Comparison and implementation of MPC and simple predictive control into a heat pump system

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Abstract. Heat pumps in combination with thermal energy storage systems offer the potential to response to fluctuating renewable energy sources, e.g. photovoltaics. To fully exploit this flexibility and financial potential, predictive control strategies are needed. Since an additional effort due to detailed knowledge and programming skills is required to create the model predictive control (MPC) strategies, a fast and easy implementation is prevented. Therefore, a second model-based approach is developed with a predictive but rule-based control. This simplified approach uses predictive models as well but energy balancing to determine the heat pump operation and the state of charge of thermal storage units throughout the day. In this paper, two predictive approaches were compared with two rule-based controls and evaluated for their potential for PV self-consumption and cost savings in annual simulations. In addition, one rule-based PV optimized control (PVC) and the predictive approaches, MPC and the simple predictive control (SPC), are implemented in the real operation in a plus energy building. In simulation, the best result is achieved by the MPC with a cost saving of 8.3 % due to a high PV energy consumption but mainly to the best efficiency with a SPF of 4.5. Despite the predictive approach of SPC, SPC and PVC achieve very similar results with cost savings of 2.5 % and 0.8 %. Since the costs of PV include taxes, these moderate cost savings are achieved. Excluding these taxes, there are significantly higher cost savings of up to 34 % for MPC. In real operation, differences between simulation results and measured data become apparent. This gap between the set point output of the simulation and the set point input of the real components poses a challenge to the implementation of efficient and cost-effective control like the MPC.

Keywords. MPC, simple predictive control, PV self-consumption, operating costs
DOI: https://doi.org/10.34641/clima.2022.154

1. Introduction

Heat pumps in combination with thermal energy storage systems offer the potential to response to fluctuating renewable energy sources, e.g. photovoltaics. To fully exploit this flexibility and financial potential, predictive control strategies are needed. Model-based control approaches range from simple calculations to very complex and detailed models with long computation times. The modelling effort can therefore be very high, so that the implementation in a real plant is inhibited. Simplified predictive approaches can reduce these inhibitions. However, the question is which predictive approaches lead to good operation and results.

In previous research work, several studies examined MPC strategies to reach operating costs savings in a range of 10 % to 30 % and an increase of PV direct consumption of up to 30 %. Fischer et al. [1] shows cost savings of 6 % to 11 % for constant electricity prices and up to 16 % for variable electricity prices in comparison to a default rule-based controller. Likewise, the application of MPC can favorably influence Photovoltaics (PV) self-consumption. Pichler, M. et al. [2] shows in an annual simulation that the targeted MPC control of a heat pump can increase the PV direct consumption in a single-family house by 30 %. In addition, Salpakari and Lund [3] find that when MPC is applied to heat pumps, PV systems are beneficial because the amount of PV electricity fed into the grid is reduced by up to 88 %. Self-consumption of PV electricity can be profitable when electricity prices are higher than the feed-in tariff. The study also targets an energy cost reduction of 25 % in the case of flexible market electricity prices in Finland compared to a rule-based controller. A publication by Bechtel et al [4] shows cost savings of a maximum of 24 % for a single-family house in Luxembourg when variable electricity prices based on the electricity market are applied. In some cases, field tests of model predictive control strategies are realized in residential and office buildings. De Coninck et al. [5] implemented a MPC control with non-linear models in an office building and showed that the MPC provides a similar or better thermal comfort than the reference control while reducing the energy costs by more than 30 %.

In contrast to the complex modelling and programming of an MPC, advanced system control strategies with a predictive approach can reduce the programming effort and still achieve good results. Few works on simple predictive controls in the building sector are provided in the literature. Rolando and Madani [6] present a control algorithm developed in a Swedish research project that shows annual energy savings of 10 % by predicting solar energy gains in single-family homes.

The mentioned research works on advanced system control strategies with a predictive approach show a similar potential of cost saving to MPC. Therefore, in the following work, an MPC and a simple predictive control approach will be compared in simulation and in a real energy system of terraced houses in Germany. The real heat pump system, which supplies eight terraced houses, is to be operated in such a way that it optimally uses the PV power of the shared PV system. The heat pump system consists of two central modulating heat pumps (MWPs) and eight decentral on/off heat pumps (boosters) for providing domestic hot water (DHW). In addition, the energy system of the terraced houses consists of a shared PV and battery system.

