Influences of Hot Water Tank States and the Order of Test Days to Gain the Annual Efficiency of Heat Pump Systems Evaluated Using Modelica

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Abstract

Within the scope of this paper, an actual experimental procedure to evaluate a heat pump's (HP) long-time efficiency is formulated as a pure simulation issue using the modeling language Modelica. Hereby, a long evaluation period is reduced to 4 typical test days. The aim of this paper is to investigate in a cost-efficient manner the influence of shifting energy in thermal energy storages (TES) throughout the experimental time. Since the concept uses particular test days according to the k-medoids clustering, the state of charge (SOC) in the end is unequal to the SOC at the beginning of the test cycle. The paper shows that ordering the test days from warm to cold and back to warm leads to the least mean deviation of inner energy with $\Delta\overline{U} = -0.94\ \mathrm{kWh}$.

Introduction

Long-time efficiencies of heat pumps (HP) determined in field tests often deviate in a non-negligibly manner from efficiencies predicted by normative standards. Since these standards are based on stationary testing, in a current research project an alternative evaluation method using dynamic boundary conditions is developed in order to gain a performance factor which is closer to reality.

This approach makes use of the Hardware-in-the-Loop (HiL) concept. Hereby, real hardware components of the HP system are installed on a test facility, where desired boundaries can be set and forced to the hardware interfaces. In this context of an air source HP, the boundaries are on the one hand the source conditions, in particular the outdoor air temperature and humidity. A climate chamber, which is one part of the test facility, emulates these outdoor air conditions. The second part of the test rig is a hydraulic test bench that on the other hand emulates the thermal sink to represent a building's heating circuit. Detailed simulation models generate the necessary information for the emulation, like outdoor air temperature, relative humidity as well as the heating circuit's volume flow rate and return temperature. These models are formulated in the object-oriented language Modelica (2016). They consist of a weather model, a model representing user behavior and complex models for the building construction and piping network. Moreover, to receive a working HiL environment, the simulation is coupled to the test facility. Due to value exchange in real-time appropriate and dynamic boundaries are set for the emulation.

In order to determine with the explained concept a realistic efficiency within a manageable time horizon, particular days, which are meteorologically representative for one year, are selected by applying the k-medoids clustering (Vinod (1969)). The issue addressed in the scope of this paper is that, different from reality, thermal energy in the system's storages is shifted between test days representing different periods of the evaluation cycle. For instance, thermal energy could be shifted from a winter to a summer day. The thermal energy storages (TES) are part of the HP system and therefore part of the control volume. This shifting also means that the state of charge (SOC) of thermal storage tanks at the beginning and at the end of the test cycle is not the same. As the deviations are dependent from the order of the above-mentioned representative days, different arrangements are investigated. To examine the problem as economically as possible, the experimental part was transferred into a simulation model. Thus, in the scope of this paper simulations with different orders of typical days in combination with varying parameters are performed and the results are discussed.

State of the art

COP and SCOP

At the current state of the art, a HP's long-time efficiency, in general for one year, is defined by the seasonal coefficient of performance, the so-called SCOP. For electrically driven HPs, (1) defines the SCOP.

$$\mathrm{SCOP} = \frac{\int_0^{1\,\mathrm{a}} \dot{Q}_\mathrm{th}}{\int_0^{1\,\mathrm{a}} P_\mathrm{el}} \qquad (1)$$

Hereby $\dot{Q}_\mathrm{th}$ denotes the thermal power that is provided by the HP. P_el is the electrical power that is consumed by the HP. For the purpose of determining the necessary powers, testing institutes perform experiments with HPs on a test rig under static boundary conditions according to the European standard DIN EN 14511 (2013) in order to gain the momentary efficiency of the HP, which is called coefficient of performance (COP). Afterwards, further

