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Dynamic testing of heat pump systems with predictive energy management systems using Hardware-in-the-Loop methodology

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Abstract

In order to evaluate heat pump systems adequately, in this paper the framework of the so-called Hardware-in-the-Loop concept is applied to create dynamic and realistic boundary conditions. In particular, this means real components of a heat pump system are installed on a test facility, while the boundary conditions are emulated based on a real-time simulation of a complex building model. A future challenge in terms of evaluating heat pump systems in a fair manner are upcoming intelligent and complex control algorithms like predictive control. Hereby, a pure energetic assessment is insufficient, since these energy management systems often aims to reduce cost or to increase thermal comfort. Therefore, we suggest to involve among others also economical aspects as well as aspects of comfort in the characterization procedure of heat pumps. On the one hand, one advantage of the Hardware-in-the-Loop concept is, e.g. to be able to investigate indoor air temperatures and include this knowledge in the evaluation procedure. On the other hand, issues of creating further interfaces for this evaluation methodology are discussed in the paper.

Hence, we compare a reference experiment of a chosen winter day to the same test day but using an energy management system. This energy manager controls the heat pumps compressor and aims to minimize the operational cost taking a simulated photovoltaic system into account. The investigated heat pump system is an air source heat pump coupled to a combined hot water storage tank. The results show an increase in the day related performance factor but higher deviations between actual and set room air temperatures. In general, the paper clarifies the necessity of enhancing evaluation procedures for heat pump systems with focus on future complex energy management systems.

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1. Introduction

In terms of evaluating heat pump (HP) units the state of the art is to perform tests under static boundary conditions to gain the so-called coefficient of performance (COP) [1]. On the basis of these COPs for different boundary conditions, a seasonal COP (SCOP) is projected in general for one year based typical operating points [2], [3]. Hereby, the COP is denoted by the ratio of the thermal and electrical power, whereas, the SCOP is defined by the ratio of the provided thermal energy and the consumed electrical energy for the considered time period.

A further approach, which this paper focusses on, is to conduct so-called Hardware-in-the-Loop (HiL) experiments, in which dynamic boundary conditions are applied. Therefore, the test objects under investigation, in this context the whole HP system, in particular HP unit, thermal storage tanks and auxiliary pumps, are connected to a test facility. This test environment exists of a climate chamber and a hydraulic test bench. In cases of air source HPs the evaporator, if it is a split device, or the whole HP is located in the climate chamber that then emulates dynamically desired outdoor air conditions. Additionally, the hydraulic test bench creates the thermal sink conditions, in other words the piping network of a building's heating circuit (HC). The desired volume flow rate and return temperature of this building's HC is calculated in a parallel simulated building model. In order to achieve dynamic behavior for the whole experimental setup, the simulation is performed in real-time and necessary values are exchanged each second between test rig and simulation. By applying this methodology and monitoring the consumed thermal and electrical powers it is possible to determine the HP system's efficiency for the experiment's time period. For this investigation procedure we determine a specific number of test days that represent a whole year. Hence, the monitored energies are scaled up to one year, in order to determine the SCOP. If we only perform a one day HiL experiment and measure the HP system's efficiency, we call this the day related performance factor. Furthermore, the simulation results reveal insights in, e.g. room temperatures and how thermal comfort is ensured with this particular HP and its control strategy, taking into account the type of heat distribution system. This exclusive information cannot be explored with the current normative methodologies. Although the HiL principle is a known concept, it is generally applied to systems of smaller size than whole heat generation systems. Furthermore, the context to evaluate the long time efficiency with the HiL methodology is a promising new approach.

With current standard control strategies of HPs it is possible to adapt a plug and play solution for the described evaluation procedure. This means a manufacturer delivers their HP system, which then is coupled to the test facility at our institute and the dynamic testing can be performed. But when thinking of more complex control strategies like predictive or adaptive control algorithms this plug and play solution is not realizable in such a manner. Since these complex and energy saving control strategies will probably be part of future HP systems, we also have to take this into account in our research projects and in enhancing the evaluation methodology. For example, adaptive controllers need a certain training time or adaptive ones need interfaces to exchange forecast values that influence the controlling variables of a HP directly. Fig. 1 displays in an overview on the left-hand side our current coupling regime on the test facility and on the right-hand side framework for future HP systems with complex controllers that need a further interface in the scope of the dynamic testing procedure.

