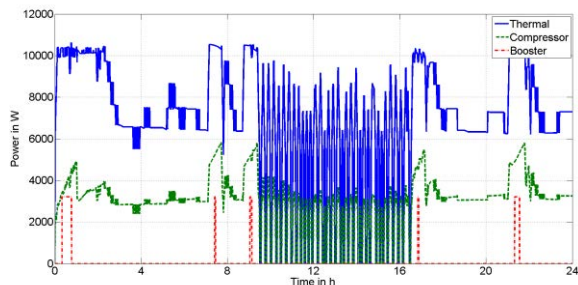


Figure 12 Power information in SiL

It has proved with the help of the SiL simulation approach, that the proposed HEMS prototype fulfils the desired functionalities and can basically meet the DHS and DHW demands.

HIL VALIDATION RESULTS

Since the complicated dynamic behaviours of the HP and the DHW tank are difficult to be modelled, these numerical models are replaced by real components. The remaining numerical parts (SFH and weather) are coupled with the physical parts via the thermal and hydraulic interfaces of the HiL test bed. In HiL phase (Figure 13), the HEMS prototype is installed in a PC-node, which is connected with the real components via a real-time capable bus system. The emulation systems, including the climate chamber and the hydraulic test bed, are controlled by the LabVIEW program in Windows-node, where the boundary conditions from Dymola models, such as the weather conditions and heat sink temperatures, can be emulated. The simulated and measured system states are exchanged through an Ethernet switch.

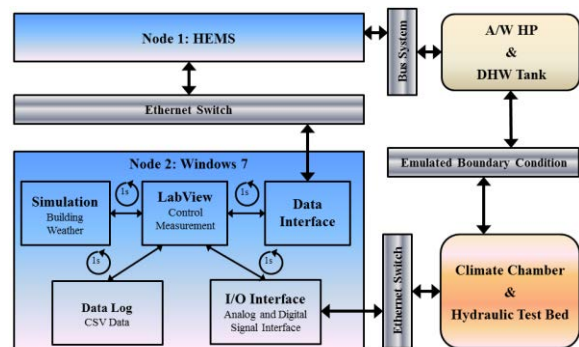


Figure 13 HiL simulation infrastructure

As shown in Figure 14, the convective room temperatures obtained in HiL simulation have less drops (3 times) in comparison to the SiL results (5 times). This difference is caused by the tank modeling errors and the resultant different control decisions in SiL and HiL simulations. However, the room temperatures can be maintained between 20 °C and 22 °C during most of the time, which symbolizes a satisfying thermal comfort in the SFH. Significant indoor temperature overshoots (above 22 °C) can be found especially in the southern rooms between 11th and 15th hour, which is caused by the high intensity of the irradiating sun light. In spite of the deviation in tank operation, the room temperatures show a good accordance with the SiL results.

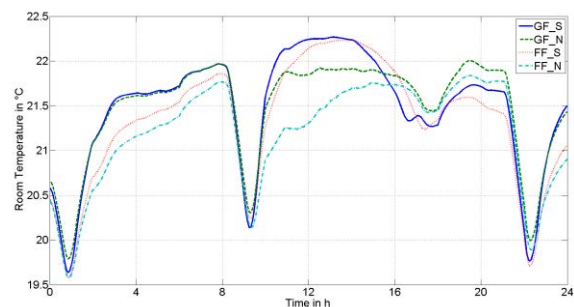


Figure 14 Room temperatures in HiL

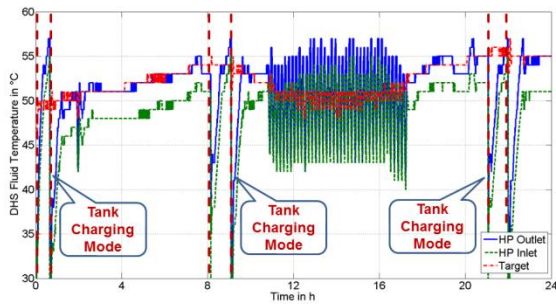


Figure 15 DHS fluid temperatures in HiL

The measured HP in- and outlet temperatures are represented by the green and blue lines respectively in Figure 15. The target outlet temperature (red), derived from the heating curve, can be well tracked. Considering the accuracy class of the temperature sensor applied in the HP, all the HP data are logged in a resolution of 1 °C. As simulated in SiL, the compressor starts the transmittent operation between 10:00 and 17:00, which corresponds to the simulated results. The DHW tank charging periods have been marked by the dashed zone.

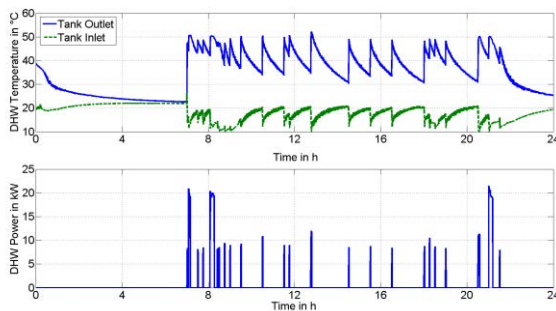


Figure 16 DHW consumption in HiL

The DHW demands are emulated as mentioned. The measured outlet (blue) and feed-in city water (green) temperatures of the tank (measurement valid only during the DHW usages) as well as the resultant power consumption profile of the DHW usages are plotted in Figure 16. According to the second subplot in Figure 16, there are mainly two kinds of power consumptions: the small DHW applications consume about 10 kW and the big ones do approx. 20 kW. With the current HEMS algorithm, the outlet temperature of the DHW tank is located in the range of 48 °C and 53 °C, covering over 95 % of the desired temperatures in DHW applications.