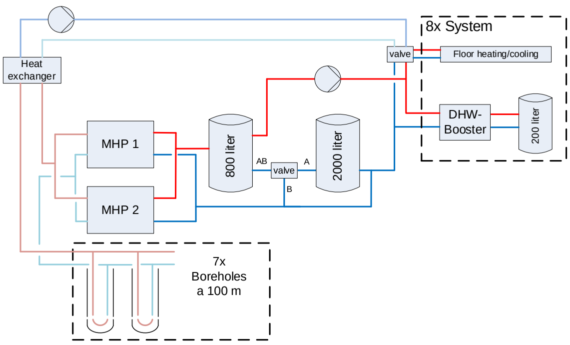

Fig. 1 – Heat pump system of eight terraced houses.

Besides two rule-based controls, two Model Predictive Control (MPC) strategies are implemented, which are based on different system and forecast models as well as different optimization algorithms. Since an additional effort due to detailed knowledge and programming skills is required to create the MPC strategies, a fast and easy implementation is prevented. Therefore, a second model-based approach is developed with a predictive but rule-based control. This simplified approach uses predictive models as well but energy balancing to determine the heat pump operation and the state of charge of thermal storage units throughout the day.

2. Research Methods

To determine and compare the potential and differences of the two predictive control approaches, they are first compared in an annual simulation. In a second step, the real operation of the MPC and SPC will be implemented in the energy system of the terraced houses and tested over several weeks.

In the annual simulation, the results of the control approaches (set points) are entered into the energy system model. The forecast horizon is 48 h in a 15 minute time step, whereby only the first 24 hours are transferred to the system model as setpoints. This results in 366 simulation runs in year 2020. In addition, the two control approaches were compared with two rule-based control approaches to evaluate the predictive approaches. The rule-based approaches include a heat-guided (HC) and a PV-optimized (PVC) control. The process of the annual simulation is shown in Fig. 2.

For offering an overview of the potential of the different control strategies monitoring data from the terraced houses for a period of 12 months from January 2020 until December 2020 is chosen. The measured PV power as well as measured thermal and electrical load are used as ideal prediction for the MPC and SPC. For the simulation of the energy system, controlled by the outputs of HC, PVC, SPC and MPC, the measured data serve as actual PV production and loads. The operation and comparison are implemented in MATLAB [7]. Boundary and start conditions are the same in the four cases.

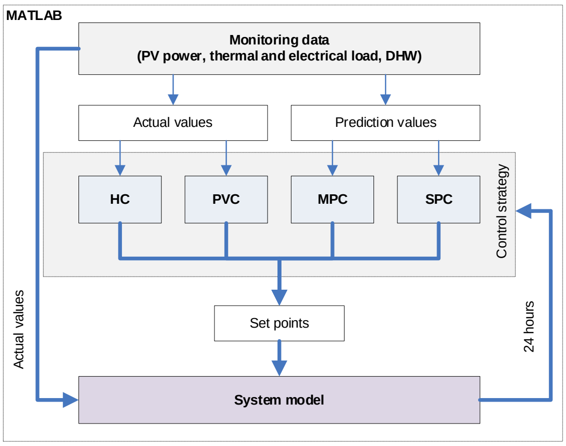

Fig. 2 – Process of annual simulation

First, the system model is described, which serves as the basis for all modelling of the controls. In this model, the energy system is represented, which is controlled by the outputs of the different controls.

2.1 System model

In general, the system models base on energy flows coupled in an energy node. The model of the thermal storage is an energy node of incoming and outgoing thermal power with constant thermal losses and presented in equation (1). The MHPs are represented by a polynomial for B5 °C/W35 °C with a variable modulation speed.

$$\sum_{n=1}^{2} \dot{Q}_{MHP,n}(t) + \dot{Q}_{cap}(t) = \dot{Q}_{loss}(t) + \dot{Q}_{th}(t) \quad (1)$$

Depending on the operation plan (set points) of the control strategy, the MHPs adapt their thermal power either to the thermal building load or to the available PV power. Equation (2) shows thermal adaption where Q_{MHP} the thermal power of one MHP is. Equation (3) shows electrical power, where P_{MHP} the electrical power of one MHP is.

$$P_{MHP} = p1 * \dot{Q}_{MHP}{}^{4} + p2 * \dot{Q}_{MHP}{}^{3} \ldots + p3 * \dot{Q}_{MHP}{}^{2} + p4 * \dot{Q}_{MHP} + p5 \quad (2)$$

$$Q_{MHP} = q1 * P_{MHP}{}^{6} + q2 * P_{MHP}{}^{5} \ldots + q3 * P_{MHP}{}^{4} + q4 * P_{MHP}{}^{3} \ldots + q5 * P_{MHP}{}^{2} + q6 * P_{MHP} + q7 \quad (3)$$

The model of the DHW storage is an energy node of incoming and outgoing thermal power with a constant thermal loss. Each boosters is represented by one operation point at 25 °C/55 °C with a thermal power of 3 kW and COP of 4.3.

