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Hardware-in-the-Loop test bench setup and its application to determine seasonal performance of heat pump systems

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Abstract

In this paper we present a Hardware-in-the-Loop (HIL) test bench that is able to manage whole home energy systems (HES) in order to determine their seasonal performance. Previous investigations have shown, that the measured and calculated seasonal coefficient of performance (SCOP) of heat pumps (HP) have a significant deviation. As for the reason to that there are several impacts to name. One would be the non-static behavior of the HP, another the dynamics of heat source (e.g. weather) or the heat sink (e.g. user and building behavior). Finally, the HP controller strategies (e.g. on/off mode, defrosting, source-regeneration) and the act in combination of all HES components (e.g. HP, storage, pumps, etc.). In order to take all these influences into account, an alternative SCOP determination method is introduced. Thus, a HIL test bench is needed to deliver the necessary dynamic data. Besides the technical details and the control strategies of the test bench, the simulation is discussed as well. Finally, the HES installed at the test bench is shown and first results are drawn. These will indicate that the HIL method, the measuring system and the test bench are not only suited but necessary to examine todays and future HES.

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Key Words: Hardware-in-the-Loop, heat pump systems, simulation, seasonal performance

1 Introduction

Previous investigations on the seasonal performance coefficient (SCOP) of heat pumps (HP) have shown that there is a discrepancy between the measured and the calculated SCOP [1]. Various efforts have been made to close that gap, including a method [2] that uses the measured data of 3 to 5 typical days [3] to determent the SCOP . Hereby, the method takes into account the whole home energy system (HES) and not only the heat pump as a single component. This may consist of a buffer storage or a combined domestic hot water (DHW) tank, one or more pumps, mixing units and more. Also, it requires the performance data of these days in order to predict the SCOP. By using the Hardware-in-the-loop (HIL) method dynamic constrains are taken into account, such as the users ventilation behavior, a varying room set temperature, the weather and many more. Furthermore, one is able to observe the HES behavior during standard operation mode and especially during the times is doesn't contribute to the heating demand. These may be defrosting procedures or source regenerations programs. Although, the manufacturers try to increase the HES performance by introducing system controller or controllers which use higher, computer supported algorithms, a proof of concept is lacking. Conventional performance indicators that are based on static measurements are not fit to provide a data basis for these evaluations. In order to perform HIL experiments over a period of several days, a robust HIL test bench has to be set up. Furthermore, even if dynamic, boundary constrains have to be set. Thus, building simulation and test bench hardware have to perform as one. Because the new SCOP determination method [2] is still under active development, this paper will focus on the HIL test bench, its features and the HIL method according to this field of use. However, first results are shown which lead to conclusion that the chosen setup is suited for the task.

2 EXPERIMENTAL SETUP

2.1. The HIL- test bench

The HIL test bench at the E.ON Energy Research Center is designed to handle air/water- and water (brine)/water-HPs up to a thermal power of 30 kW. It is separated into a climate chamber and a hydraulic bank of 8 hydraulic circuits varying in size in order to fit the designated power level (0-5 kW, 5-14 kW and 14-30 kW). In order to minimize the error for the consumed electrical power, the electrical measurement comes in different levels as well. Thus, current transformers are chosen to cover a range from 0 to 30 A and 30 to 100 A, which they transform to a range of 0 to 5 A. Each phase is measured separately, making it possible determine individual consumers. Early tests suggest, that especially a separated measurement of the compressor and the heating rods give a better understanding of the operational mode of the investigated HP. The whole electrical measurement equipment is set up with the intention to be as flexible as possible. Therefore, we do not support a plug and play solution, but every HP has to be install by one of our electricians. Thus, fuses and cable sizes are chosen correctly and the HP is hooked up to the emergency switch. If it is necessary, the electrical power measurement can be switched to measuring just current, voltage, apparent power, reactive power, power factor or frequency. This can be helpful if the test object is a single component such as a compressor or a power source supplying the grid like a combined heat power unit.

Whenever a HES uses air as a heat source (or sink in case of active cooling) the climate camber comes into use. The following schema (Figure 1) illustrates the air conditioning setup in the climate chamber:

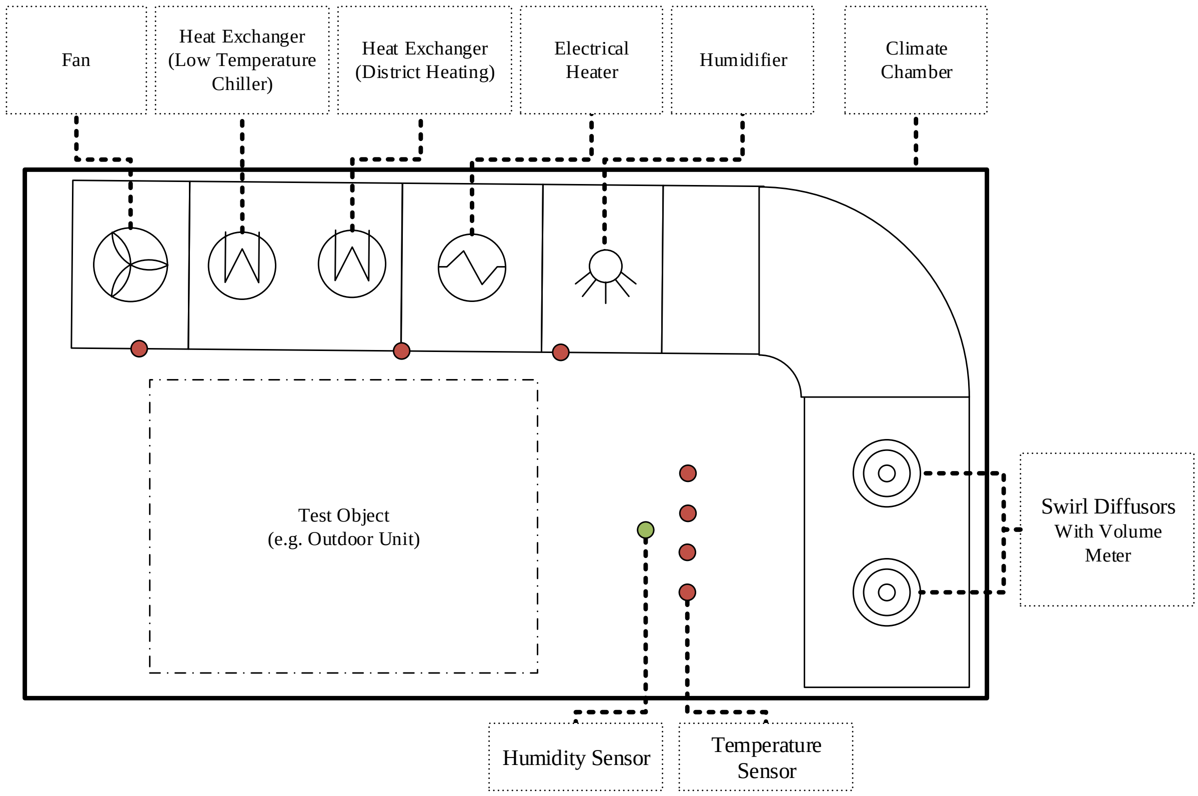

Figure 1 Climate Chamber

The air is sucked in by a fan and then cooled down by the low temperature heat exchange. After that the two-stage electrical heater heats the air up again to meet the set temperature in the climate chamber. The climate chamber is supplied by a low temperatures refrigerator which enables an active cooling (cooling while HP is off) down to -17°C. A welcome side effect of the active cooling is that the heat exchanger works as an air dehydrator. Combined with a steam humidifier and an advanced control strategy the desired set point for the relative humidity is met satisfactorily. The heat exchanger also works a capacity, so discrete events of the HP (e.g. status change from heating to defrosting) can be buffered and evened out with the electrical air heaters. Whenever it is necessary to defrost the heat exchanger, warm brine is pumped into the secondary circuit to melt the ice. The event is triggered by a controller which monitors the volume flow control voltage. Since, the humidifier uses water steam to humidify the air none additional energy is required to evaporate the water. Thus, the humidifier works adiabatically and can be put after the temperature control without any consideration. After the steam humidifier the air mixes until it is released by 4 swirl diffusors. Attached to them are volume meter to ensure a constant volume flow via active control. Even at a nominal air flow rate of 3000 m³/h the flow velocity at the test object is below 1,1 m/s, if the fan of the test object is turned off. This very low flow velocity is indispensable, because otherwise the climate chamber would support the heat transfer at the HP for which the fan is destined. The following diagram (Figure 2) shows the climate chamber at work with an active HP installed. The axes display the relative humidity in % respectively the temperature in °C, both at the test object, over the time. The displayed period contains a time span of 50.000 s, which is about 14 h. The overall quality of control is satisfying, however there are some exceptions to that. As mentioned before, the low temperature heat exchanger needs to defrost to prevent the air volume flow from decreasing. This process is responsible for the outlier at the times 12.000 s,38.000 s and 45.000 s. During the defrosting the volume flow is set to 0 m³/h, which leads to a drop of the temperature due to the active HP. In addition to this phenomenon is to name that the simulation starts a new day at 45.000 s. Therefore, a discrete change of the set point values also leads to a drop of the brine temperature of the heat exchanger. The controller tries to compensate this behavior which results in an overshot at 49.000 s. These observations suggest that some countermeasures have to be implemented. During the period from 17.000 s to 36.000 s a small oscillation of the temperature can be noted. This is due to the fact, that the HP shows an on/off behavior during that time. Going from 0 kW electrical power up to 3 kW and down again. Another instability can be found for the relative humidity in the period from 36.000 s to 45.000 s. Here, the set point value for the relative humidity is close to 100 %. In case of an overshot safety measures prevent the humidifier from producing more steam which leads to an on/off behavior at this point.