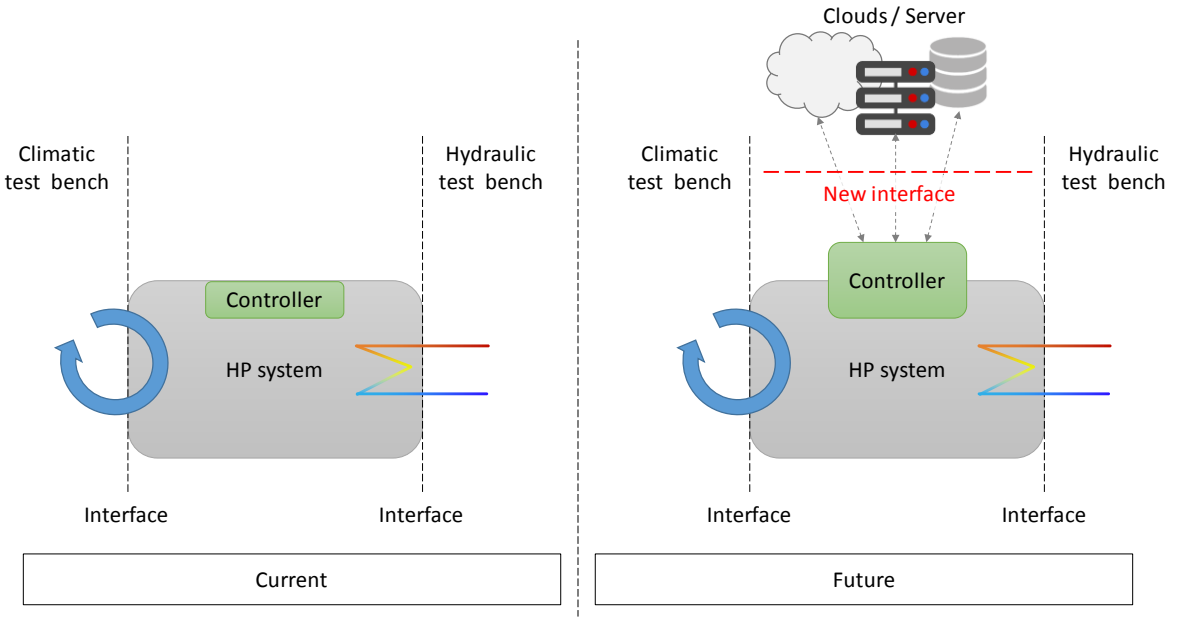


Fig. 1. Dynamic evaluation regime: left: current plug and play solution; right: future approach with additional interface

Finally, in this paper we also present results of first experiments in which a reference experiment of a winter day is compared to the same experimented day but with a rudimentary energy manger. The paper discusses the challenges of forcing a created schedule on the HP's controller, but also quantifies the improvement of the day related performance factor by using this energy management system (EMS). Besides this energetic analysis, additionally issues of e.g. thermal comfort are addressed.

2. Description of current heat pump evaluation method under dynamic boundary conditions

In the scope of this paper, the investigated HP is an air source HP that is able to provide thermal power for domestic hot water (DHW) and space heating to a typical one family house. In order to keep the used hardware anonymous, we do not disclose absolute values of the HP's capacity or the dwelling's design heating needs. Fig. 2 shows the HiL setup and component arrangement for the experiments. The HP unit itself is located in the climate chamber, where the outdoor air conditions for the chosen days are emulated. Therefore, values from the weather model of the simulation, in particular the outdoor air temperature and relative humidity, to which the building model is exposed, are directly the set values for the climate chamber. Moreover, an electrical heater is part of the HP system in order to provide necessary backup heat. Within this work, a combined hot water storage tank with a volume of 800 l for DHW as well as for space heating was used. The tank's volume is oversized on purpose to optimize the HP's runtime for periods with high solar irradiation, since a model of photovoltaic (PV) cells is also part of the simulation setup.