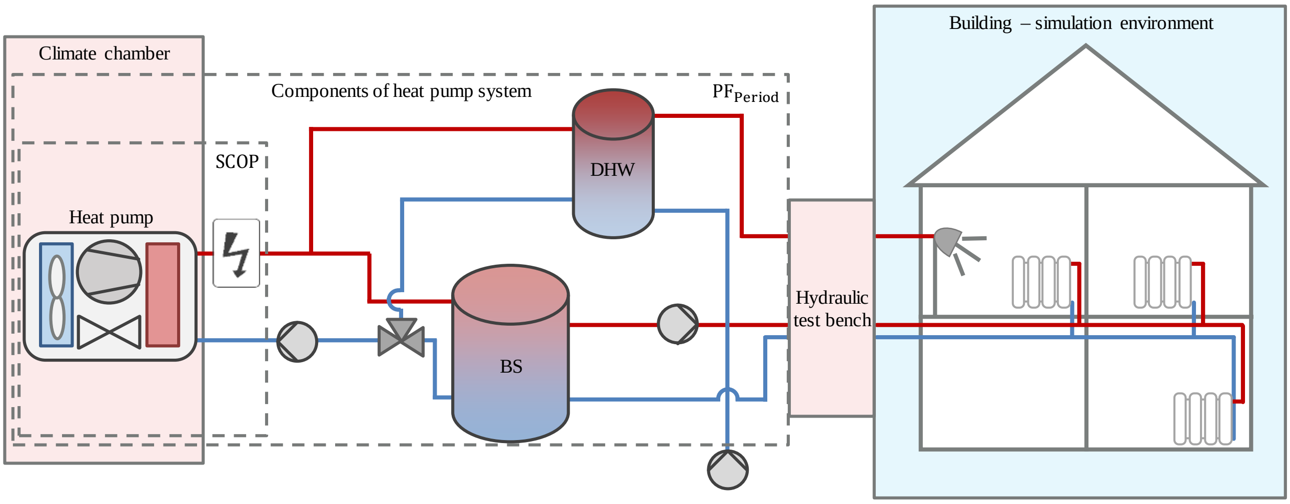

Figure 1: Overview of HiL experiments and analogously of the simulation setup

norms like the European standard DIN EN 14835 (2013) or the German guideline VDI 4650 (2014) are applied in order to project the SCOP based on measured COPs of different operating points.

Evaluation of heat pump systems using the Hardware-in-the-Loop methodology

In contrast, at our institute we pursue a different approach of determining the long-time efficiency of a HP or even of a whole HP system. This includes auxiliary components like circulating pumps, HP's controllers and TES's such as buffer storages (BS) for the heating circuit or domestic hot water (DHW) tanks. As the end consumer is more interested in the efficiency of the whole HP system, the control volume within the scope of this work encompasses all components. Pursuing this approach, the end consumer is able to better estimate the period of the investment pay back. As a consequence, the power P_{el} now includes the electricity consumption of all electrical devices belonging to the HP system. Analogously, $\dot{Q}_{\mathrm{th}}$ expresses the thermal power that is provided to the heating circuit and the DHW stream and not only the heat flow transferred in the HP's condenser. In this context we name the long-time efficiency $\mathrm{PF}_{\mathrm{Period}}$. Hereby, the index "Period" indicates the reference period, e.g. one year. Figure 1 shows the different control volumes to be able to distinguish between the conventional SCOP and the in this work used $\mathrm{PF}_{\mathrm{Period}}$. Furthermore, besides the following written description, Figure 1 supports the explanation of the applied approach. To gain the $\mathrm{PF}_{1\mathrm{a}}$ we use the methodology of HiL in combination with selected typical test days. Hereby, we test the hardware components of a HP system on a test rig. This test rig is able to emulated desired air conditions in a climate chamber and to emulate a heating circuit via a hydraulic test bench. Parallel, we simulate a building in real-time and its heating circuit's piping network in order to dynamically calculate the current heat demand. Additionally, a DHW demand is simulated and emulated by the hydraulic test bench. The two parts, test rig and simulation, are coupled to each other. This creates the possibility to test a real HP for any preferred day of the year under realistic and dynamic boundary conditions. The test days are meteorologically representative days of one year, which are gained by applying the statistical approach called k-medoids clustering (Huchtemann (2016), Vinod (1969)). With this methodology 4 days of a test reference year (TRY) are chosen in terms of representative hourly values for the outdoor air temperature as well as the direct and diffuse solar irradiation. A simulative study (Huchtemann (2016), Engel (2015)) revealed that a number of 4 typical days results in less than 4 % deviation to the reference SCOP of a whole year. The study includes three different heat pump systems: only air source, air source supported by a solar thermal collector, ground source. Furthermore, a number of 4 test days ensures a reasonable testing time, when performing real world HiL experiments. The resulting typical days according TRY (2010) region 5 are 16$^{\mathrm{th}}$ March, 26$^{\mathrm{th}}$ March, 24$^{\mathrm{th}}$ July and 22$^{\mathrm{nd}}$ September. Region 5 is a part in the west of Germany. Each of these typical days represent $n_{\mathrm{days},i}$ days of the year and serve therefore as weighting factors. (2) displays the calculation of the $\mathrm{PF}_{1\mathrm{a}}$.