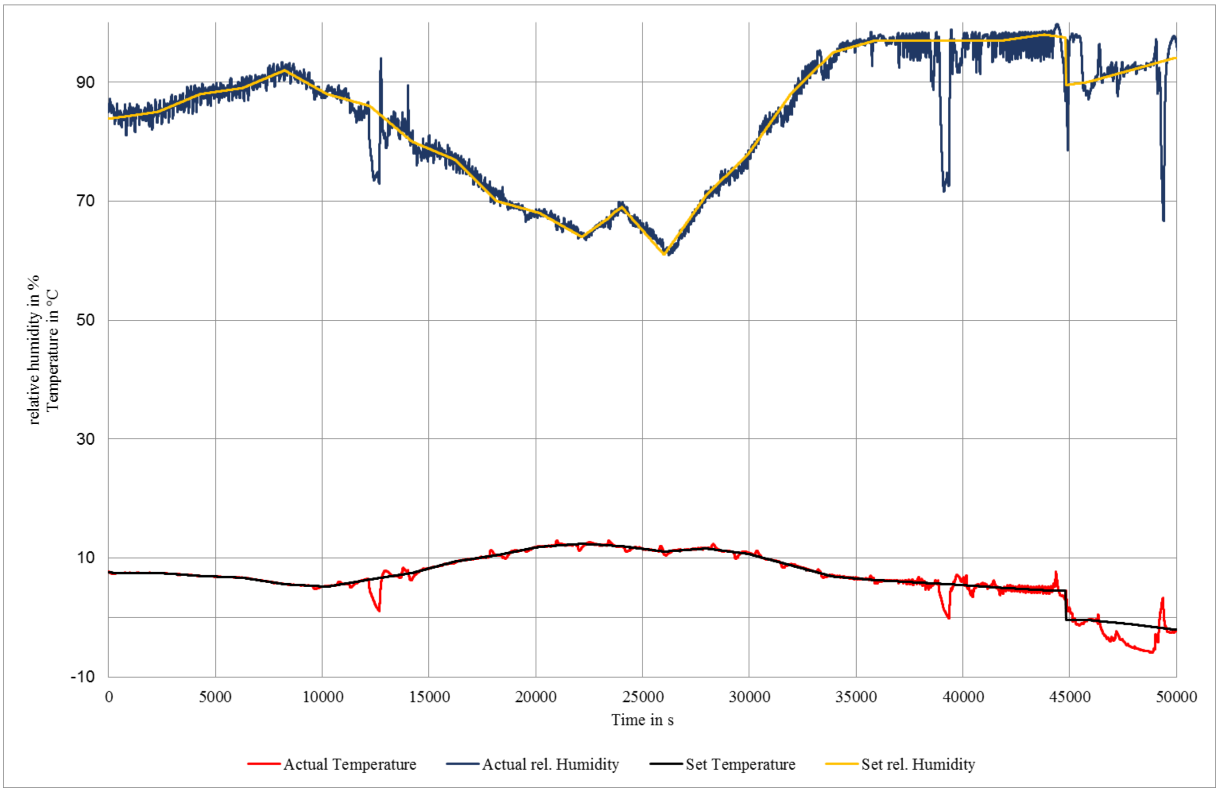

Figure 2 Developing of temperature and relative humidity at the test object

Located next to the climate chamber is the hydraulic test bench which consist of 8 hydraulic circuits as shown in Figure 3. Each of the hydraulic circuits can function as heat sink or source, it can be chosen between district heating (at a temperature of 70 °C) or cooling (at a temperature of 8 °C) or an external source. In order to switch modes motor valves have been installed (No. 4-7). The temperature control is done by a mixing loop and regulated by a high precision solenoid mixing valve (No. 3). The valve has a lift of only 8 mm which makes fast as well. Depending on the test object respectively test system it may be necessary to generate the volume flow by the installed hydraulic pump. In other cases, the pump can be by passed to reduce the hydraulic resistance using valve No. 2. To ensure a realistic volume flow the hydraulic resistance has to be fit to the simulation. Therefore, the pressure difference (No. 10) and the volume flow (No. 9) are measured and controlled by another high precision solenoid mixing valve (No. 1).