As well, the battery model is an energy balance of incoming and outgoing electrical power with inverter efficiency and calculated by equation (4). The battery is not controlled and serves a passive component that is charged and discharged by the electrical energy balance of PV power (P_{PV}), electrical consumption of MHPs (P_{MHP}) and boosters (P_b).

$$P_{PV}(t) * n_{loss} + C_{bat,cap} = \cdots \sum_{n=1}^{2} P_{MHP,n}(t) + \sum_{n=1}^{8} P_{b,n}(t) \quad (4)$$

The validation of models with energy balancing showed moderate but sufficient accuracy in the real energy system [8] and in a hardware-in-the-loop test bench [9].

2.2 Prediction models

For the use of predictive controls, MPC and SPC, forecasting models are used to generate the thermal and electrical load forecast.

Artificial neural networks (ANN) in Python with the library Tensorflow (Apache, 2019) determine the prediction of thermal building load and household electricity. Both ANN are recurrent, trained with measured data of 15 months from the energy monitoring of the terraced houses and deliver prediction data for 24 hours in a 15 minutes timestep. Inputs are date information (month, day, hour), ambient temperature and horizontal global solar radiation. In addition, the ANN of the household electricity has inputs of historic values of one day and one week ago. During a long-time operation of the MPC in April 2020, the ANN of thermal building load receive values of RMSE of 3.7 kW and NRMSE of 19 %, the household electricity values of RMSE of 1.6 kW and NRMSE of 14 %.

2.3 MPC

In this paper, the MPC approach is realized by a mixed-integer linear programming (MILP). As the system model, all energy models base on energy flows coupled in an energy node in order to receive linear models (see equation (1)). The characteristics of the MHPs differ, as they are represented by fixed operation points at B5 °C/W35 °C between which the MILP can interpolate. The interpolation is enabled by the additional software GUROBI [10], for using the Special Ordered Set (SOS) option and is integrated in MATLAB.

The cost function (J) bases on operating costs (c) for the consumed electricity, including household electricity, the MHPs and the DHW-HPs depending on the consumption of grid ($E_{el,grid}$), PV ($E_{el,PV}$) or battery ($E_{el,Bat}$) as well as a bonus for grid feed-in ($E_{el,\text{feedin}}$). The PV costs include costs for insurance (0.0243 €/kWh) and national taxes for renewable energies (0.064 €/kWh). Battery costs consists of PV costs and losses of 20 %. In this context, the battery price results from PV price multiplied by a factor of 1.2. The energy prices are shown in Tab. 1.

Tab. 1 - Electricity prices.

Energy prices	Price
Grid electricity	0.34 €/kWh
PV electricity	0.0883 €/kWh
Battery electricity	0.0883 €/kWh *1.2
PV feed-in electricity	0.11 €/kWh

The results of this MPC approach provides an SOC determining the set value for the MHPs. The SOC is divided into 8 areas, respectively allocated to a set value of 32 °C to 46 °C in a 2 K step. The boosters receive the set temperature of the storage tank as set value when they are to be on (60 ° C) or off (45 ° C). The minimum value of 45 °C ensures the comfort limits of the habitants. A detailed description of the MILP MPC can be found in [11].

2.4 SPC

The SPC is based on a modification of the electrical operation of the MHPs, which results from the thermal building load forecast. As balancing of the loads is performed on electrical loads the thermal building load forecast is converted into an electrical load with a constant COP, which should reflect the operation of the heat pumps. Electrical operation loads that occur after PV production are shifted forward to times with PV production. The modified electrical operation results in set point for the MHPs. Therefore, the electrical operation is converted back to a thermal building load using the polynomial in equation (2) that reflect the characteristic curve of the heat pump at B5 °C/W35 °C. The shifting of the loads is limited up to the maximum storage level, which is 46 °C. Without PV production the set point is 32 °C, while with PV production the set point results from the shifted loads. Fig. 3 (above) shows electrical operation of the MHPs from the thermal building load forecast, the modified electrical operation and the PV power forecast. Below in Fig. 3 is the set temperature, which results from the modified electrical operation. The same procedure is repeated for the boosters, but with a constant COP of 4.3.