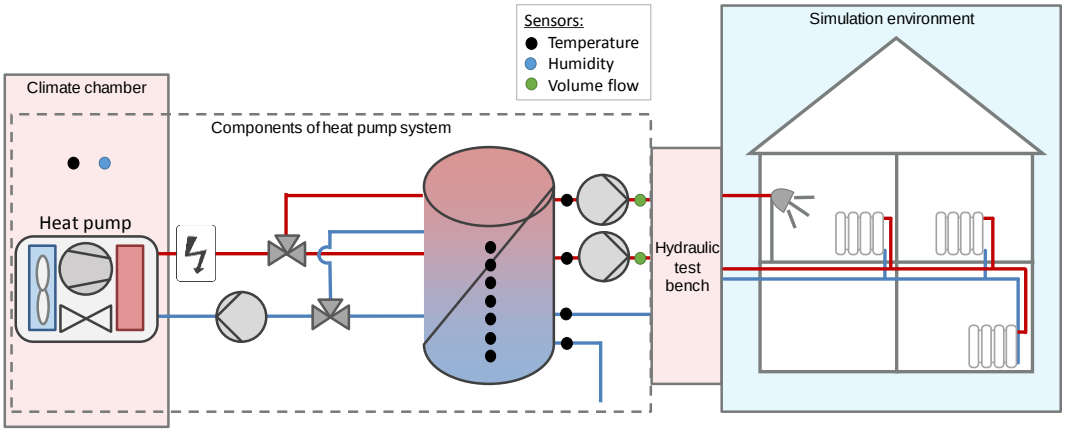


Fig. 2. Overview of HiL setup

The electrical power of all electricity consuming hardware components of the HP system is monitored with one 3-phase measurement module. Furthermore, the temperatures in the flow and return pipes of the emulated HC as well as the DHW related temperatures at the tank's inlet and outlet port are measured values. Besides these temperatures, further meters detect the volume flows that are provided for space heating and DHW demand to calculate the consumed thermal power. The circuits for space heating and DHW are emulated by two separate water circuits of the hydraulic test bench in order to provide the best possible control quality. Moreover, 7 temperatures sensors are attached on the tank's surface to determine in a vertical axis the temperature spread over the tank height.

To create a dynamic real-time HiL experiment, necessary values are exchanged between test facility and simulation with a frequency of 1 Hz. Table 1 displays an overview about these exchange variables.

Table 1. Overview of exchanged values in the HiL experiment

Measured values at test rig / input for simulation	Set values for test rig / outputs of simulation
DHW: temperature (hot) at tank's outlet port	DHW: temperature (cold) for tank's inlet port
DHW: mass flow at tank's outlet port	DHW: desired mass flow at tank's outlet port
HC: supply temperature	HC: return temperature
HC: pump's head	HC: volume flow
	Weather: outdoor air temperature
	Weather: outdoor relative humidity

The modelled and simulated building is a one family house with a living area of 158 m² and 10 heated rooms. The heat distributions system consists of a detailed piping network and conventional radiators with a nominal supply temperature of 55 °C. The radiator valves are controlled via PI controllers in combination with linear actuators to regulate the valve openings. All 10 rooms have different and varying scheduled set temperatures. Furthermore, the simulation is fed with varying air exchange rates and internal heat gains. Profile L of EN 16147

[4] represents the DHW tapping schedule which is based on reaching given amounts of thermal energies with a daily sum of 11.655 kWh.

In order to characterize the HP system's efficiency for one year adequately, in this research project we pursue the approach of performing experiments for chosen typical and for one year representative days [5], [6]. In particular, this means we determine a specific number of days from a whole data set of one year by applying the so-called k-medoids clustering methodology [7]. The chosen test or typical days then represent the whole year in a satisfying manner. With the gained day related performance factors, we are able to extrapolated the key indicators in combination with weight factors to a SCOP for one year.

This paper focusses on the comparison between a reference experiment and a second experiment where we applied a simplified EMS that creates a forecasted schedule for one day, which is then written on the HP's controller unit. Since not the projection of a yearly SCOP is focus of this work, only 1 day of this set of typical test days was chosen and performed in the HiL experiment. The chosen day is 15th December of the test reference year 2004 from the German Meteorological Service [8].

In the conducted work we also took into account the phenomenon of the non-negligible storage capacity of the building's thermal mass. In other words, this means we pre-simulated with a constant supply temperature 5 days prior the typical day in order to bring the whole hydraulic system's as well as the building's mass into an equilibrium state and, therefore, an appropriate state for the starting point of the typical day in the experiment. This is necessary as we do not want to shift energy that is stored in the building's thermal mass between whole seasons. The building has to be in the appropriate state for the specific day that is investigated.

Advantages that come along with the HiL methodology are also on the simulation side. Here we can couple a suitable or any desired building and can modify all models and simulation parts in a very detailed manner. This shows the potential of the whole HiL testing methodology.

But, as mentioned in the introduction, at the moment analogous to current labeling methods, a HP's characteristic is determined only by the electrical and thermal energies. When it comes to adaptive or predictive control we are facing further challenges. The discussion in the following chapters will give a general overview about EMSs, their role in building energy systems, and will show first ideas how to deal with issues coming along with investigating HP systems with EMSs.

3. Control mechanisms in future EMSs in context of building energy systems

Home EMSs have been recently investigated to make use of the flexibility that is provided by combinations of HPs and thermal storages. These systems are more and more electrically supported by PV cells due to increased installation of such panels on residential buildings. Several concepts for EMSs have been proposed in the literature which can generally be categorized as predictive or reactive EMS.