$$\mathrm{PF}_{1\mathrm{a}} = \frac{\sum_{i=1}^{i=4} \frac{n_{\mathrm{days},i}}{365} \cdot \int^{\mathrm{day}_i} \dot{Q}_{\mathrm{th}}(t)\, dt}{\sum_{i=1}^{i=4} \frac{n_{\mathrm{days},i}}{365} \cdot \int^{\mathrm{day}_i} P_{\mathrm{el}}(t)\, dt} \qquad (2)$$

Hereby, Table 1 lists the number of days $n_{\mathrm{days},i}$ belonging to the i^{th} cluster.

Table 1: Dates and number of days in one cluster

i	Date	$n_{\mathrm{days},i}$
1	16$^{\mathrm{th}}$ March	120
2	26$^{\mathrm{th}}$ March	75
3	24$^{\mathrm{th}}$ July	48
4	22$^{\mathrm{nd}}$ September	122

As a consequence, in the HiL procedure the whole series of typical days is performed as one 4-day long experiment. The monitored thermal and electrical powers are then projected according to (2) to gain the $\mathrm{PF}_{1\mathrm{a}}$.

Energy shifting

The changeover between two typical test days, e.g. from a winter day to a spring day, comes along with two issues of thermal storage capacity that mislead the energetic analysis.

1. The thermal state of the building's mass is not correct for the spring day, when changing from the previous colder day. The building's mass is still colder than it would actually be on the spring day.
2. The buffer and DHW storage might have been charged on the colder first day, when the HP's efficiency is worse due to the colder ambient air temperature. During the warmer day, the system benefits from the charged tank and can heat the building for a longer period on the second day. Additionally, in the end of the 4-day series the TES's might have a lower or higher state of charge (SOC) than in the beginning of the experiment.

The first issue can be solved by pre-simulating a couple of days, in this work 10 days, such that the building finds itself in steady-state and an appropriate thermally charged state. Regarding the second issue, since the tanks are part of the real hardware components, it is impossible to pre-condition the storages via simulations. This leads to the consideration of diverse strategies to arrange the test days, which is topic of this paper. For this purpose, we have chosen a purely simulative approach in order to quantify the influence on the HP system's $\mathrm{PF}_{1\mathrm{a}}$ in a cost-efficient way.

Simulation Setup

Designing and planning the simulations

The modeling was realized in the open-source and object-oriented modeling language Modelica (2016) and the simulations were performed with the software environment Dymola (2016). Models for this investigation were mainly used from the freely available library "AixLib" (AixLib (2016), Müller (2016)).

In general, the HiL approach is translated into a simulation problem. For this purpose the actual hardware components according to Figure 1 are replaced by simulation models: heat pump, hot water storages, valves and pumps. Within the simulation setup, these models are treated in the simulations as if they were real hardware components. In particular, this means when switching from one typical day to the next one in the chosen order, parts that normally belong to the experimental configuration are initialized with the values of the end of the prior test day. In contrast the remaining models of the simulation setup are initialized with the state from the end of the prior calendar day. This is achieved by pre-simulating each test day (see Table 1) in order to bring e.g. the building's mass into a for that date appropriate condition. To realize this approach, we combine result files from chosen sub-models from two different simulations and apply them as initialization values for the simulation of the following test day. The pre-simulations especially address and solve the first issue of the energy shifting problems.

