Impact of the Weather Forecast Quality on a MPC-driven Heat Pump Heating System

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Abstract. Electrically driven heat pumps offer in combination with thermal energy storage systems the potential to response to fluctuating renewable energy sources, e.g. photovoltaics. To fully exploit this flexibility and financial potential, smart predictive control strategies such as Model Predictive Control (MPC) are needed. For such a controller, weather forecast data are mandatory to perform the optimization. Several sources of weather forecast data are available with variable forecasting quality. In this study, the impact of the weather forecast quality on a realistic heat pump heating system is investigated in experiments and simulations. Therefore, the operation of a MPC strategy is carried out for a perfect forecast compared to two imperfect forecast scenarios over a consecutive period of 4 days on a Hardware-in-the-Loop test bench with a geothermal heat pump and a thermal energy storage system. In order to evaluate the benefits in real operation compared to rule-based controllers, a heat-controlled (HC) and a PV self-consumption optimized controller (PVC) are also operated on the test bench. In addition and as a validation process, all scenarios are simulated and compared to the measurement results. Compared to a standard rule-based HC strategy the PV self-consumption can be increased by using a PVC and MPC strategy by 6.2 % and 38.9 %, respectively. The accurately the weather forecasting quality is in general the higher the performance of the HP heating system. Thus, the PV self-consumption is reduced for high-quality and low-quality weather forecasts by 4.6 % and 11.1 %, respectively, compared to a perfect MPC. Even a MPC with low-quality weather forecast data can achieve higher system performance as a simple rule-based HC strategy. For achieving higher system performance by using a MPC instead of a rule-based control strategy like PVC the, forecasting quality has to be as accurate as possible.

Keywords. model predictive control, weather forecast, self-consumption, experimental study
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1. Introduction

The demand-side flexibility of residential buildings is becoming more and more relevant to operate and stabilise the power grid properly. The heating (and cooling) demand of such a building can be regarded as flexible in terms of shifting and storing electrical energy in both battery and thermal energy storage systems. Electrically driven heat pumps offer in combination with thermal energy storage systems the potential to response to fluctuating renewable energy sources, e.g. photovoltaics. To fully exploit this flexibility and financial potential, smart predictive control strategies, such as Model Predictive Control (MPC), are mandatory.

A MPC strategy rely basically on solving an optimization problem periodically, by considering weather forecast data, e.g. the solar irradiance and the ambient temperature, in combination with a system model to optimize the subsequent control sequence. Its accuracy is occasionally based on the model complexity and, if applicable, the weather forecast quality. MPC strategies have shown a major interest in recent research [1, 2], as they provide advantages in terms of operational cost savings, system performance, indoor comfort and energy flexibility. Operational cost savings for a MPC strategy of up to 11 % and 16 % for constant and flexible electricity prices, respectively, were determined by Fischer et al. [3] in comparison to a standard rule-based controller. For a similar comparison, Bechtel et al. [4] exhibited cost savings of up to 24 % for a single-family house and flexible electricity prices. Pichler et al. [5] carried out an annual simulation study on an MPC-driven heat pump heating system. They determined an increase of the photovoltaic self-consumption of up to 30 % in a single-family household.

The literature on MPC strategies, which investigates the weather forecast in general, utilizes keywords such as "perfect", "idealized" or "optimal" MPC to refer to operating conditions exhibit an agreement between the weather forecast and the measured ("real") weather conditions. Such kind of conditions can only be met in simulations, where the forecast data is well known. Thus, a perfect MPC can be considered as a benchmark for other control strategies, e.g. rule-based strategies or MPC strategies with lower forecast quality, to determine the upper limits of the benefits under optimal forecasting conditions. In general, it is not applicable to field test operation. Such a benchmark study was carried out by Mendoza-Serrano and Chmielewski [6]. The authors compared a MPC-driven heating, ventilation, and air conditioning (HVAC) system provided with perfect and "zero" forecast information. Compared to their reference situation, they exhibited cost reductions for the perfect and the "zero" forecasts of up to 31 % and 27 %, respectively. The authors emphasizes the strong influence of the forecast information on the system performance. Allen et al. [7] determined cost savings of up to 13.1 % with a perfect forecast and 11.1 % with a non-ideal forecast. A reduction of the overall system energy consumption of the heating system in a single family house of up to 15 % was simulated by Rolando et al. [8] by means of TRNSYS simulations. The authors implemented a predictive rule-based controller, to which the perfect solar irradiance forecast was applied to over the whole heating season. Lazos et al. [9] reviewed the potential of energy and cost savings in commercial buildings by implementing an optimized energy management algorithm. The authors highlighted the strong influence of high quality weather forecast data on the accuracy of predicting the evolution of the building load or energy generation. However, they stated possible savings from 15 % up to 30 %, by using rather weather predictive than non-weather sensitive control strategies. Löhr and Mönnigmann [10] compared a "yesterday-based" prediction, which utilizes the previous day weather data as prediction for the subsequent day, to a controller with a perfect forecast. Both controllers performed well. They concluded, that the system performance decreases only slightly by using historical / yesterday weather data as the tomorrow's forecast. Péan et al. [11] carried out an experimental study to evaluate the weather forecast quality on the performance of a MPC controlled air-to-water heat pump in cooling mode in a residential building. Within a three day testing profile, they compared a perfect weather forecast to a (imperfect) forecast from a commercial service. The setup with imperfect forecast resulted in an increase of the total electrical energy demand and the operational costs of 5.8 % and 11.2 %, respectively.