Predictive scheduling integrates forecasting methods and deliver an operation plan for a future horizon while reactive energy management only consider current information to optimize the operation of building energy system. A representative concept for reactive EMS is a multi-agent system which is a network of software agents that cooperate together to achieve both local and collective tasks. In a multi-agent based EMS every subsystem, like ventilation, energy generation and storage units as well as the user's demand or comfort standard, of the building energy system is assigned an agent [9]. Predictive EMSs are mainly formulated as optimization problems using mathematical programming, e.g. mixed integer linear programming (MILP), mixed integer nonlinear programming (MINLP) or metaheuristic for instance evolutionary algorithms. Depending on the underlying model, predictive EMSs integrate different forecasting methods for weather variables, demand loads, i.e. space heating, DHW and electrical demand as well as PV generation.

The forecasting models must be fitted or trained to capture the characteristic of the corresponding application or object. Therefore, it is critical to consider a learning phase in the initial deployment phase of a EMS to ensure that the model is adjusted to the available hardware and to ensure that the necessary data or interfaces are

established. Further, the forecasting models can be configured or formulated to include an adaptive learning behavior which may improve the forecasting accuracy with time.

An EMS optimizes the operation of the building energy system while pursuing a resident-specific target such as cost reduction, thermal comfort or integration of renewable energy. This optimized operation strives to fulfil the goal of the whole system, e.g. by shifting the operation of the HP to the time slots where PV generation is available, and does not align with conventional control modes of heating systems which aim to operate the unit independently of other available loads or generation.

4. Challenges coming along with future complex EMSs

When considering the above mentioned intelligent and more complex control algorithms, which are part of future HP systems, then the currently applied plug and play procedure for the evaluation methodology has to be enhanced.

One issue is that an exclusive energetic characterization in terms of integrating thermal power and divide it by the consumed electrical energy is not sufficient. A demonstrative example is an energy system consisting of a HP system that is supported by (PV) cells. Hereby, the electricity produced by the PV system and self-consumed by the HP has to be denoted as free electricity to assess the whole hybrid energy system fairly. Moreover, in case of using a predictive controller that shifts the HP's times of operation into time periods with high solar radiation, this could lead to a bad momentary COP but in terms of economical assessment such control behavior is beneficious. A further question is how to deal with forecast uncertainties when creating a schedule for the HP that is equipped with a predictive EMS. Therefore, e.g. statistically reliable types of uncertainties have to be forced on the HP controller during the evaluation phase. The current energy labels do not take these aspects into account. But future HP systems will probably use predictive control algorithms like that and, thus, fair and more realistic evaluation methods are inevitable.

Furthermore, in terms of adaptive algorithms, a challenging aspect is how to handle necessary training phases when dealing with learning algorithms. A hypothetical idea is to perform an accelerated learning phase. Therefore, it must be possible to compress the HP's time signal and couple the simulation model to the HP's controller and perform a defined training period with a certain time factor. Besides the time, which must be made accessible and scalable by the manufacturer. Additionally, all in- and outputs of the controller must be accessible for the mentioned types of complex control strategies.

Regarding a multi-agent based EMS all components the individual agents of the whole building energy system must have the possibility to communicate and interact with each other. In the context of evaluating a HP system which can be part of a hybrid building energy system, a solution might be to use appropriate models for the remaining components of the energy system that are equipped with agents. For this purpose, as well an interface between simulation and the HP's agent must be provided.

Another aspect that we can assess with the HiL testing methodology is characterizing the satisfaction of comfort requirements. This can be achieved by evaluating the simulation's results. A HP might have a good SCOP but delivered most of the time a not sufficient supply temperature or mass flow rate. As a conclusion desired room temperatures might not be reached. Besides economical and comfort aspects two further topics are an ecological or exergetic assessment. But within the scope of this paper we do not address these issues.

5. Description of the used energy manager

Within a research project the accessibility to a HP control platform was established and an own implementation of an EMS is used. It uses a predictive scheduling EMS to optimize the operation of the energy system, composed of HP unit coupled to a thermal water storage tank and assuming a locally installed PV unit.

The EMS is based on [10] and is formulated as a mixed integer linear problem with the goal to reduce the operation costs. The predictive EMS integrates forecasts of

- space heating demand,
- electrical demand,
- DHW demand,
- PV generation,
- outdoor air temperature

as well as tank temperatures from the past and delivers an operation plan or schedule for the considered HP operation periods for the next day with a time resolution of 15 min. In this first implementation outdoor air temperature and PV generation are assumed as a perfect forecast. The optimization model is formulated in python and the Gurobi optimizer is used as solver. Moreover, the EMS is able to write on the HP's controller platform.