Besides a varying order of the typical days, we also investigated two different volume pairs for the two separate TES's, the BS and the DHW tank. The mean volume of the DHW tank is calculated according to Viessmann (2011), where the simplified approach shown in (3) is explained assuming a temperature of 60 °C at the DHW tank's outlet.

$$V_{\mathrm{DHW}} = \mathrm{No}_{\mathrm{Pers}} \cdot f \cdot 25\,\mathrm{l} \qquad (3)$$

Here, $\mathrm{No}_{\mathrm{Pers}}$ denotes the number of the household's persons which is 4 in the scope of this paper. Furthermore, since $\mathrm{No}_{\mathrm{Pers}} < 10$, the factor f equals 2, this results a mean DHW tank volume of $V_{\mathrm{DHW}} = 200\,\mathrm{l}$. In terms of the parameter variation volumes with $\pm 20\,\%$ content were chosen such that tanks with a small/large volume of $V_{\mathrm{DHW,s}} = 160\,\mathrm{l}$ and $V_{\mathrm{DHW,l}} = 240\,\mathrm{l}$ were implemented depending on the variant.

Additionally, the mean volume of the BS was also designed according to Viessmann (2011) in order to fulfill requirements for runtime optimization. This results in a mean volume of $400\,\mathrm{l}$ and as a consequence with $\pm 20\,\%$ in a small volume of $V_{\mathrm{BS},s} = 320\,\mathrm{l}$ and a large volume of $V_{\mathrm{BS,l}} = 480\,\mathrm{l}$.

In addition to the variation of the typical day order and the tank volumes, also the control strategies for both tanks are varied. Whereas in control strategy CS_1 the DHW tank is charged within the hysteresis ranges $45..63$ °C based on a temperature sensor placed in the top of the tank, in CS_2 the boundaries $55..60$ °C are valid. The buffer storage is equipped with one sensor at the top and one at its bottom. When the bottom temperature exceeds a defined deviation above the target temperature the HP is turned off until the top temperature falls below the target temperature minus the specified temperature difference. Then the HP is turned on again. The target temperature is the flow set temperature according to an appropriate heating curve. For CS_1 the defined temperature difference is $\pm 5\,\mathrm{K}$ compared to the target temperature. For CS_2 $\pm 1\,\mathrm{K}$ is defined. In a summarized manner, Figure 2 displays the variation design and declares the four variants as "Var1" to "Var4".

For each of these 4 variants a reference simulation for one year was performed in order to compare the projected $\mathrm{PF}_{1\mathrm{a}}$ to the simulated $\mathrm{PF}_{1\mathrm{a,Ref}}$ of the one-year reference simulation. These one-year simulations do not require any result manipulation or applying pre-simulations.

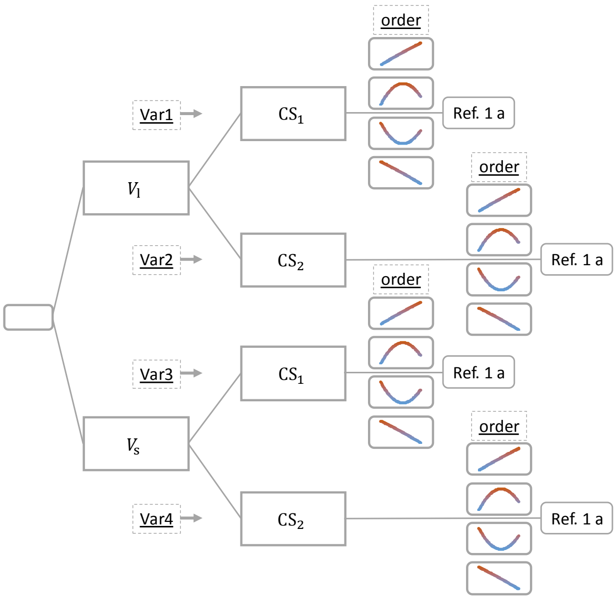

Figure 2: Design of simulative investigation with overview of evaluated variants.