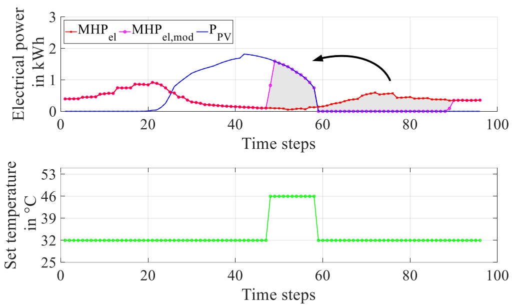

Fig. 3– Modification of electrical operation of MHPs (above) and resulting set temperature (below)

2.5 Rule-based controls

For comparing the MPC and SPC to standard heat pump operation, two common rule-based controls are introduced. The PV control (PVC) aims to increase the PV self-consumption by operating the heat pumps during PV surplus and charge the thermal storage to its maximum. PV surplus means the available PV power after satisfying the household electricity. In this case, the MHPs adapt to PV power, using equation (3). During grid and battery operation, the MHPs adapt to the thermal building load using equation (2). As well, the boosters charge to maximum storage capacity while PV surplus after MHPs or charge to minimal storage capacity while grid and battery consumption.

The heat control (HC) only operates the MHPs in adaption to the thermal building load (equation (2)) and the boosters to charge the minimal storage capacity.

2.6 Simulation

For the comparison of the control strategies, measured data of the energy system of the terraced houses is used. The process of the annual simulation is shown in Fig. 2. The energy consumption and production for the period of 12 months are shown in Tab. 2.

The results of the simulation for the 12 months period show low differences for the energy shares, but differences for operating costs. The results of the PV self-consumption and the self-sufficiency of the comparison are shown in Fig. 4. In general, the results do not vary significantly between the different control strategies. HC shows less PV direct consumption and highest grid consumption.

Tab. 2 – Energy consumption in 2020

Energy consumption	
Thermal load	36.56 MWh
DHW load	26.66 MWh
Electrical load	30.85 MWh
PV production	85.88 MWh

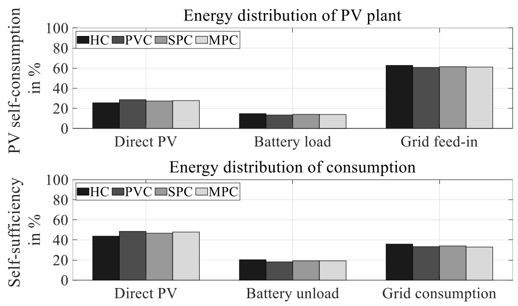

Fig. 4 – Energy shares regarding PV self-consumption and self-sufficiency

Fig. 5 gives an overview of operating costs and total energy consumption in comparison to the HC, which serves as standard control. In total, the operating costs under HC operation are 3,172 € for the energy consumption including household electricity, heating, DHW and bonus from grid feed-in. The MPC achieves most of the cost savings as well as less energy consumption. Even PVC and SPC have slightly higher energy consumption, the operating costs are less. The MPC cost saving of about 10 % confirms the results of Fischer et al. [1] when German energy prices are applied. Taxes for renewable energies reduce the potential savings from increased PV use. Without the taxes for renewable energies, that means PV costs of 0.0243 €/kWh, a much higher cost saving can be achieved. The PVC achieves cost savings of 13 %, the SPC of 15 % and the MPC of 34 %. These cost savings of the MPC are in a range of EU-wide simulation studies, such as Salpakari and Lund [3] and Bechtel et al [4]. Although the differences between PVC und SPC are small, favourable results are shown for the predictive approach.

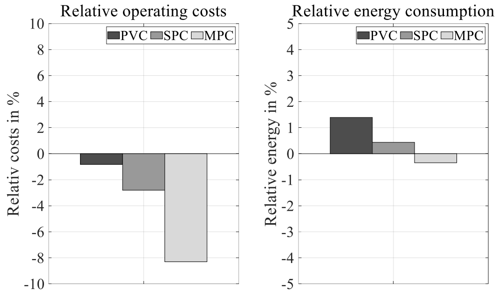

Fig. 5 – Operating costs and total energy consumption

The differences of the energy consumption results from different values of Seasonal Performance Factors (SPF) for the MHPs and consequently for the system. The SPF values of the control strategies are shown in Tab. 3. High modulation speed during PV adaption lowers the SPF.