The output of the EMS is an on/off signal for the compressor. At the current state we control the compressor modus, either on or off. We do not control the electrical heater nor do we set any flow temperature. In a next step, however, we plan to include these strategies in the EMS as well. To reduce operational costs, the compressor consumes the electricity generated by PV in order to overheat the combined hot water storage tank. This scenario does not consider an overheating of the building's thermal mass.

This predictive EMS was used in a one-day HiL experiment and the results are compared in the next chapter to the corresponding reference experiment. The particular test day was 15th December of the test reference year [8] with a mean outdoor air temperature of around 0 °C.

6. Results

6.1. Room temperatures and thermal power

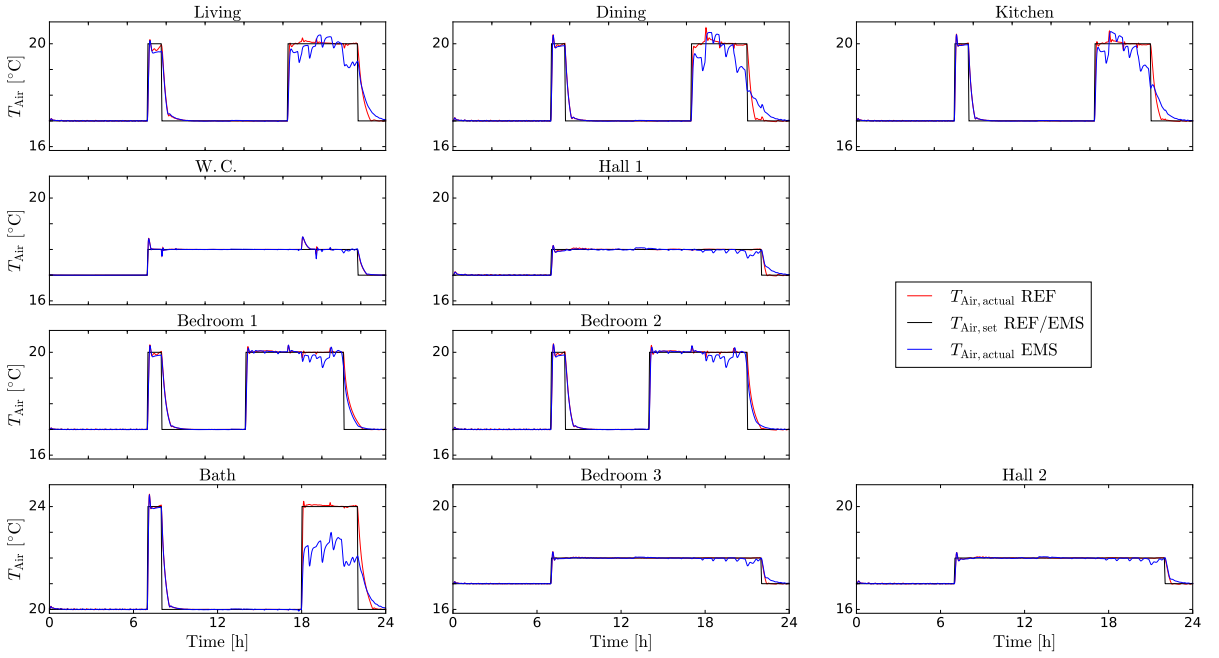


Fig. 3. Room air temperatures: actual and set values

Illustrating the aspect of thermal comfort, Fig. 3 displays the actual room temperatures during both experiments in comparison to the set temperatures. The temperatures during the heating up phases as a reaction to the steps in the room set temperatures show a quick and satisfying behavior. But the quality of keeping the desired set temperatures, especially in the evening hours, is worse in the experiment with enabled EMS. This phenomenon might occur due to a lower state of charge of the thermal storage than within the reference experiment. This leads to a lower supply temperature and a lower heat flow rate of the heat distribution system. The bath has a higher set temperature compared to all other rooms which leads to very high deviations.

Fig. 3 clarifies that an exclusive energetic evaluation and characterization of a HP system is not sufficient. Also the compliance to a set temperature profile and the users' comfort level must be part of a characterizing key performance indicator. This indicator could also be a weighted composite value of matching energetic, economic and comfort requirements.