The different typical day arrangements are based on the daily mean outdoor air temperatures $\bar{T}_{\mathrm{oda}}$. Besides the qualitative illustration in Figure 2 via curves, additionally Table 2 gives an overview about the chosen order of test days.

Table 2: Order of typical days according to daily mean outdoor air temperature

Naming:	*1)	*2)	*3)	*4)
Date [MM/DD] ($\bar{T}_{\mathrm{oda}}$)	Numbered order			
03/16 (7.0 °C)	2.	4.	2.	3.
03/26 (1.4 °C)	1.	1.	3.	4.
07/24 (18.3 °C)	4.	3.	1.	1.
09/22 (13.5 °C)	3.	2.	4.	2.

*1) monotonically increasing "cold-to-warm"

*2) parabolic "cold-warm-cold"

*3) parabolic "warm-cold-warm"

*4) monotonically decreasing "warm-to-cold"

Models

The thermal sink in the scope of this paper is a one family house with 9 heated rooms. The building is insulated according to the German Thermal Insulation Ordinance (1982/84), which leads to a nominal heat load of 13.5 kW. The rooms are equipped with conventional radiators with a nominal flow temperature of 55 °C and return temperature of 45 °C. The room set temperatures are set constant throughout all the simulations but with different values between 18 °C and 24 °C. In terms of the heat generation an on/off controlled air source compressor HP provides the two tanks with necessary thermal energy. Both tanks have heat losses through the insulation withdrawn by a fictive environment of 18 °C. Whilst the BS is discretized into 15 layers, the DHW tank uses a discretization of 5 layers. The layers are equally spread in direction of the vertical axis and are assumed to have a homogenous temperature each. The BS does not include a coil, which means all four ports are directly connected to the water volume. In contrast, the DHW tank is equipped with a coil on the heat pump's side. In order to take stratification into account, both models use heat transfer approaches considering buoyancy. Based on the conductance of water and buoyancy, the BS model calculates an effective heat conductivity according to Viskanta et al. (1997). The DHW tank model solely transfers heat between two layers when the upper layer's temperature is higher than the one of the layer below. The model neglects an induced mass flow rate but the heat flow has the same magnitude as the enthalpy flow that is associated with the buoyancy induced mass flow rate (Buildings Library (2016)). Both models neglect influences of the jet momentums.

Furthermore, the mass flow rates for the DHW taps are scheduled according to prEN 16147 (2015) Profile L assuming a tank outlet temperature of 60 °C that should be ensured. This leads to a daily tapped sum of 200 l and a withdrawn thermal energy of 11.7 kWh.

The simulative investigations performed in the scope of this work delivered quantified values for influences on the PF_{1a} regarding different tank volumes, control strategies and arrangement of typical days. Thermal capacities are taken into account in the detailed simulation models and are treated in analogy to real experiments. Moreover, the simulation setup allows the possibility for further design variations, e.g. regarding the heat distribution system or even the whole building.

Analysis and Results

Changeover of two typical days

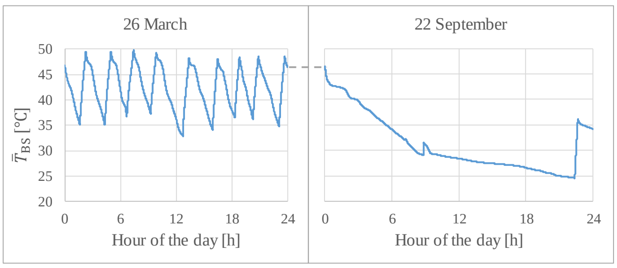

Figure 3: Example for changeover from a cold to a warm typical day by showing the behavior of the BS's mean temperature.