Our literature review reveals, that commonly a perfect MPC strategy is compared to both a rule-based algorithm and a MPC strategy with no weather forecast data. Nowadays, more and more devices / controllers are connected with the internet or can be equipped with receiving aerials and thus, have access to historical or forecast weather data. Especially the quality of the weather forecast services, which rely basically on the forecast horizon and the used forecasting model, and their influence on a heat pump heating system have to be investigated. Furthermore, most of the reviewed articles are based on simulative investigations and did not consider the operation in a realistic heat pump heating system. In a previous simulative study, Betzold et al. [12] compared different control strategies of a geothermal heat pump heating system. The authors emphasized cost savings of 3 % to 10 % by utilizing a MPC controller instead of a rule-based control strategy. An experimental verification of the cost savings potential is of particular importance in a realistic operation environment due to the low differences achieved in the simulations.

In this study, the impact of the weather forecast quality on a realistic heat pump heating system is investigated. Therefore, the operation of a MPC strategy is carried out for a perfect forecast compared to two imperfect forecast scenarios over a consecutive period of 4 days on a Hardware-in-the-Loop test bench with a geothermal heat pump and a thermal energy storage system. In order to evaluate the benefits in real operation compared to rule-based controllers, a heat-controlled (HC) and a PV self-consumption optimized controller (PVC) are also operated on the test bench. In addition, as kind of a benchmark or validation process, a preliminary simulative study of the above mentioned MPC, HC and PVC strategies is carried out and is compared with the measurement results.

2. Research Methods

In order to implement MPC strategies, knowledge about the expected thermal behaviour of the building (heating and domestic hot water demand), the moment and the amount of renewably generated energy gain as well as the operating behaviour of the technical building equipment is necessary. Additionally, for weather-based MPC strategies weather forecasting services or historical weather data have to be implemented.

2.1 Weather data

The basic requirement for a weather-dependent MPC strategy is weather forecast data in good quality, to achieve the best possible benefits in terms of cost savings or increase of system performance. For this study, three different sources of weather data are utilized, to create a profile of five consecutive days: measured / real weather data and two types of forecasting services.

All sources provide the solar irradiance G and the ambient temperature T_a in 15 minutes intervals for the location of the suburban district "Herzo Base" of the city of Herzogenaurach (Germany) for the 7th until the 11th of March, 2021, as can be seen in Figure 1. The measured weather data (abbr. and index MEAS), which were recorded with appropriate sensors on the roof a single-family house at the mentioned location, is used as the perfect weather forecast in the experiments and simulations. Furthermore, an internet-based Weather Forecast Service (WFS) and an installed Weather Forecast Centre (WFC) provide forecast data at the given location and period of time. The latter represents a long wave receiver, which receives its data from a commercial service.

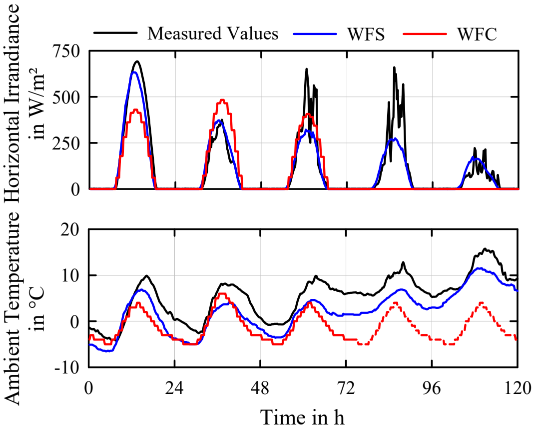

Fig. 1 – Horizontal irradiance and ambient temperature profiles of the three different weather data sources for five consecutive days from for the 7th until the 11th of March, 2021.