Tab. 3 – Seasonal Performance factors of control strategies

	SPF_{MHPs}	SPF_{system}
HC	4.46	4.43
PVC	4.23	4.27
SPC	4.38	4.38
MPC	4.51	4.46

The simulation study was repeated with the measurement data from the year 2019 and very similar results are obtained for the four control strategies. Regarding the results of years 2019 and 2020 the PVC has an energy consumption from 1.4 % to 1.7 %, the SPC from 0.2 % to 0.4 % and the MPC from – 0.3 % to – 0.6 %, compared to HC. The potential of cost saving is for the PVC in a range of 0.2 % - 0.8 %, for the SPC in a range of 2.8 % - 4.6 % and for the MPC in a range of 8.3 % - 9.6 % under PV costs with taxes for renewable energies.

3. Real-life implementation

To test the control strategies in real operation, the MPC and SPC are implemented in the real energy system of the terraced houses. Since October 2018, the energy system has been operated with the PVC installed in an energy management software which controls the heat pumps. In contrast, the MPC and SPC will run on the software MATLAB and the set points will be transferred to the energy management system via an SQL database and set to the heat pumps from there.

Fig. 6 shows the process of the control strategies. When operating the predictive controls, the MPC or SPC are started at a certain time T. The MPC starts every hour, the SPC only once a day at 6 am. The created operation plan is passed on to the Set/Check Loop. The Set/Check sets the set values into the SQL database and checks the operation of the system for disturbances and deviations of the operation plan, and if necessary, sets set values for switch on or off. This ensures the operation reliability during time slot of next set values. In this paper this process is called online simulation.

In previous work [11] the MPC flow process was successfully tested and SPC was also successfully integrated into the process in this work. The energy management software includes communication with the controllable components of the energy system, the logging of measurement data and functions for setting up a rule-based control strategy. The PCV was implemented in the energy management software, which operates the plant independently of MATLAB and most of the time. In addition, the energy management software can pass values from the SQL database to the energy system. The structure makes it possible to implement many control strategies for a reliable operation.

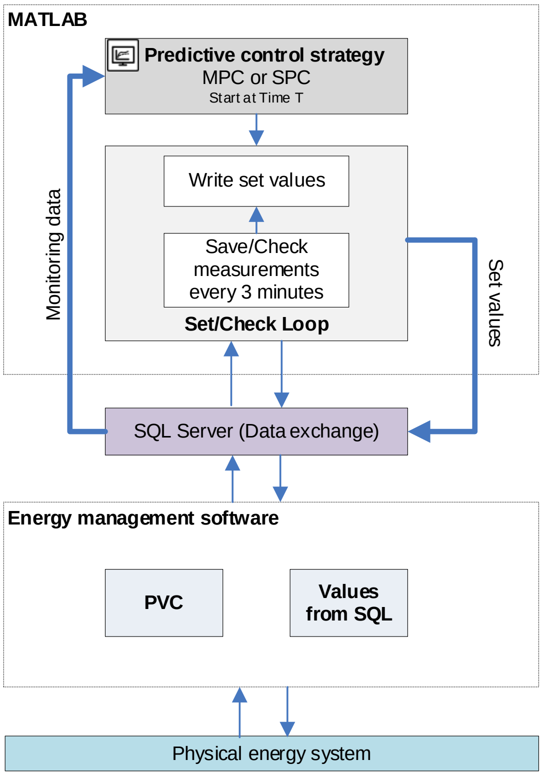

Fig. 6 – Process of control strategies

For the evaluation of the PVC, long operating times from October 2018 until now are available. However, the MPC and SPC were only operated over several weeks, so that a direct comparison is not possible due to the short period of time and the different boundary conditions (e.g. weather, user behaviour, etc.). In order to give an impression of the control strategy, characteristic values from the target specification (online simulation) and from measured values from the real operation of the MPC and SPC are compared. In addition, the measured results of the PVC are presented over the period from year 2019 as no additional control strategy was tested in this year.