Fig. 4 shows the curve of the thermal power $\dot{Q}_{\mathrm{th}}$ that is calculated based on the monitoring data noted on the right-hand side of equation (1). Hereby, the density and specific heat capacity are assumed to constant values of $\rho = 1$ kg/l and $c_p = 4180$ W/(kg K), respectively. Furthermore, the indices denote the supply (Su), return (Re), tank outlet (Tank) and tank inlet (Cold) temperatures.

$$\dot{Q}_{th} = \dot{V}_{HC} \cdot \rho \cdot c_p \cdot (T_{Su} - T_{Re}) + \dot{V}_{DHW} \cdot \rho \cdot c_p \cdot (T_{Tank} - T_{Cold}) \qquad (1)$$

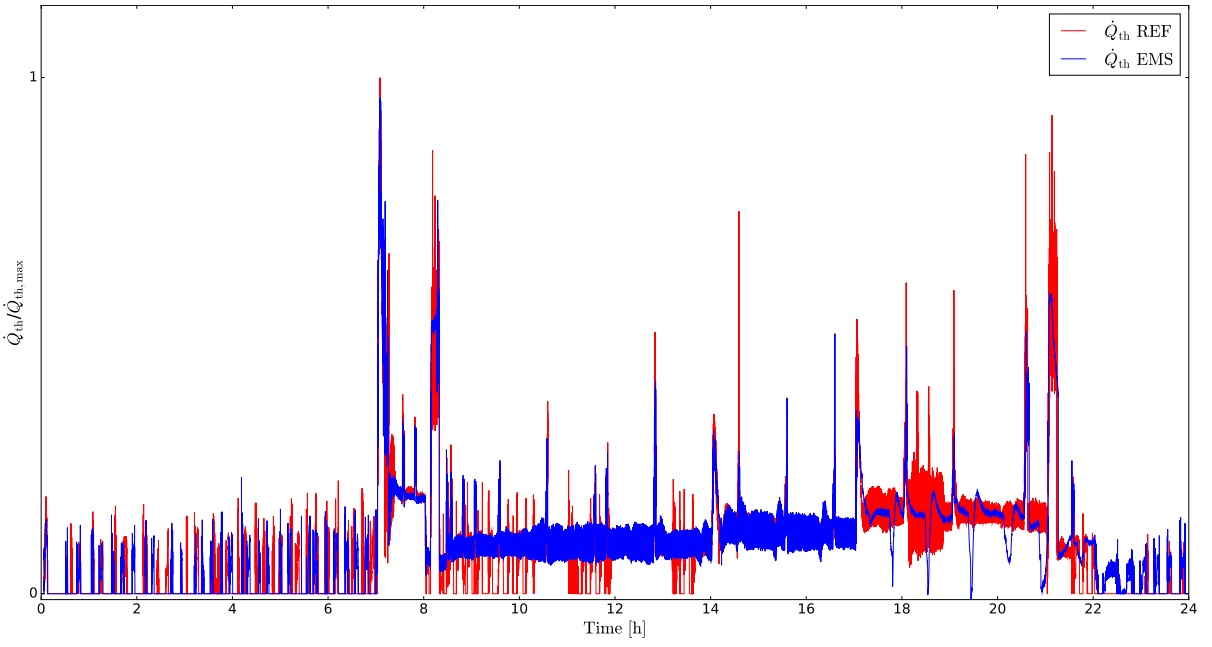


Fig. 4. Thermal power for the reference experiment and the experiment with enabled EMS

In the beginning of the day the rooms' set temperatures are at a low level of 17 °C, which results in a relatively low heat demand in the first 7 h of the day. In these hours in a cyclic behavior small amounts of volume flow are

pumped through the HC. Later the sink model requests higher set temperatures that come along with a more constant heat power demand. The total consumed thermal energies, i.e. the integrals of the shown power curves, result in a relative difference of 7.10 %. Since every experiment is individual due to unique reactions of the HP systems this difference is acceptable.

6.2. Consumption of electrical power and behavior of thermal circuit

With focus on the consumed electrical power during the experiments, Fig. 5 shows in the two upper plots a) and b) the net electrical power. Hereby, the net electricity is the sum of the electrical consumption of all components, which are installed on the test rig and that belong to the HP system, with the produced PV electricity subtracted from this sum. Only the curves' behavior makes it possible to distinguish between the activated electricity consumers, which are mainly the electrical backup heater and the compressor. The nominal power consumptions of the electrical heater and the compressor are 6 kW and 3 kW, respectively. The electrical heater operates in 2 kW steps where each step can be activated individually. As a consequence, the maximal electricity consumption is 9 kW.