It is worth noted, that the WFC does not provide any valid weather data starting off 1 am of the 4th day of the selected period of time. The received data shows constant values of $G = 0$ W m^{-2} and no data for T_a, which indicate communication faults. An inspection of the received data of 2021 shows that communication faults occur regularly and frequently. At 25.6 % of the time no or faulty data was received. In addition, the transmission is normally interrupted in longer consecutive time intervals. Thus, the selected interval of time for this evaluation represents the typical data availability for this weather forecasting service. For any further evaluation, the values of the irradiance are set as received, whereas the ambient temperature is set to values recorded 24 h earlier. Thus, the 4th and 5th day of the WFC profile is almost equal to the 3rd day, as can be seen as the dotted red line in Figure 1.

Qualitatively the three profiles resemble each other in temporal progression, but exhibit some major differences in their absolute or integral values. The horizontal irradiation for the whole five days aggregates to 13.3 kWh m^{-2}, 11.7 kWh m^{-2} and 9.3 kWh m^{-2} for the measured, the WFS and the WFC profile, respectively. The maximum deviations can be identified between the measured and the WFC profile on the 1st day, with a difference of 1.7 kWh m^{-2}. The mean ambient temperature can be calculated to 5.4 °C, 2.2 °C and – 1.2 °C for the measured, the WFS and the WFC profile, respectively. Without regarding the non-valid ambient temperatures of the WFC profile, a maximum difference of up to 10 K can be reported at the end of the 3rd day (72 h) between the measured values and WFC profile. Whereas the temporal progression of the temperature only influences the heating demand of the simulated building, the solar irradiance influences both the building simulation (internal solar gains) and the PV generation.

The WFC profile features the highest deviation to the measured (perfect) weather data in all aspects. Thus, this weather data set is referred to as “low-quality” in terms of the forecasting quality. In contrast, the WFS profile performs significantly better and is referred to as “high-quality”.

2.2 Building simulation

By means of TRNSYS building simulations the profiles of the space heating load of a single family house (SFH) is simulated on the basis of the three given weather data sets. As a basic system and building concept the SFH and heating system, described in the IEA SHC TASK32 by Heimrath and Haller [13], are used. They defined a SFH with three types of building standards in terms of their annual area-related heating demand, namely SFH30, SFH60 and SFH100. E.g. the building SFH60 exhibits an annual heating demand of approximately 60 kWh m^{-2}. Each building type have a heated gross area of 140 m^2. Some minor changes were made on the pre-defined standard values of the simulation, to adapt the simulated heating system to our test bench, e.g. the volume of the thermal energy storage. For this investigation the building standard SFH60 and no domestic hot water demand are considered. This building standard is quite similar to the buildings at the suburban district “Herzo Base”.

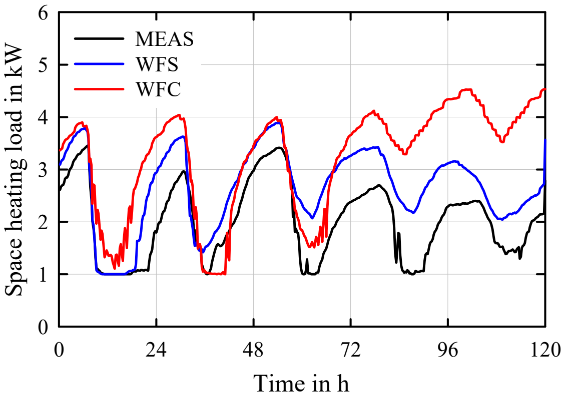

Fig. 2 – Space heating load profiles for the building standard SFH60 and the three considered weather data sets. Due to limitations in terms of its controllability of the used test bench, the space heating load is increased by 1 kW at each time step.

The profiles of the space heating load for the building standard SFH60 and the three considered weather data sets can be seen in Figure 2. As the measured weather data shows the highest irradiation and mean ambient temperature, the heating loads and the heating demand is accordingly low. Due to the partially non-valid weather data of the WFC profile the space heating load rises gradually after 72 h and lead to a significantly increased heating demand.