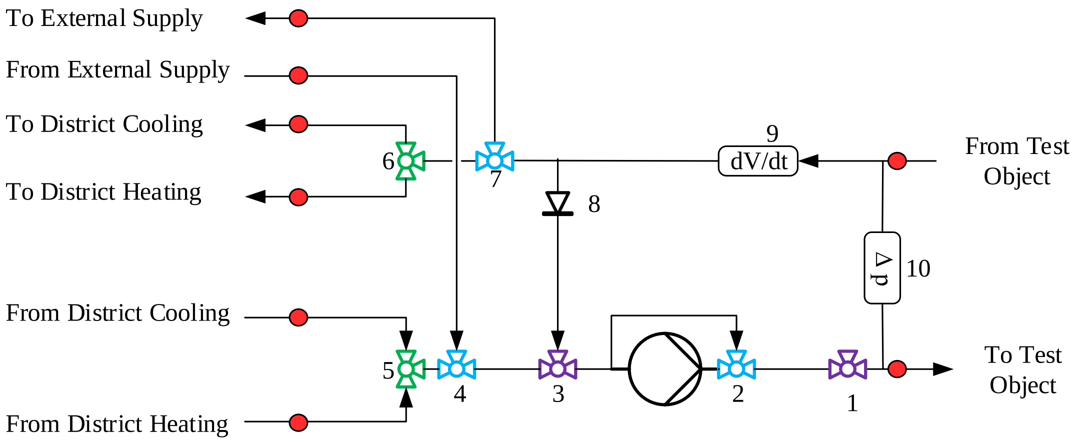

Figure 3 Schema of a hydraulic circuit

This highly flexible setup makes it possible to use the same hydraulic circuit for DHW, floor heating, radiator, convector or heat source emulation. Hereby, the thermal dynamic and physical response is calculated by the simulation. The accurate fulfillment of the set points is done by the implemented controllers and the parameters which adapt the test bench to the task.

2.2. Software Setup

In order to meet future demands towards flexibility and to reuse software if possible, the control software is designed in an object orientated structure. Therefore, the programmable logic controller (PLC) can use different controller and parameter sets accordingly. These parameters are stored in a MySQL database making it easy to document the current setting. The control software is developed in Beckhoff's TwinCAT 3. As for a general structure a state machine is implemented. The main states are:

0 Initialization
 The PLC loads the parameters for the controllers, the sensors and the actuators from the database and stores them in the instance of the according object.

1 Reading
 Input values are being converted to native values (e.g. voltage to volume flow) and combined values are calculated (e.g. mean temperature, humidity ratio by mass).

2a Automatic control
 All controls are active, this is the test bench's normal running state.

2b Manual control
 All controls are deactivated, the user can set values by choice.

3 Safety
 A set of strict safety rules overwrite values set by controllers or the user, if necessary. This mode shall prevent any damage to the test bench or the test objects. A prior conducted risk management analysis has outlined any potential hazard.

4 Writing
 Output values are being converted to signal values (e.g. number of revolution to voltage) and send to the actuators.

During one PLC cycle each main state is called from 1 to 4. The initialization state is only called upon startup or if requested. The user is able to decide which state of category 2 is run through by setting the according transition value. To connect the PLC and the Simulation a graphical user interface (GUI) running as middleware has been implemented. Figure 4 shows the software setup of the HIL test bench.

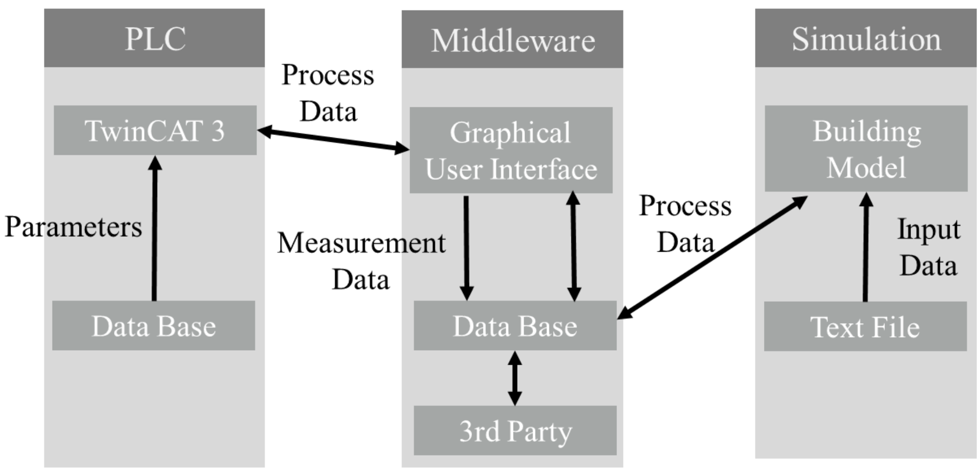

Figure 4 Test Bench Software Setup

Process data is gathered or send from or to the PLC using Beckhoff's Automation Device Service (ADS) which can be called directly by .NET applications, like the GUI. The GUI manages the data exchange between the simulation and the PLC via a MySQL database. Therefore, a set of functions have been implemented to read and write form and to the current data exchange table within the database. These functions are compiled to a C++ DLL file in order to easily make changes to the database connection without changing the code of the simulation. Also, other software such as LabVIEW can use the C++ functions to connect to the data exchange table. This communication makes it possible to switch simulation platforms or include third party devices, such as energy manager or tools from the test object manufacturer. The exchange functions use the data table as a stack buffer ("last in first out"), therefore clients will always have values to read even if they are out of sync. The GUI also gives a visual feedback of the test bench. The climate chamber and the hydraulic circles are drawn like Figure 1 and Figure 3 but with real time data. In addition to that, some histograms, dynamic diagrams and configuration wizards makes it possible to keep up with the test bench's data and to setup a HIL experiment.