Figure 3 illustrates the behavior of the BS's mean temperature after the changeover from a colder to a warmer day. Due to the almost negligible heat demand of the building's heating circuit during 22th September, the storage uses the reserves provided by the prior colder day. On the one hand this is advantageous for the HP, since it needs less activations in the beginning of the next day. But on the other hand the thermal energy was expensively generated on the cold day, although the control for a warmer day does not require such high temperatures.

Furthermore, the SOC during the changeover between two test days comes along with a certain level of coincidence. This means it depends whether the storages are at the time just before midnight already charged or whether they will be charged at the beginning of the following and eventually warmer day. This issue of coincidence is impossible to avoid in the experimental procedure and is therefore also neglected within this simulative investigation.

Inner Energy

One phenomenon of interest is the difference of the tanks' inner energy. Therefore, (4) defines

$$\begin{aligned}\Delta U &= U_{\text{end}} - U_{\text{start}} \\ &= m_{\text{BS}} \cdot c \cdot (\bar{T}_{\text{end}} - \bar{T}_{\text{start}})_{\text{BS}} \\ &\quad + m_{\text{DHW}} \cdot c \cdot (\bar{T}_{\text{end}} - \bar{T}_{\text{start}})_{\text{DHW}}\end{aligned} \tag{4}$$

as the difference of the inner energy. Hereby, m denotes the TES's mass, $c = 4180\,\text{J/(kg K)}$ the specific heat capacity of liquid water and $\bar{T}_{\text{end/start}}$ the mean temperature of the specified tank at the end and the beginning of the test series, respectively. With this measure the energy is quantified which has either been provided by the HP and is still stored and remains unused at the end of the test period or was never generated by the HP and the building used from the initial reserves of the storages. This effect occurs due to the chosen boundaries of the control volume that in this work includes all actual hardware components. Since the TES's lead to a temporal energy shifting, ΔU has to be taken into account.

Figure 4 displays all 16 differences of the inner energy sorted by the particular order of typical days. Additionally, the mean values for each order are shown. For clarity reasons two values ΔU of "Var1" are not shown due to their values of $-16.64\,\text{kWh}$ and $16.82\,\text{kWh}$ belonging to the order "cold-to-warm" and "warm-to-cold", respectively.

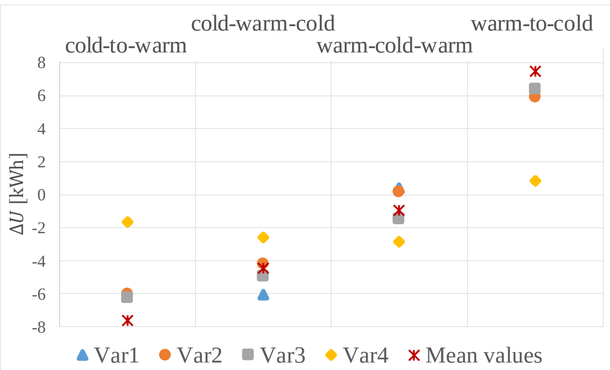

Figure 4: Difference of inner energy ΔU (sum of both tanks) between the end of the last and the beginning of the first test day.

Figure 4 shows that in general the parabolic order "warm-cold-warm" results in the least shifted energy. Although this is not consistent for the analyzed variant "Var4". Hence, as this is the variant with small tank volumes and the control strategy using narrow hystereses, all 4 inner energy differences (yellow markers) are comparatively small anyway in terms of absolute values.

Relative deviation of the long-time performance factor

As a conclusion, from that point of view the recommendation is to decide for the order "warm-cold-warm". In contrast, from the long-time efficiency's point of view, Figure 5 shows that the order "warm-to-cold" leads to the best results in terms of the relative deviation $\Delta\text{PF}_{\%}$ which (5) defines.

$$\Delta\text{PF}_{\%} = \frac{\text{PF}_{1\text{a,Ref}} - \text{PF}_{1\text{a}}}{\text{PF}_{1\text{a,Ref}}} \tag{5}$$