Tab. 1 – Total heating demand of the defined building standards by Heimrath and Haller [13] and the three considered weather data sets. Only SFH60 is considered in any further investigations.

Building standard	MEAS in kWh	WFS in kWh	WFC in kWh
SFH30	152.2	202.4	252.1
SFH60	**240.6**	**318.1**	**387.5**
SFH100	350.5	454.6	544.9

In total, an amount for the space heating demand of 240.6 kWh, 318.1 kWh and 387.5 kWh can be calculated for the measured, WFS and WFC weather profile, respectively (see Table 1). The test bench used possesses a limitation in terms of its controllability of the requested heating load. Values of the heating load lower than 1 kW can result in control deviations between the set and actual value, which normally results in higher heating demands as expected. To overcome this limitation, the simulated space heating load profiles are raised by 1 kW at each time step, as can be seen in Figure 2.

2.3 Photovoltaic generation profile

For each weather data set the photovoltaic (PV) generation profile is simulated in advance to the experimental study. The PV load is calculated in accordance with an isotropic sky model by Shukla et al. [14] on the basis of the horizontal irradiance, the PV area (40 m^2), the inclination angle (60°, c.f. the slope of the roof of the reference building) and the efficiency of the PV modules (17.89 %) and inverter (95 %).

The resulting PV generation profiles can be seen in Figure 3 with maximum values of up to 5.2 kW. The total amount of PV generation within the period of five days is 93.1 kWh, 78.5 kWh and 66.4 kWh for the measured, the WFS and the WFC weather data profile, respectively.

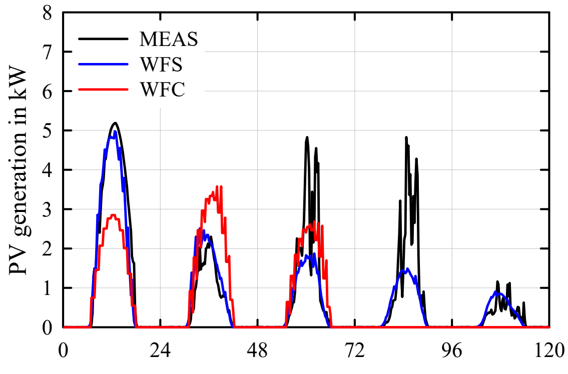

Fig. 3 – Photovoltaic generation profiles for the three considered weather data sets.

2.4 Residential load profile

Both for the preliminary simulations as well as the experimental study a residential load profile is mandatory. In combination with the PV generation a surplus in the electrical energy of the building can occur. This enables the controller to operate the heat pump in a flexible and dynamic way. Combined with the electrical load of the heat pump, the residential load is responsible for the total electrical energy consumption of the building. The residential load profile is based on measured data of one of the buildings, on which the measured weather profile was performed. The time span is identical to that of the weather profiles.

The residential load profile and the PV generation profile for the measured weather data set can be seen in Figure 4. Thus it appears that residential and PV peak loads rarely occur simultaneously. Normally PV peak loads result from high solar irradiance at noon, whereas the residential peak loads rather appear in the evening hours. The total residential energy consumption is 48.1 kWh with a baseload of approximately 0.2 kW.

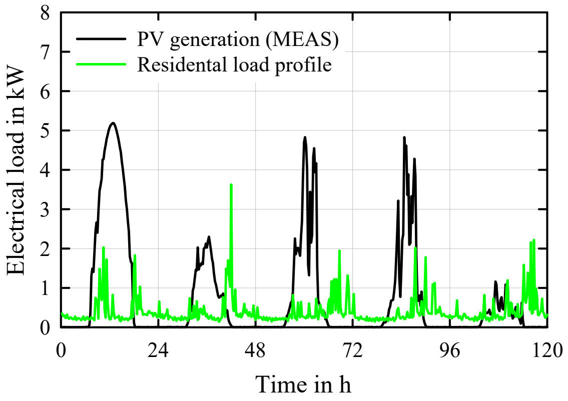

Fig. 4 – Residential load and PV generation profile.