2.3. Measurement System

As mentioned earlier the test bench is designed to handle multiple performance classes of HPs. All flow temperatures are measured by Pt100 (1/10 DIN Class B) resistance sensors, which are placed in the center of the hydraulic pipes (Figure 3 Schema of a hydraulic circuit, red dots). The volume flow itself is determined by a magnetic inductive flow meter (Figure 3, No. 9). The following Table 1 contains 4 example calculations regarding the uncertainty of the coefficient of performance (COP). The COP is set to a value of 4,00 to make the results comparable. The calculations are performed according to the guidelines of "Guide to the Expression of Uncertainty in Measurement" [4].

Table 1 Uncertainty of COP

Performance class	A	B	C	D	Unit
thermal power	2,10	6,30	14,10	21,00	kW
electrical power	0,53	1,60	3,50	5,30	kW
COP	4,00	4,00	4,00	4,00	-
Uncertainty of the COP	± 0,151	± 0,150	± 0,149	± 0,159	-
relative uncertainty	± 3,8	± 3,7	± 3,7	± 3,9	%

All 4 performance classes show an uncertainty of less den ± 0,16 with a COP of 4,00. This results in a relative error of less den ± 4 % throughout the performance classes.

2.4. Test System – HIL Test Bench Interface

Thus, the HIL environment is able to emulate outside conditions and building behavior, the observed system boundary can be spread from just the HP to the whole HES. Therefore, not only the refrigerate circuit is considered but also auxiliary consumers, system effects and system losses. So to say, the HES is handled as a "black box". The following chart (Figure 5) displays the system boundaries. The boundary marked "Heat Pump" contains the refrigerate circuit of the HP. The thermal condenser power is measured as well as the electrical power of the fan and the compressor. Depending on the HP, an auxiliary heating rod is installed and must be taken into account. Hereby, the heating rod is sometimes not measured but calculated as the difference between heat supply provided by the HP and the head demand of the building [6] . As for an energetically point of view this method is correct but it assumes that the HP is always used prior. This is a logical assumption but internal tests have shown that the heating rod is used to provide heat while the HP is in defrost mode. This supports the thesis of measuring all consumed electrical energies to cover all kind of behavior. Thus, the boundary "Home Energy System" is introduced. Besides the heating rod, it includes the loading cycle pump and the heating cycle pump. To determine the net thermal energy that enters the rooms, the boundary is set accordantly. All other thermal losses are therefore taken into account, which results in a user-orientated point of view.

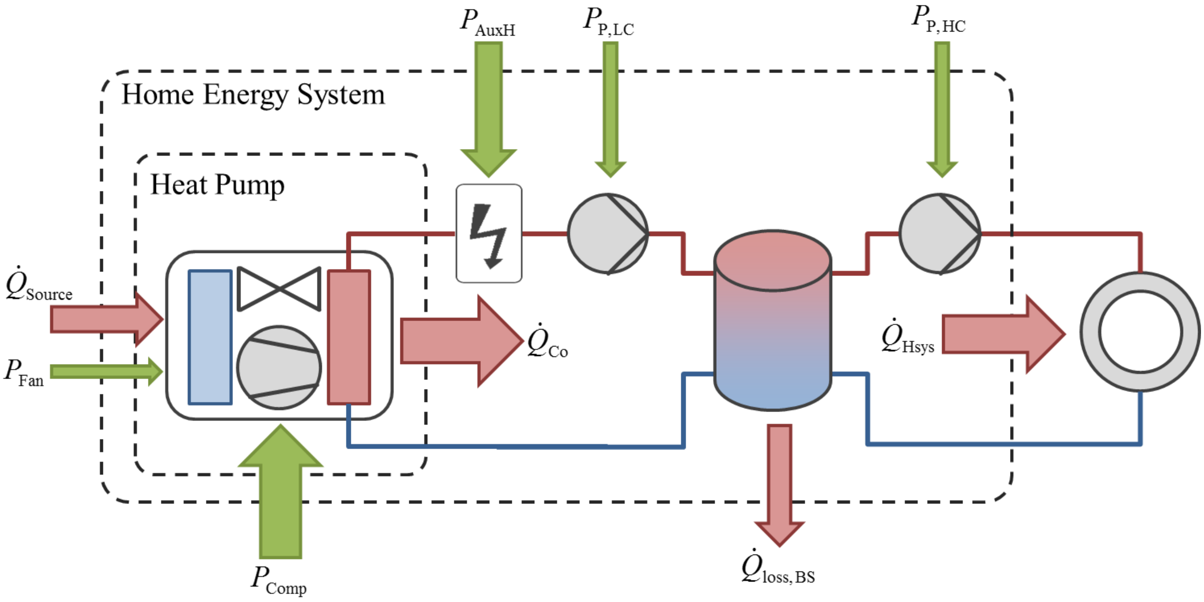

Figure 5 System Boundaries of the HES

The net thermal power going into the heating system ($\dot{Q}_{Hsys}$) and the consumed electrical power ($P_{Total} = P_{Aux} + P_{P,LC} + P_{Comp} + P_{Fan} + P_{P,HC}$) are the values if interest for the SCOP calculation.

