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DECARBONISATION THROUGH INNOVATION

"Model predictive control brought to practice"

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Abstract

The integration of renewable energy sources into the electricity grid requires flexible consumers to maintain grid stability. Heat pump systems, combined with thermal energy storage and building thermal inertia, can provide such flexibility. Model predictive control harnesses this potential by enabling predictive and cost-optimized operation while maintaining comfort constraints. In this study, we present results from an industrial field deployment of MPC in a pool of residential heat pump systems. The analysis combines three levels: qualitative behavioural signatures, quantitative year-on-year comparison of a representative system against similar buildings, and pool-level aggregation. Results indicate significant potential for energy cost savings and improved PV self-consumption, while maintaining user comfort. The work demonstrates the practical feasibility and robustness of MPC in real-world operation.

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Keywords: Model predictive control; Heat pumps; Field deployment; Energy efficiency.

1. Introduction

The decarbonization of the building sector requires a rapid increase in the use of electrically driven heat pumps. When operated flexibly, heat pumps can support the integration of renewable energy by shifting electricity consumption according to grid needs and price signals. Model predictive control (MPC) offers a promising approach to enable such flexibility. By using system models and forecasts of weather, electricity prices, and user demand, MPC allows anticipatory and cost-optimized operation of heating and domestic hot water systems.

While the benefits of MPC have been shown extensively in simulation and laboratory studies [1], practical implementations under real operating conditions remain scarce [2]. Real-world environments introduce significant challenges, such as uncertain user behaviour, varying building characteristics, and incomplete system data. Demonstrating the feasibility and robustness of MPC in this context is therefore a crucial step toward large-scale deployment.

This paper presents results from an applied research project conducted in collaboration with an electricity supplier and a heat pump manufacturer. It builds upon preliminary cooperative research projects "Flex+" [3] and "Energieschwamm" [4], which assessed the feasibility of large-scale MPC for residential heat pump systems under commercial operating conditions. The current project demonstrates the implementation into a cloud-based infrastructure and its deployment across more than 40 operational heat pump systems.

A field-based performance evaluation was conducted to assess MPC behaviour and benefits at both the individual system level and the entire pool, combining detailed case analysis with aggregated performance indicators. The results demonstrate that MPC enables stable and cost-efficient operation while enhancing the utilization of renewable electricity under real-world conditions.

2. Methodology and Approach

2.1. Field Setup und MPC Implementation

The control architecture originates from a multi-year research project conducted jointly with an electricity supplier and a heat pump manufacturer. The MPC strategy was integrated into the heat pump manufacturer's cloud-based infrastructure, which supports remote maintenance, monitoring, and software updates. Each connected heat pump continuously transmits operational data, including power consumption, temperatures, and system states to the cloud platform. An overview of the system layout and the data flows is shown in Figure 1.

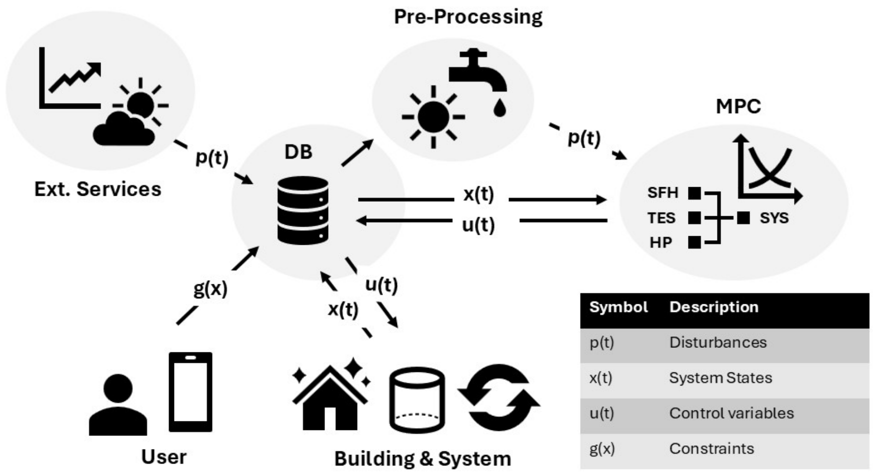

Figure 1: Schematic representation of MPC architecture: Heat pumps connected to central cloud infrastructure. API to external services, such as weather forecast and day-ahead el. price.