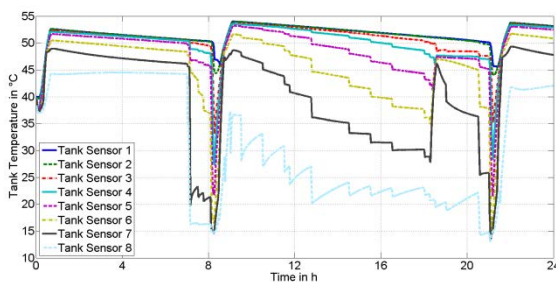


Figure 17 Tank temperatures in HiL

The temperature distribution inside the tank is visualized in Figure 17. Compared to the simulated result of the tank layer 3 (Figure 11), some discrepancies can be figured out, where the measured temperature in layer 3 is more stable and always higher than the simulated one. The inadequate modeling of the thermal layers inside the tank leads directly to different HEMS decisions and thus to variant behaviours in SiL and HiL simulations.

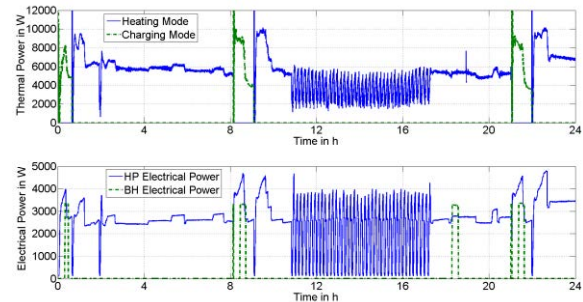


Figure 18 HES power information in HiL

From Figure 18, the thermal power generation and electrical power consumption of the HES can be retrieved. The overall energy efficiency of the total HES during the SiL test can be evaluated by the index performance factor (PF) as followed:

$$PF = \frac{\int(\dot{Q}_{th_HP} + \dot{Q}_{th_BH})dt}{\int(P_{el_HP} + P_{el_BH})dt} \quad (5)$$

Using the measured power data in Equation 5 and assuming that the electrical efficiency of BH is 0.9, the PF of the HES during the test horizon can be rated at 2.1, which means that by using 1 kWh electrical energy, 2.1 kWh thermal energy can be produced in HES. Compared to B/W HP system, the PF of A/W HP system is strongly affected especially by cold ambient climate and high indoor thermal comfort and DHW requirements.

CONCLUSION

The satisfying indoor thermal comfort and the high PF of HES are two desired objectives in the design process of a HEMS. In this work, the SiL/HiL simulation assisted design and validation approaches of HES have been introduced with help of the Modelica libraries and the HiL test platform. By means of an exemplary HES in a SFH, the rule-based control concept of the HEMS prototype has been proposed and functionally verified by the SiL approach. The measurement results in HiL test have validated the fulfilment of the design requirements.

ABBREVIATION

- HES = Home Energy System
- HEMS = Home Energy Management System
- HP = Heat Pump
- SiL = Software-in-the-Loop
- HiL = Hardware-in-the-Loop
- CoP = Coefficient of Performance

RES	= Renewable Energy Source
A/W	= Air-to-Water
B/W	= Brine-to-Water
DHW	= Domestic Hot Water
DHS	= Domestic Heating System
SFH	= Single-Family House
TWV	= Three-Way Valve
TRV	= Thermostatic Radiator Valve
EnEV	= Energieeinsparverordnung
BH	= Booster Heater
BUH	= Back-Up Heater
DWD	= Deutscher Wetterdienst
PF	= Performance Factor

NOMENCLATURE

F_t	= Tank Flow Rate
T_t	= Tank Outlet Temperature
F_p	= Target DHW Flow Rate
T_p	= Target DHW Temperature
F_c	= City Water Flow Rate
T_c	= City Water Temperature
$F_{t,m}$	= Measured Tank Flow Rate
$P_{t,m}$	= Measured DHW Power
T_s	= Sampling Period
E_p	= Remaining DHW Energy
C_p	= Heat Capacity of Water
ΔT	= Temperature Control Error
k_p	= Gain Factor of PI Controller
τ	= Time constant of PI Controller
$T_{m,t}$	= Referential Tank Temperature (Sensor 3)
$T_{t,s}$	= Tank Set Temperature
$T_{hys,BH}$	= BH Hysteresis
$T_{hys,TWV}$	= Three-Way Valve Hysteresis
$T_{hys,mod}$	= Hysteresis of Compressor Modulation
τ_1	= Activation Delay Time of BH
τ_2	= Activation Delay Time of BUH
$\dot{Q}_{th,HP}$	= Thermal Power of the HP
$\dot{Q}_{th,BH}$	= Thermal Power of the BH
$P_{el,HP}$	= Electrical Power of the HP
$P_{el,BH}$	= Electrical Power of the BH

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