2.5. Simulation Model

Next to the test bench, the building simulation model is a necessary component of the HIL method. The simulation time is slowed down to real time and synced to the test bench data. In addition to the shared data, external inputs such as weather data, user behavior, internal gains and room set temperatures are also taken into account. The "Institute for Energy Efficient Buildings and Indoor Climate" uses MODELICA and the development environment Dymola to ensure an object orientated modeling approach. All components of the building model are available for public use in the "AixLib" [7] library. One of the main advantages of the modeling language MODELICA is that physical and thermodynamic equations can be directly implemented. This enables one to troubleshoot down to the fundamental basics or having full insight of the model. For the first experiments, we modeled a one-family-house (OFH) with a nominal heat load of 9 kW. The insulation and building standard is set to the German heat protection ordinance of the year 1984. The two-storey-house consists of 10 heated and 3 non heated rooms, including the attic. This results in a total floor area of 158 m². The room set temperatures vary throughout the day between 17 °C and 20 °C for living rooms, 20 °C and 24 °C for the bathroom. As mentioned before, internal gains are also considered and vary from 0 to 680 W, as is the air exchange rate for each room which varies from 0,1 to 0,8 h^{-1}. A tow-pipe heating system with radiators provides the space heating. The nominal flow temperatures are 55 °C for the inlet and 40 °C for the outlet. This likely uncommon temperature spreading is because the model has to be comparable to the ones our project partners developed using another modeling language. In order to reach the desired room temperature, a PI controller controls the thermostatic valves. This control strategy prevents an unacceptable over or under heating of the rooms, which would reflect on the system performance. As mentioned earlier, the weather data is also a considered input to the model. Since the test bench can only emulate air temperature and humidity, the radiative solar gains do only enter the simulation. In this, they depend on the daytime, declaration of the sun and the gradient of the building surface. For each time step, the simulation uses these given conditions plus the measured inlet temperature and volume flow of the real heating system and calculates the thermal flows in and through the building. Finally, the resulting outlet temperature of the heating system is send to the test bench as new set point. Since we are investigating heat pump systems, the DHW consumption has to be looked at because the associated high temperatures challenge this technology especially. For the experiment we implemented a DHW consumption model which taps hot water according to the German DIN EN 16147 [8] profile "L". Since the HES is not able to provide constant flowrates and temperature from the first second, the total heat quantity and minimum flowrates and temperatures are introduced to defined a valid tapping. In order to accomplish a tapping at a target temperature T_{TapSet}, usually below the storage temperature, the hot water has to be mixed with cold water. The hydraulic circuits do not support mixing cold and hot water from the district supply. Thus, a virtual mixing [9] has been implemented.

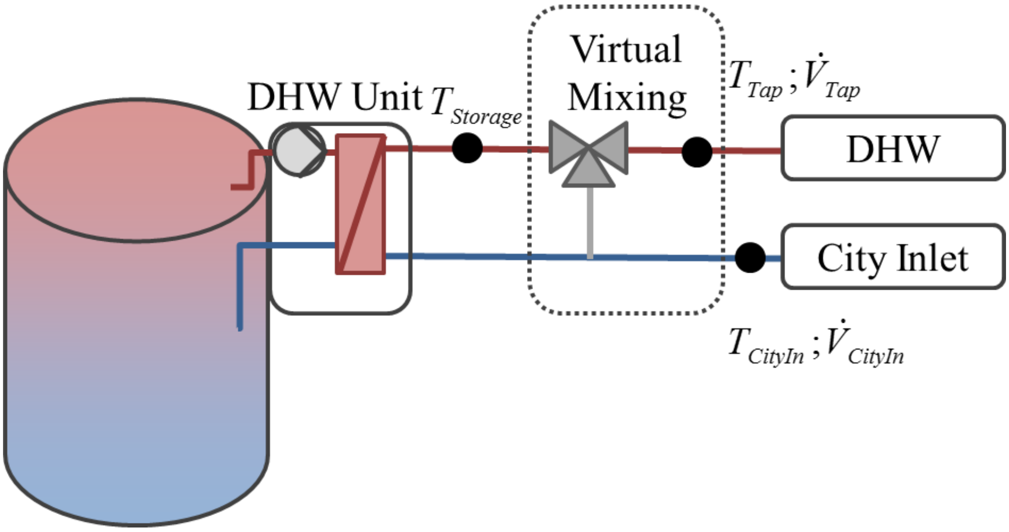

Figure 6 DHW Virtual Mixing

Furthermore, the city inlet water is set to a set point value of $T_{CityInSet} = 10\ °C$ and the set point flowrate $\dot{V}_{CityInSet}$ is calculated by the following equation (1):

$$\dot{V}_{CityInSet} = \begin{cases} \frac{\dot{V}_{TapSet}\left(T_{TapSet} - T_{CityInSet}\right)}{T_{Storage} - T_{CityIn}}, & T_{Storage} \geq T_{TapSet} \\ \dot{V}_{TapSet}, & T_{Storage} < T_{TapSet} \end{cases} \tag{1}$$

The model integrates the measured thermal flow for each time step as following:

$$Q_{Total} = \int \dot{Q}_{Actual} dt = c_p \cdot \rho \cdot \int \dot{V}_{CityIn} \cdot \left(T_{CityIn} - T_{Storage}\right) dt \tag{2}$$

If Q_{Total} has reached Q_{TapSet} from the profile, the tapping is complete.