2.5 Hardware-in-the-Loop test bench

The comparative experimental study is carried out on a Hardware-in-the-Loop (HiL) test bench, which combines several heat generation units and a variety of thermal energy storage systems (TES). The heating demand, the domestic hot water demand and the source temperature of the heat pump are emulated. The HiL concept ensures a flexible, dynamic and realistic investigation of one single component or the whole heating system.

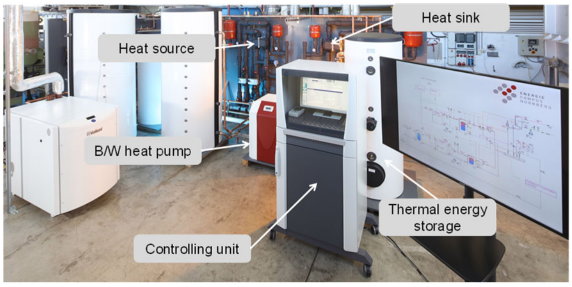

Fig. 5 – Hardware-in-the-Loop test bench for innovative heating systems at TH Nürnberg.

In this study, a brine/water heat pump (HP) is utilized in combination with a 500 litres TES. The HP exhibits a standard heating power of 10.9 kW and an electrical power of 2.2 kW at its operating point B0/W35. A Coefficient Of Performance (COP) of 4.9 is obtained. The test bench and its main components used for this contribution can be seen in Figure 5. A hydraulic scheme and the installed sensors are presented in Figure 6.

Throughout the experimental study, standard manufacturers' settings for the HP internal controller are set. However, operationally relevant settings were changed, e.g. the monoenergetic or the return line temperature set point related operational mode. To ensure, that the external control strategy (MPC, PVC or HC) can switch on/off the HP properly, without being omitted by the internal HP controller, the return line temperature set point is set to 55 °C. The evaporator of the HP is provided with almost constant temperatures $T_{\text{evap,FL}}$ of 10 °C.

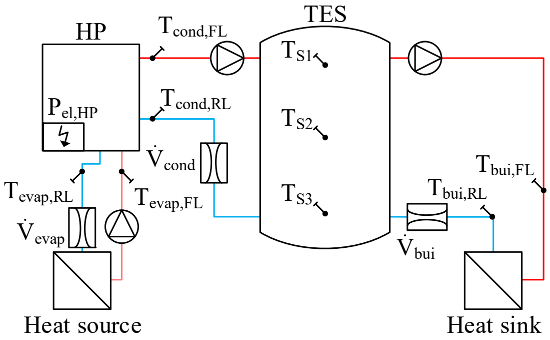

Fig. 6 – Hydraulic and sensor schema of the Hardware-in-the-Loop test bench at TH Nürnberg.

Appropriate sensors are installed in the HiL test bench for a detailed evaluation of the thermal behaviour of the HP heating system, as can be seen in Figure 6. The outgoing heating demand of as well as the delivered heating load to the TES can be assessed separately. The electrical power of the HP is measured by an energy meter. In addition, three temperature probes are installed equally spaced over the height inside the TES, to estimate the State Of Charge (SOC) or the storage stratification.

2.6 Simplified system simulation model

For the described control strategies (MPC, PVC and HC) a simulation model of the HP heating system is mandatory, to evaluate the SOC of the TES. The SOC is a main feature of each control strategy, to regulate the HP operation. As described by Hummel et al. [15] and Betzold and Dentel [16], a simplified system model is sufficiently accurate at frequently update intervals of the control strategy.

In accordance with Betzold et al. [12], the TES is assumed to be fully mixed, as it is represented as one single temperature node T_S in the simplified system model. As the TES is stated as the main storage component in the heating system its energy balance

$$C_S \frac{\mathrm{d}T_S(t)}{\mathrm{d}t} = \dot{Q}_{\text{HP}}(t) - \dot{Q}_{\text{Load}}(t) - \dot{Q}_{\text{S,loss}}(t) \qquad (1)$$

can be calculated as a function of the heat pump heating power $\dot{Q}_{\text{HP}}$, the space heating load $\dot{Q}_{\text{Load}}$ and the storage ambient heat losses $\dot{Q}_{\text{S,loss}}$.