Whereas, during the day with enabled EMS, often only the compressor is turned on, the electrical heater does not consume electrical power. In general, the modulation of the electrical heater in the reference experiment leads to a more fluctuating behavior, whilst the power curve of the experiment with EMS shows a comparably constant base load. Plot c) in Fig. 5 shows the on/off signal for the HP's compressor. The electrical heater sometimes operates in times when an off signal was sent, which is noticeable in the early morning hours (compare Fig. 5 plot b)), when stepwise 2 kW of the electrical heater are enabled. Additionally, the electrical backup heater is activated five times between 8 AM and 1 PM and once at the evening of the day with EMS (see Fig. 5 b) and c)). Vice versa, when the on signal was written, the compressor operated at its nominal load of 3 kW.

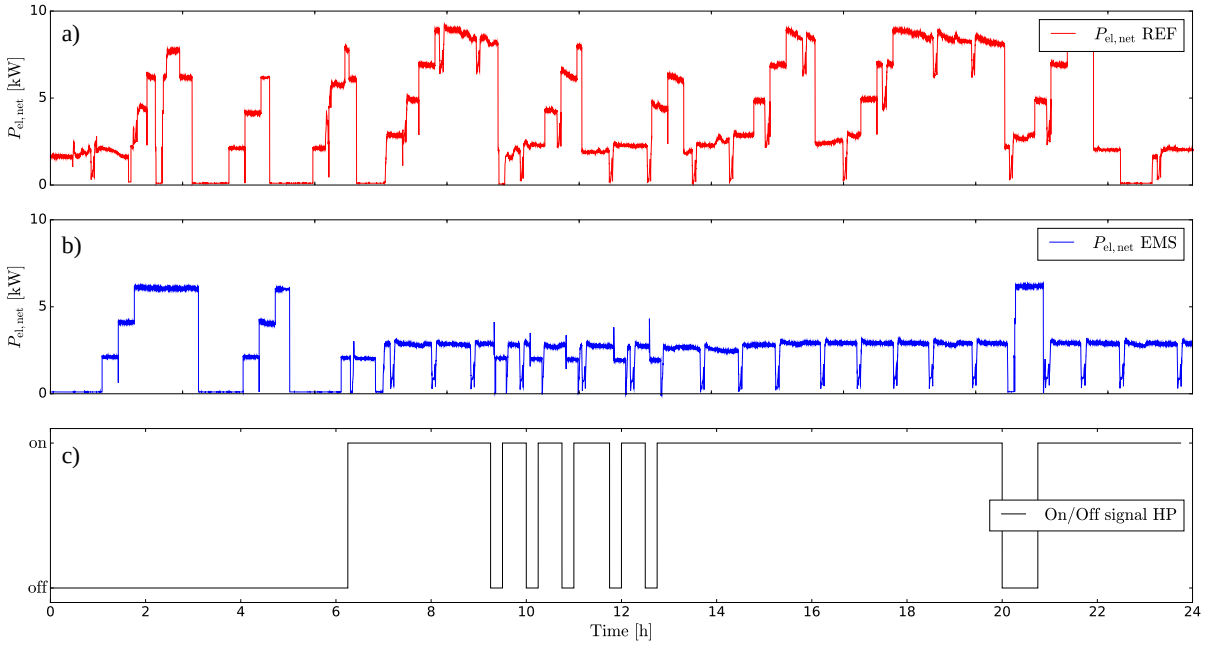


Fig. 5. Net electricity consumption for a) the reference experiment and b) the experiment with EMS; c) on/off signal sent to HP

Lower supply temperature in the system with EMS are balanced by higher mass flow rates in the HC. This leads to a smaller temperature lift and thus to an efficient operation of the HP. Therefore, Fig. 6 shows the temperature spread for both experiments and the corresponding volume flows during the one day experiment. But it has to be mentioned that for the installed radiators this temperature level is not always sufficient to keep the desired set temperature (compare bath in Fig. 3).