3 HIL- Tests

As mentioned before, the HIL tests have to be shortened in time to make a practical appearance. Thus, Huchtemann et al. developed a k-medoid clustering method to reduce the number of testing days but with a consistently good calculation of the SCOP [3]. After detecting the key influences on the SCOP of a HES by a simulative sensitivity analyses, days are being grouped into a particular amount of clusters. Though, the aim is to minimize the distance of the key influences for each cluster. Simulations have determined an appropriate amount of 3 to 5 cluster centers, leading to an error in reference to a whole-year-simulation of less than 5 % [3]. The SCOP is then calculated as following:

$$SCOP = \frac{\sum_{i=1}^{3\,(5)} w_i \int_{00:00}^{24:00} \dot{Q}_{Hsys\ i}}{\sum w_i \int_{00:00}^{24:00} P_{Total\ i}} \tag{3}$$

According to the cluster size the weighing factor w is introduced. It is defined as the number of days in one cluster divided by the total amount of days. Wherever or not domestic hot water (DHW) consumption is taken into account, this amount changes from a whole year to just the heating period. However, for the experiments the days 175, 271 and 349 of the test reference year 2014 are the calculated cluster centers.

The installed HES consists of an air / water heat pump with a nominal thermal power of 9 kW, a 300 l multi-layer storage and a heat transfer unit. The heat pump itself is install in the climate chamber it is then connected to an indoor unit via water pipes, which leads to the necessity of cycling the water through the system in order to prevent frosting. The indoor unit contains a heating rod, a membrane expansion vessel and a 3-way valve to switch between loading the space heating layer and the DHW layer. The mentioned heat transfer unit is connected to the space heating layer of the storage and is also the system boundary to the hydraulic test bench. It has a hydraulic pump which electrical consumption is also measured. Attached to the storage is a DHW unit which is indirectly supplied by the topmost layer of the storage. The DHW unit has no additional heating rod. The heat pump system comes with a system controller which requires some additional sensors. One is the outside air temperature and humidity sensor which is also installed in the climate chamber. Another temperature sensor has to be installed at the top most layer of the storage. For this experiment the actual room temperature is not emulated to the system controller therefore the room temperature feedback function is disabled in the controller software. This is not uncommon if the controller is installed in the cellar or the building connection room.

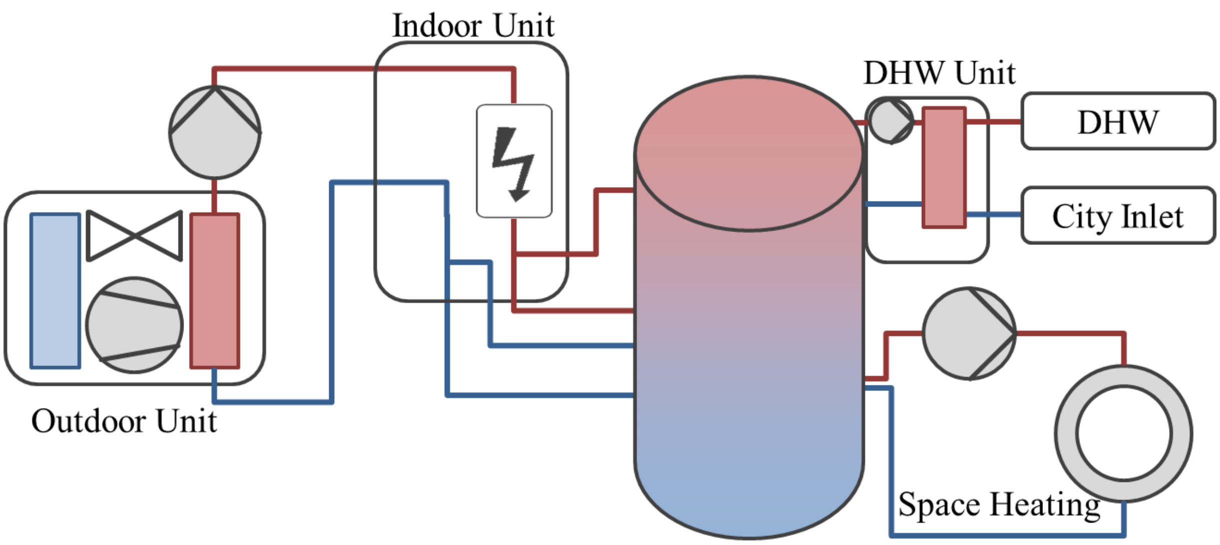

Figure 7 Installed HES

3.1. First Results

This chapter shall make an introduction to the results accomplished by the HIL test bench. However, at that point of time we are not able to present final results. Also, please note, that since the SCOP by HIL method is still under active development, results are normalized in order to protect the used HES from false conclusions. Also manufactures and explicit model descriptions are omitted.