3.1 Real operation of PVC

The standard operation in the energy system of the terraced houses is PVC. In order to not only obtain an overview of the characteristic values of the PVC in real operation for the year 2019, the offline simulation results of the PVC for the year 2019 from the upper chapter are also presented. In the simulation model, however, other boundary conditions are partly applied. The temperature limit of the thermal storage in the model is 46 °C, in the implemented PVC it is 39 °C in 2019.

Tab. 4 – Comparison of offline simulation and measured data of PVC in year 2019

	Simulation	Measurement
PV production	85.1 MWh	85.1 MWh
Energy consumption	49.3 MWh	47.9 MWh
PV self-consumption/ incl. Battery	28 % / 42 %	26 %/ 36 %
PV self-sufficiency/ incl. Battery	49 % / 67 %	45 %/ 62 %
Operating costs	2,843 €	3,430 €
SPF_{MHP}	4.2	4.8

The comparison of offline simulation and measurement in Tab. 4 clearly shows differences, which reflect the different boundary conditions for the maximum storage level. In particular, the lower PV self-consumption and PV self-sufficiency lead to higher operating costs of 17 %. In contrast, the SPF of the MHP is better. This could be due to an efficient modulation level throughout the year and a lower supply temperature below 35 °C. Since the characteristic curve of the MHP in the model (see equation (2) and (3)) is only dependent on modulation level and has its best operation in the modulation range of 30 % to 40 %, it can be assumed that high or low modulation levels are selected more often in offline simulation.

3.2 Real operation of MPC

Compared to PVC the operation of MPC was operated for several weeks in February and April 2021. During the operation in February 2021 adaptions to the model were identified and implemented. The comparison of online simulation and measured data is from 22.03.2021 until 03.05.2021 and is shown in Tab. 5. Although the values of the PV self-consumption and the PV self-sufficiency are very similar, the operating costs show a clear difference. However, since about 27 % more PV was produced in the measurement than in the PV forecast of the online simulation, there is a higher feed-in in absolute values. The same is shown in the energy consumption, but the relative (13 %) and absolute grid consumption is not significantly higher in the measurement. The low operating costs of the measurement arise mainly from the significantly higher profit from the PV feed-in tariff. The SPF is significantly worse in the measurement, although there is the same heating and DHW consumption. This shows that the targeted compressor control from the online simulation cannot be implemented in real operation at the MHPs.

Tab. 5 – Comparison of online simulation and measured data of MPC

	Simulation	Measurement
PV production	10.0 MWh	12.7 MWh
Energy consumption	5.2 MWh	6.0 MWh
PV self-consumption/ incl. Battery	30 % / 38 %	29 %/ 40 %
PV self-sufficiency/ incl. Battery	58 % / 78 %	59 %/ 79 %
Operating costs	118 €	42 €
SPF_{MHP}	4.8	4.2

3.3 Real operation of SPC

Similar to the MPC, the SPC has only been in operation for a few weeks. The SPC was in operation from 13.01.2022 to 22.01.2022 as well as from 04.02.2022 to 13.02.2022. The results from both operation periods are presented in Tab. 6.

The load forecasts receive very good results for thermal building load with an NRMSE of 16 % / 15 % and household electricity with an NRMSE of 15 % / 14 %. But nevertheless, the PV production and energy consumption are higher than in the online simulation, as already seen in the MPC operation. The load forecasts tend to lower results.

The operating costs are 20 % higher in the measurement, which results from a higher consumption, especially of the grid consumption. In addition, the PV self-consumption is lower. Due to the absolute lower feed-in, the bonus from feed-in is not relevant for the amount of the operating costs.

The SPF, although slightly lower, is quite well in line. Due to the low PV production, the MHPs were only occasionally operated in the high temperature range, so that the characteristic curve from the simulation was reproduced well.

Tab. 6 – Comparison of online simulation and measured data of SPC

	Simulation	Measurement
PV production	1.2 MWh	1.4 MWh
Energy consumption	2.9 MWh	3.3 MWh
PV self-consumption/ incl. Battery	70 % / 92 %	56 %/ 84 %
PV self-sufficiency/ incl. Battery	30 % / 40 %	25 %/ 34 %
Operating costs	679 €	818 €
SPF_{MHP}	4.6	4.4

4. Discussion

In the simulation, the MPC achieves the best results in energy consumption and cost savings, although it does not have the highest PV self-consumption. These results come from the high SPF resulting from the better operation strategy of the MPC. Unlike the other control strategies, the MPC specifically takes advantage of the better efficiency of the MHP in partial load operation. Not only during PV, but also during grid consumption, the thermal storage is charged to operate the heat pump at the optimal operating point continuously. Therefore, the lowest grid consumption results, which is weighted the most by the energy prices.