The storage capacity C_S is equal to the product of the storage volume $V_S = 500$ litres, the fluid density $\rho_W = 1000\ \text{kg m}^{-3}$ and the fluid specific heat capacity $c_{p,W} = 4.18\ \text{kJ kg}^{-1}\ \text{K}^{-1}$ (both for water). The heating power $\dot{Q}_{\text{HP}}$ is assumed to be constant and is set to a typical mean operating point, which occurs during the simulations and experiments (B10/W40). Based on heat pump efficiency measurements on the test bench, the heating power and the electrical power is set to constant values of $\dot{Q}_{\text{HP}} = 12.94$ kW and $P_{\text{el,HP}} = 2.45$ kW, respectively, in operation of the heat pump. Likewise, the ambient heat losses are assumed to be constant with $\dot{Q}_{\text{S,loss}} = 0.043$ kW. The building thermal load $\dot{Q}_{\text{Load}}$ can be calculated from an energy balance between the TES and the heat sink. However, the space heating load profiles are predetermined by the building simulation (see Figure 2).

2.7 Model Predictive Control

In this research, a mixed-integer linear programming (MILP) optimization algorithm is used, as described by Betzold et al. [12], which is based on the simplified system simulation model. The MPC is realized in MATLAB [17]. The operating limits are defined by a minimal and maximal storage temperature of 25 °C and 45 °C, respectively, as well as by the complete cover of the thermal and electrical load. The cost function is based on operating costs for the residential load, the heat pump electrical power and the PV generation separated in grid feed-in, grid consumption or PV self-consumption. The assumed prices for each type of electricity are listed in Table 2. The price for PV self-consumption includes taxes and insurance.

Tab. 2 – Electricity prices used for the MPC cost function.

Type of electricity	Price in €/kWh
Grid consumption	0.34
PV self-consumption	0.0883
PV / Grid feed-in	0.11

The optimization horizon is set to 24 h with an optimization time step and optimization interval of 15 minutes both. Thus, every 15 minutes the MPC is restarted with new initial boundary conditions to generate the subsequent control sequence. As the optimization horizon is set to 24 h and the weather profiles provide a five day period of data, the experiments and simulations can only last four consecutive days (96 h).

2.8 Evaluation metrics

A robust evaluation of the experiments or simulations in terms of operational costs or cost savings is only possible, if the total runtime of the heat pump is similar in each scenario. Differences in the operational costs then exclusively occur due to the point in time, when the heat pump is switched on beneficially, thus at high PV generation and at most no grid consumption. But in the experimental study the overall runtimes exhibit differences in each scenario. Mainly caused by a non-documented variable compressor after-run time, a difference of 0.2 h is accumulated over the 4 day period between two scenarios, even if the amount of start-up events are equally. This amount of time corresponds to an increase of electrical energy of about 0.5 kWh and causes an increase in operational cost of up to 0.16 € (c.f. Table 2). In contrast, both the absolute operational costs and the operational cost differences between the examined scenarios are such low, that the influence of the weather forecast quality cannot be evaluated in terms of operational costs. Thus, we define other system parameters to assess the experiments and simulations properly.

PV self-consumption: The fraction of PV generation, which is consumed directly within the building (residential or heat pump electricity) is referred to as the PV self-consumption.

Self-sufficiency: The fraction of the total building energy demand (residential plus heat pump electricity), which can be covered by the PV generation is referred to as the self-sufficiency of the building.

Mean State Of Charge (SOC): The mean SOC value of the thermal energy storage is calculated over the measurement or simulation period of 96 h. This value can be referred to as its mean thermal workload within the operating limits of 25 °C (0 %) and 45 °C (100 %) of the storage temperature.

3. Preliminary simulation study

As a validation process, a preliminary simulative study is carried out in MATLAB and is compared with the measurement results. This investigation focuses primarily on the influence of different types of control strategies on a HP heating system. The main objective is the validation of the functionality of the HiL test bench as well as the confirmation of the results presented by Betzold et al. [12]. Beside the MPC, a PV self-consumption optimized Control (PVC) and a Heat Controlled (HC) strategy is implemented. Further details of this rule-based algorithms are presented by Betzold et al. [12]. On the basis of the measured weather data set and for each of the control strategies (MPC, PVC and HC), the HP heating system is examined experimentally on the test bench and via simulations in MATLAB.

In general, the metrics of the simulations agree well with the experimental measurements in a qualitative perspective, as can be seen in Figure 7. The measured PV self-consumption exhibits a high accordance with the simulation results. The differences between the measured and the simulated values for the MPC and PVC control strategy amount to 0.1 and 0.2 percentage points, respectively. The difference for the HC strategy is slightly higher and can be calculated to 1.7 percentage points. A similar high accuracy can be evaluated for the mean SOC value. Differences up to 2.3 (MPC) and 0.4 (HC) percentage points can be identified. The measured values of the PVC strategy do not exhibit any deviation. The measured values of the self-sufficiency of the HP heating system possess an increase by a mean value of 4 percentage points compared to the simulation.