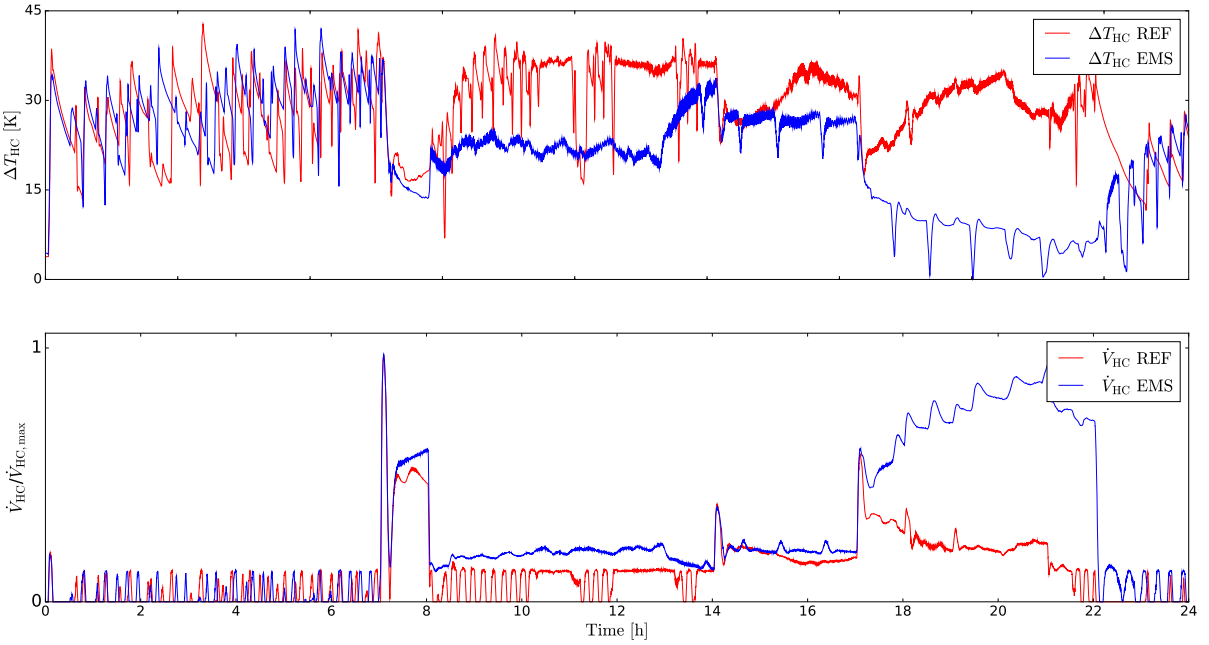


Fig. 6. Temperature spreads between flow and return temperature and as well as volume flow through the HC

6.3. Relative comparison of day related performance factor

With a resulting increase in the day related performance factor of 72.63 % we could detect a significant improvement in terms of energetic evaluation by implementing the EMS. Nevertheless, it is important to keep in mind that the EMS used a perfect forecast. Additionally, this energy manager is a first test module, which is able to turn on and off the compressor but cannot control the electrical heater directly. Moreover, which is the main aspect of this paper, this energetic evaluation number is not the only value that should characterize a HP system's efficiency for a longer period.

7. Conclusion and Outlook

The paper illustrates an alternative methodology for characterizing HP systems by using the concept of HiL. It is shown that such a testing procedure under dynamic boundary conditions is suitable for the quantification of the HP system's long time efficiency as well as for investigating a HP's operating principles more detailed than compared to applying static tests. But since complex control strategies will be part of buildings' future EMSs,

challenges in combination with the explained testing methodology are illustrated. On the one hand, theoretical approaches and solutions for these challenges are described. On the other hand, a first implementation of a predictive scheduling EMS is introduced and practical experiments were conducted. In this context, we present the issue of creating a working interface between EMS and the HP's controller platform. EMSs that connect different components of a hybrid building energy system must be served with a connectable interface. Therefore, in the upcoming field of research, cooperation with manufacturers is indispensable. Nevertheless, within the comparison of the two one-day experiments a significant increase of the day related performance factor of around 73 % could be established. But this improvement must be treated with caution since partially a perfect forecast was assumed and the state of charge of the thermal storage tank was different at the end of both experiments. These phenomena led to a not directly quantifiable influence. However, this first implementation of a EMS clarifies the potential for energy savings due to intelligent energy management.

Besides the mentioned technical issues, additionally, aspects of enhancing the characterizing value for HP systems by more indicators are discussed. The operation of an EMS which aims to minimize the operational cost is clearly not characterized fair when only addressing the energetic efficiency. Although the day related performance factor shows in this experiment a non-negligible improvement, the characterization of a HP must include the whole intelligence of the aggregation of all components.

Furthermore, besides energetic and ecological aspects, also the quality of generating a good thermally comfortable environment must be evaluated. For example, in the second experiment the compliance between the rooms' air temperatures to the corresponding set temperatures partially do not show satisfying congruence (compare Fig. 3). Involving this aspect, a characterizing key performance indicator would be reduced by this failure in thermal comfort.

Aside from these aspects, additionally, ecological and exergetic analyses could be part of prospective evaluation procedures. Moreover, future experiments should be conducted with an enhanced interface to the HP's controller platform. Nevertheless, the presented methodology of applying dynamic boundary conditions using the HiL concept, provides a suitable technique to perform a multi-perspective, realistic and fair evaluation of a HP heating system that makes use of a complex EMS.

Acknowledgements

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