When new customers join the flexibility program, an onboarding process collects basic building and system information through a guided questionnaire (e.g., building type, heated floor area, number of occupants). These inputs are used to parameterize the thermal model that captures the main dynamic properties of the building and heating system.

The MPC is executed centrally in the cloud once per day, triggered by the availability of day-ahead electricity price data from the electricity supplier. The optimization considers a 48-hour prediction horizon with a temporal resolution of 15 minutes. Only the control sequence for the first 24 hours is transmitted to the heat pump and executed locally.

The optimization problem is formulated as a mixed-integer linear program. The heat pump is modelled using piecewise-linear approximations of performance maps that relate compressor speed and operating temperatures to electrical power consumption and thermal output. These maps are derived from polynomial functions of evaporator temperature, condenser temperature, and compressor speed, which are linearized around multiple operating points.

In addition to the compressor speed, the heat pump model includes discrete decision variables representing the operating mode. At each time step, the system operates in exactly one of three mutually exclusive modes: off, space heating, or domestic hot water preparation.

A lumped-capacitance model is used to forecast the space-heating demand and thermal building behaviour. The ambient temperature is obtained from an external weather forecast service. Electricity price forecasts are taken directly from the energy supplier's day-ahead market data. Systems equipped with photovoltaic generation or thermal storage are represented by extended state variables and coupling terms, while direct heating systems use a reduced model structure. Model parameters are initialized from user-provided building data and continuously calibrated using operational feedback.

During normal operation, the MPC runs once per day to provide the day-ahead control sequence. However, the system also monitors deviations between predicted and measured states in real time. If significant discrepancies occur - caused, for example, by unexpected user behaviour or weather forecast errors - the heat pump switches to regular control, until all system states are within their specific limits. This hybrid control approach, combining cloud-based optimization with local execution, allows robust and flexible operation under real-world conditions while maintaining scalability across a heterogeneous field of heat pump systems.

2.2. Evaluation Approach

Evaluating the performance of MPC in real residential heat pump systems presents significant challenges. Unlike laboratory or simulation environments, where identical systems and controlled disturbances allow direct comparisons, real-world deployments are subject to variable weather, user behaviour, and heterogeneous building characteristics. Consequently, a straightforward comparison to conventional rule-based control is not feasible: there is typically no identical reference system operating under the same boundary conditions. This limitation motivates a structured, multi-level evaluation approach designed to quantify the benefits of MPC under practical operating conditions.

The evaluation is structured in three complementary levels. First, detailed case studies illustrate MPC behaviour on representative individual systems. Second, long-term comparisons assess performance over extended periods, against similar reference systems. Third, aggregated analysis evaluates performance across a pool of heat pump systems using MPC.

2.2.1. Behavioural Signatures

To investigate the operational characteristics of the MPC strategy under real-world conditions, three representative systems are selected for detailed analysis: one ground-source and two air-source heat pumps, of which two are equipped with photovoltaic systems. None of the systems include a dedicated thermal storage for space heating. Thermal flexibility is therefore provided only by the building envelope and internal mass. Domestic hot water operation is excluded to isolate space-heating dynamics.

High-resolution measurement data is used as the basis for this analysis and aggregated to hourly averages for visualization and evaluation. The selected multi-day periods allow the examination of how each system responds to varying ambient conditions and electricity price signals. The evaluation focuses on space-heating electricity consumption, indoor temperature, and relevant external factors, forming the basis for identifying characteristic MPC operation patterns under diverse configurations. The main characteristics of the selected systems are listed in Table 1.

Table 1: Selected representative heat pump systems

Name	Building				Energy System			
	Year of Construction	Heated floor area [m²]	Construction Type	Heating System	Heat pump	PV-System [kWp]	DHW-Storage [l]	SH-Storage [l]
a)	2019	200	Heavy	Underfloor	iPumpA 3-11	-	200	
b)	2019	175	Light	Underfloor	iPumpA 3-11	5	200	
c)	2019	205	Medium	Underfloor	iPumpT 3-13	20	200	

2.2.2. Single-System long-term comparison to classical control

Direct comparison between different control strategies under real operating conditions is inherently difficult, as no identical ground truth exists. To approximate a meaningful reference, four highly comparable buildings located within the same residential district are selected. All four are semi-detached houses of the same construction type, with the same floor area, east-facing orientations, and identical heat pump and heat emission systems. One of these systems operates with the MPC strategy, while the remaining three are equipped with conventional heating-curve based control, in which the supply temperature is determined as a function of the ambient temperature. This rule-based strategy is purely reactive and does not account for forecasts of weather, electricity prices, or user demand, and therefore cannot enable predictive or cost-optimized operation.