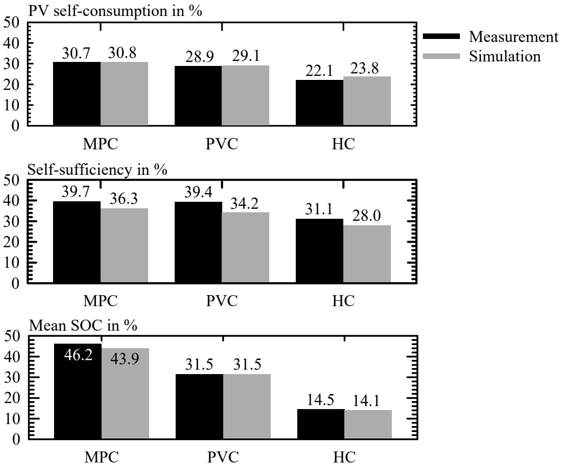

Fig. 7 – Comparison of the considered system evaluation metrics between measured and simulated data for each control strategy (MPC, PVC and HC) on the basis of the measured weather data set.

The influence of the control strategy on the system performance can be investigated as well by the considered evaluation metrics. Obviously the MPC strategy offers the highest system metrics / performance in all considered aspects. The PV self-consumption of the test bench experimental run possesses for the MPC, the PVC and the HC strategy values of 30.7 %, 28.9 % and 22.1 %, respectively. Thus, a reduction of 5.9 % (PVC) and 28.0 % (HC) compared with the MPC strategy is determined. Similarly, a reduction of the measured self-sufficiency of 0.7 % (PVC) and 21.7 % (HC) to the MPC strategy is identified. The storage capacity of the TES is used more beneficial, if a (perfect) MPC is implemented instead of a rule-based algorithm. The mean SOC value increases significantly from 14.5 % (HC) to 46.2 % (MPC).

4. Comparison of the weather forecast quality

Three experimental measurements on the HiL test bench are carried out to investigate the influence of the weather forecast quality on the MPC strategy and thus, on the HP heating system performance. The deployed MPC algorithm, which is utilized in each experiment, uses the space heating load profiles, the residential load profiles and the PV generation profiles resulting from either the perfect weather data set (MEAS), the high-quality WFS profile and the low-quality WFC profile (cf. section 2.1). Again, the measurements last a period of four days.

Highest values in all considered aspects can be determined for the perfect MPC. Thus, a clear progression is obviously visible for all evaluation metrics, as can be seen in Figure 8. The PV self-consumption of the perfect MPC achieves maximum values of 30.7 %, whereas the values of the WFS and WFC data set slightly decrease. With the high-quality WFS profiles and the low-quality WFC profiles the PV self-consumption amounts to 29.3 % and 27.3 %, respectively. This reduction is equal to a decrease of 4.6 % (WFS) and 11.1 % (WFC) compared to the perfect MPC strategy. Similar reductions can be determined for the self-sufficiency, at which the perfect MPC obtained values up to 39.7 %. Compared to the perfect MPC the self-sufficiency is reduced for the WFS profiles and WFC profiles by 2.5 % and 8.8 %, respectively.

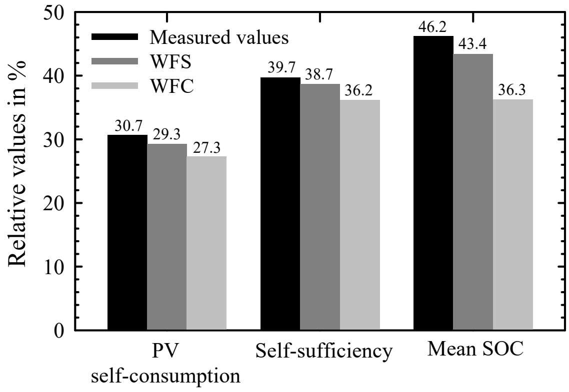

Fig. 8 – Considered system evaluation metrics for each weather data set (MEAS, WFS and WFC) in comparison.