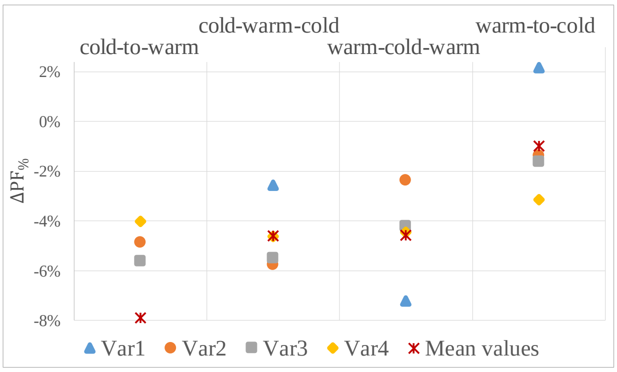

Figure 5: Relative deviation of the long-time performance factor $\Delta PF_{\%}$.

In Figure 5 also one value for $\Delta\text{PF}_{\%}$ is omitted, in this case it is the value $\Delta\text{PF}_{\%} = -17.13\ \%$ of "Var1" and the order "cold-to-warm".

The observations lead to the assumption that solely the application of typical days based on the k-medoids clustering affects the $\text{PF}_{1\text{a}}$ in a positive manner. In other words the $\text{PF}_{1\text{a}}$ has, due to the usage of the typical day method, generally a better value than the reference $\text{PF}_{1\text{a,Ref}}$. This is already indicated in Engel (2015) and might be due to the fact that the HP does not have to generate heat during the coldest days of a year. But in contrast these days are not omitted in the reference simulation of one year. Hence, in contrast to that, applying the order "warm-to-cold" results in a positive inner energy difference (see Figure 4), which means that the HP supplied thermal energy to the TES's that stayed unused in the end of the series of test days. As the target flow temperature rises with decreasing outdoor air temperature, this phenomenon occurs and leads to this unbalanced storage treatment. Nevertheless, since this effect is now quantified to influence the $\text{PF}_{1\text{a}}$ similar to the consequence of the pure application of the typical days methodology, in this case using the order from warm to cold, is beneficious in terms of determining the HP's long-time efficiency. However, this is merely valid for the in the scope of this paper evaluated HP and used input data and can therefore not be seen as a general recommendation.

Conclusions

In a first step, this paper introduces the experimental HiL methodology for evaluating a HP system's long-time efficiency including all auxiliary components like pumps, HP control and TES's. Within the next step this concept is transferred into and formulated as a purely simulative issue in the Modelica (2016) modeling language. With this cost-efficient approach investigative simulations were performed to identify a suitable order of the typical test days, which are gained by applying the statistical k-medoids clustering technique. Hereby, the analysis focusses on quantifying influences of TES's that are part of HP systems and that can store or provide thermal energy that is not recognized by the time and space dependent control volume. Despite investigating the order of typical days, additionally 4 variants in terms of different tank volumes and charging strategies are examined.

Analyzing the results shows that the parabolic order "warm-cold-warm" leads with a value of $\Delta\overline{U} = -0.94\,\mathrm{kWh}$ to the lowest mean difference of inner energy. In general, except all 4 results for the order "warm-to-cold", ΔU is negative which means that in the end of the series of typical days the TES's have a lower SOC than in the beginning. The results of "warm-to-cold" have a positive inner energy difference. In other words, the HP provided thermal energy that is stored and remains unused in the end. However, since the coldest days of the year are omitted in the evaluation procedure, due to the clustering method and application of typical days, the $\mathrm{PF_{1a}}$ has mainly a higher value than the reference $\mathrm{PF_{1a,Ref}}$. These two effects are from the same magnitude and compensate each other. This leads to the recommendation of using the typical day order from warm to cold. This order results in the lowest mean value for the relative deviation of the long-time performance factor of $\Delta\overline{\mathrm{PF}}_{\%} = -0.99\ \%$.

Nonetheless, this recommendation has to be handled with care considering that the pure application of typical days affects $\Delta\mathrm{PF}_{\%}$ less when evaluating non air source HPs and therefore the order "warm-cold-warm" might be the better choice, as in this case the least energy is shifted in the TES's.

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