In contrast, the control of HC, PVC and SPC adapts the MHPs in case of grid consumption to the thermal load and operates them, depending on the load, also in less efficient operating points. This predictive operation with a focus on efficient partial load operation out of PV periods has not been implemented in SPC and should therefore be integrated in further work. This could improve the results compared to the PVC.

In real operation, PVC, MPC and SPC were implemented in the energy system of the terraced houses. MPC and SPC were implemented in MATLAB and coupled with an SQL interface to the energy management software. The PVC runs directly in the energy management software. During the operation phases the controls were shown to be reliable and to cover the thermal loads of the building.

When comparing online and offline simulation and measured data, the main differences are in the SPF and consequently in the energy consumption. The differences come from the MHPs characteristic curve and additionally for the MPC and SPC by the load forecasts. The simple MHP characteristic curve in the simulation does not correctly reflect the SPF in operation. Especially the annual comparison of the PVC shows clear differences between measured data and simulation. Due to the higher storage temperatures, the characteristic curve in the simulation should be set at higher temperatures, e.g.: B5 °C/W 40 °C or be created with another variable, which reflects the storage tank level. In this way, the results from the measurement could be better reflected in simulation.

Real operation control by SPC was well implemented and it shows secure operation and full cover of loads.

Finally, it is shown that not only the full utilization of the storage in PV phases reduces the operating costs, but also the efficient operation of the MHPs. This efficient operation is achieved by operating points in the range of 30 % to 40 % of the maximum thermal power. In PV phases, the thermal storage should be charged over a longer time period in efficient operation points. In grid operation, it is more advantageous to use the thermal storage also as a buffer to operate the MHPs continuously in efficient mode instead of adapting to the thermal building load. In real operation, targeted compressor control cannot be implemented due to the manufacturer's specifications of these MHPs. This gap between the set point output of the simulation and the set point input of the real components poses a challenge to the implementation of efficient and cost-effective control like the MPC. However, at the same time, the advantage is that poor control implementation, incorrect load forecasts or unpredictable events can be compensated by the internal heat pump control.

5. Conclusion

In this paper, a PV optimized control, an MPC approach and a simple predictive control approach are investigated in simulation and real operation.

The annual simulation was performed with measured data from 2019 and 2020. Both annual simulations achieve very similar results. In the annual simulations, the two predictive approaches were compared with two rule-based controls and evaluated for their potential for PV self-consumption and cost savings. The two rule-based controls are heat controlled (HC) default operation and a PV controlled (PVC) operation with temperature rise in case of PV surplus.

Compared to the HC in the annual simulation from 2020, the PV self-consumption can only be increased to a few absolute percentage points (2 % - 3 %). Despite the predictive approach of SPC, SPC and PVC achieve very similar results. The relative cost saving of the SPC is 2.8 % and thus only slightly better than that of the PVC. The best result is achieved by the MPC with a cost saving of 8.3 %. The energy prices used are those of the year 2019 for the terraced houses and include taxes for PV direct consumption. Excluding these taxes, there are significantly higher cost savings of up to 34 % for MPC. The good results of the MPC are due to a high PV energy consumption but mainly to the best efficiency with a SPF of 4.5.

PCV, MPC and SPC were operated in the real energy system of the terraced houses. During the operation phases, the controls were shown to be reliable and to cover the thermal loads of the building. In real operation, differences between offline/online simulation results and measured data become apparent. Since the set point specifications from the simulation can only be transferred to the real MHPs in the form of set point temperatures, the operating plan cannot be fully implemented. In the case of PVC this is advantageous, since better results have been obtained in the measurement than in the offline/online simulation. In the case of MPC and SPC, however, worse results are obtained in real operation.

6. Acknowledgement

This paper presents results from the projects "Herzo Base - Energy storage houses - An energy flexible building and energy concept of tomorrow" (FKZ 03ET1364A) and "Herzo Opt - Monitoring of the building envelope, thermal room comfort and energy system with operational optimization" (FKZ 03ET1641A). The project is funded by the German Federal Ministry for Economic Affairs and Energy based on a resolution of the German Bundestag.

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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 are/will be available on request with privacy agreement