The following Figure 8 shows the thermal and electrical power over day 271 which is the 28th of September (TRY). As for an autumn day one would expect a medium load throughout the day. However, the diagram shows no such behavior. In the early morning hours from 10.000 s to 23.000 s the electrical load is constant at a low level while the thermal load is rising over that period. Since we are measuring the thermal power that goes into the heating system we must assume that the electrical energy is used to heat up the storage. After the first tapings in the morning, the HP controller decides to heat up the tank again and more electrical energy is needed (30.000 s to 40.000 s). However, diagram doesn’t always show a smooth adapting of the compressor (like from 31.000 s to 33.000 s) but an alternating operating mode of the HP. Especially, around the time of 50.000 s the heat pump switches several times from 0 to 100% within a few minutes. Although, we are not able to determine a performance indicator from this diagram (which is done on purpose), it is safe to say, that dynamics and the operation behavior must be taken into account.

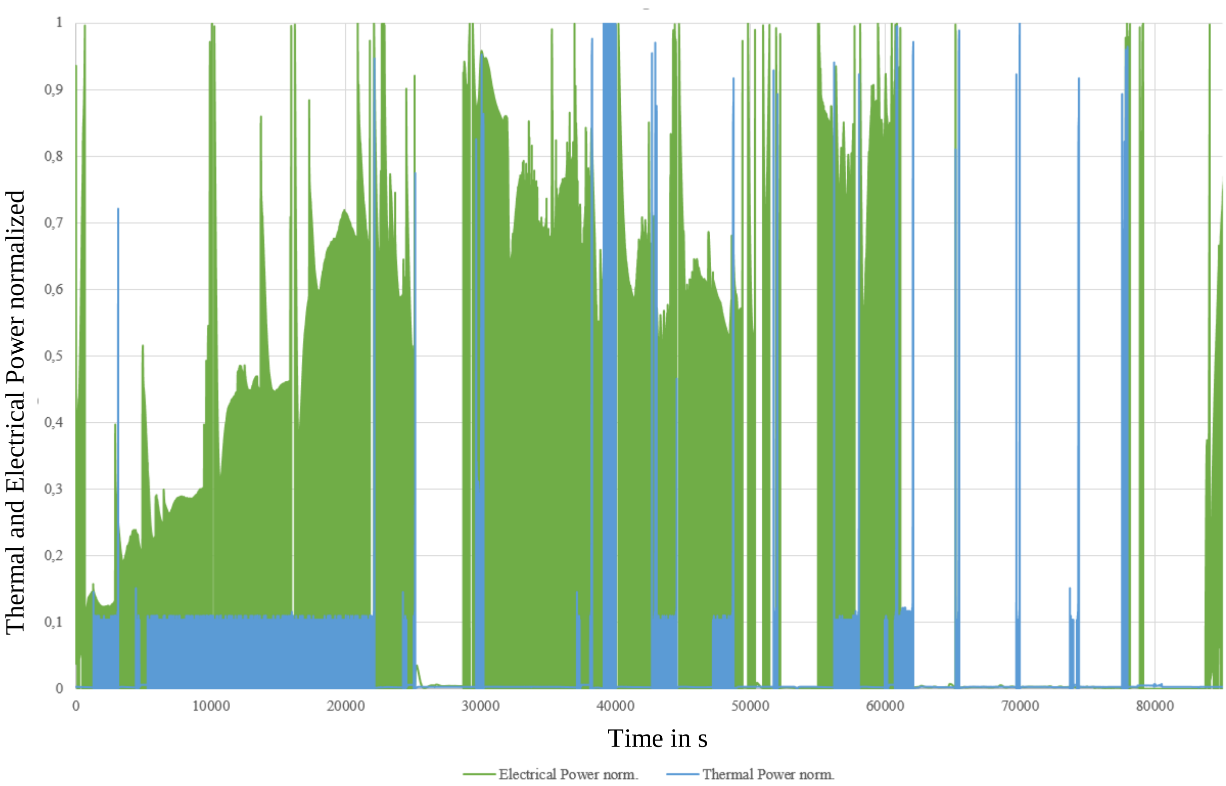

Figure 8 Electrical and Thermal Power of Day 271

4 Conclusion and Outlook

In this paper we stated the necessity to take dynamic behavior into account if performance, especially seasonal performance of a HES shall be evaluated. To do so a HIL test bench has been introduced. Besides its technical details, the control strategies of the test bench are explained to an extent. Since the HIL method consists of a physical test bench and a simulation part, the latter has been discussed as well. Moreover, the complexity of the DHW model has be stressed. Finally, the HES installed at the test bench is shown and first results are drawn. These are not meant be interpreted as quantitative statement but as indication that the thesis and overall method are fit to examine whole HP systems. As mentioned several times, the HIL test bench is designed to adapted to any HES. The necessary flexibility is found in all aspects of the test bench, especially on the hydraulic and the data handling platforms. We are positive that this HIL test bench will be able to perform to its purpose and be prepared to manage any challenge that comes in the field of HES.

5 Acknowledgements

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