The comparison covers two heating seasons (2023/24 and 2024/25). For each system, the hourly electrical energy consumption for space heating is recorded and combined with corresponding hourly electricity price and renewable energy share data from *energy-charts.info* [1]. The data is aggregated for each heating season to determine (i) the mean electricity price per kilowatt-hour consumed and (ii) the share of renewable electricity utilized. These aggregated indicators are visualized in bar charts to compare the MPC-operated system with the reference group in Figure 3, Section 3.2.

2.2.3. Pool-Level generalization

The collective operation of all MPC-controlled systems is analysed using aggregated data from the field installation pool. Two representative weeks are selected for the evaluation, one in January and one in October 2025, to cover both winter and transition-season conditions.
For each period, hourly electrical energy consumption for space heating is summed across all systems. The corresponding photovoltaic generation and electricity price signals are also aggregated on an hourly basis. These aggregated time series form the basis for subsequent analysis and visualization of pool-level operation in the results section.

3. Results and Discussion

In the following section, the results related to the previously described methods are presented, starting with the results on the behavioural signatures of the three representative heat pump systems, followed by the comparison of one optimization-based system to three similar reference systems. Lastly, the results for the pool level aggregation are presented and discussed.

3.1. System level operation and control behaviour

Figure 2 shows the hourly electricity consumption of three heat pump systems required to cover the space heating demand and indoor temperature of three representative systems over selected multi-day periods. The plots illustrate the daily operation patterns under varying ambient temperatures and electricity price signals.

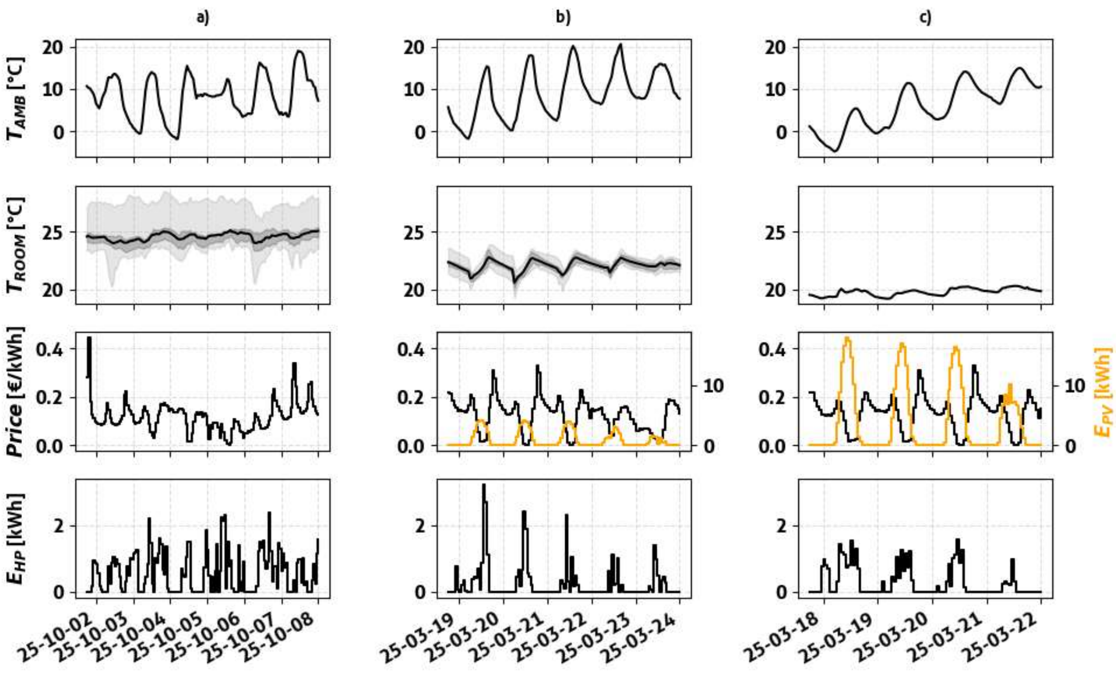

Figure 2: Behavioural signatures of three representative systems: Ambient Temperature T_{AMB}, Room temperature(s) T_{ROOM}, El. Price signal and PV Generation E_{PV} (orange), El. Energy consumption required for space heating E_{HP} – from top to bottom.