The thermal capacity of the TES is used in the most efficient and beneficial way for the perfect MPC and achieves mean SOC values of 46.2 %. This is equal to a useful energy of about 5.4 kWh. A significant decrease of 9.9 percentage points (-21.4 %) can be calculated for the mean SOC between a perfect MPC and a MPC with low-quality weather forecast. It is worth noted, that the TES, driven by low-quality WFC profiles, fall below the minimum storage temperature of 25 °C, whereby the space heating demand cannot be covered. Negative SOC values down to -1.7 % can be determined.

5. Conclusions

The functionality of the HiL test bench is validated by means of system simulations compared to measurements with equal boundary conditions. The considered metrics of the simulations agree well with the experimental measurements. In regard to the PV self-consumption and the mean SOC a high accuracy with low deviations between simulations and measurement can be achieved. Significantly higher differences are determined for the self-sufficiency. Due to significantly higher HP runtimes in the simulations, the electrical energy demand is increased, which increases the total building energy demand as well. As a result, the self-sufficiency of the building is negatively influenced. The longer HP runtimes in the simulations can be caused by the simplifications in the HP model of the simplified system model.

The influence of the control strategy on the system performance is investigated for a MPC, PVC and HC strategy on the test bench. In contrast to a rule-based control strategy (e.g. PVC and HC), a MPC offers the highest system performance in all considered aspects. The HC strategy operated the HP heating system in a non-optimized manner. The main objective of this strategy is to cover the space heating demand at any time. Due to the fact that the highest space heating demands occur at night-time, the heat pump is predominantly operated at this time. The storage temperature as well as the SOC is kept as low as possible. However, the PV generation is contracyclical to the space heating demand. Furthermore, the HC has no built-in option to operate the HP in more efficient periods of time. Thus, the grid consumption is increased and PV self-consumption or building self-sufficiency is accordingly lower. Compared to a MPC, the PVC strategy performs quite well. It offers the possibility to operate the HP in a PV optimized manner. The considered evaluation metrics are marginally lower, compared to the MPC. The significant increase in the mean SOC value of 7.1 percentage points compared to the HC strategy reveals a charging of the TES, if high PV generation is available. This strategy enables the ability to react to the fluctuating renewable energy source. We conclude, that a MPC significantly offers a more beneficial operating strategy compared to rule-based controllers. The space heating load and PV generation profiles, resulting from either the perfect (measured) weather data set (MEAS), the high-quality WFS profile and the low-quality WFC profile, are utilized by means of three experimental measurements on the HiL test bench, to investigate the influence of the weather forecast quality on the system performance. In general, the perfect MPC offers the highest system performance. A perfect weather forecast, which is in this study equivalent to measured data and thus corresponds to the real ambient conditions, can only be met in simulations. The considered high-quality forecast (WFS) is rather applicable to field test installations. However, a clear trend can obviously be determined: the accurately the weather forecasting quality is in general the higher the performance of the HP heating system. E.g. the low-quality weather data set reduces the PV self-consumption and the self-sufficiency of up to 11.1 % and 8.8 %, respectively. Primarily the non-valid weather data given at the 4th and 5th day of the profile lower the ability of the MPC to generate the subsequent control sequence in the most beneficial way. The HP is operated in more unfavourable periods of time in terms of electricity prices and PV generation.

Tab. 3 – Combination of the results from the comparison of different control strategies (PVC and HC) from Figure 7 and different qualities of weather forecast data profiles (MEAS, WFS and WFC) from Figure 8.

Metrics in %	MEAS	WFS	WFC	PVC	HC
PV self-consumption	30.7	29.3	27.3	28.9	22.1
Self-sufficiency	39.7	38.7	36.2	39.4	31.1
Mean SOC	46.2	43.4	36.3	31.5	14.5

Table 3 combines the measurement results of the preliminary study (PVC and HC strategy) and those of the weather forecast quality comparison (MPC with MEAS, WFS and WFC profiles). The results of the MPC with high-quality WFS profiles are comparable to those of the rule-based PVC strategy. Merely the usage of the TES capacity is more favourable at the MPC. Even a MPC with low-quality weather forecast data (WFC) can achieve higher system performance as a simple rule-based HC strategy. For achieving higher system performance by using a MPC instead of a rule-based control strategy like PVC the forecasting quality has to be as accurate as possible.

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8. Data access statement

The datasets generated during and/or analysed during the current study are not publicly available because of privacy of the residents but will be available on request with privacy agreement.