Columns a) to c) represent the different systems as described in section 2.2.1, Table 1. The top plot shows the ambient temperature over the contemplated periods. The second highest plot shows the room temperature curve (mean temperature, highest and lowest in case of single-room control, reference room temperature else). The third plot per column shows the dynamic electricity price and, if present, PV generation (orange). In the bottommost plot the electricity consumption of the heat pumps is shown, subject to the optimized schedule.

Differences between the systems reflect the influence of system type, building characteristics, and the presence or absence of PV generation. The graphs highlight the timing and magnitude of electricity use for space heating, and how the indoor temperature is maintained within comfort bounds across diverse configurations. Case a) illustrates the sensitivity to user driven disturbances, e.g. on 7 October, where window ventilation causes a short-term temperature drop that triggers a fallback to conventional control to remain within the comfort bounds. Cases b) and c) show how MPC exploits photovoltaic generation and low-price periods to preheat the building during daytime, with the higher thermal mass in case (c) resulting in smoother indoor temperature trajectories.

3.2. MPC vs. classical control, long-term performance analysis on similar buildings

To assess long-term performance, one MPC-operated system is compared with three reference systems using conventional heating curve control. Figure 3, on the left, shows the average electricity cost per kWh consumed to cover the space-heating demand for two heating seasons (2023/24 and 2024/25). The MPC-operated system achieves the lowest cost in both periods. Figure 3, right, presents the corresponding share of renewable electricity. Although the MPC optimization targets cost only, it also results in a higher renewable share, since low prices generally coincide with high renewable availability in the Austrian electricity market.

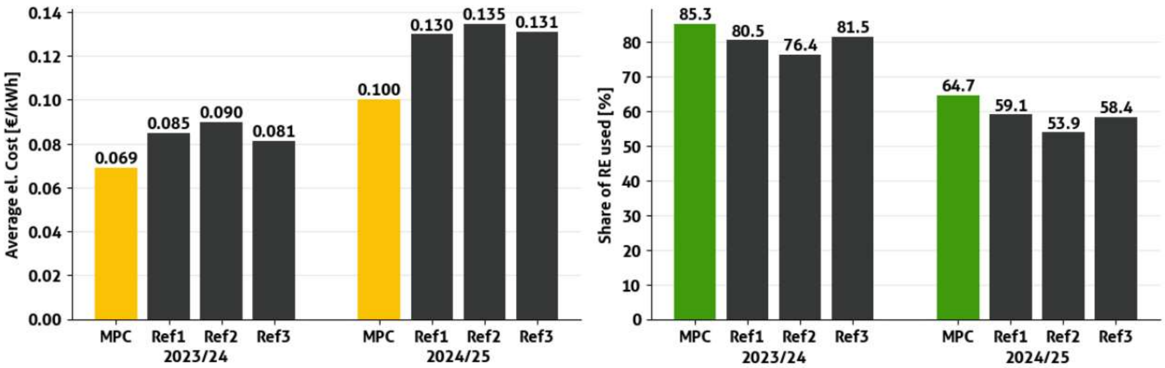

Figure 3: MPC vs. rule-based control: Average cost of electricity per kWh (left), share of renewable energy used for space heating (right) in two heating seasons

These results indicate that the MPC strategy can simultaneously reduce operating costs and increase renewable electricity utilization compared to conventional control approaches, even when optimized purely for economic performance.

3.3. Aggregated pool analysis

To assess the collective behaviour, its response to external signals and effect on the electricity grid, aggregated data from all operational systems are analysed.

Figure 4 and Figure 5 present the aggregated electricity consumption of the heat pumps, total photovoltaic generation, and electricity price signals for all MPC-controlled systems during one week in January and one week in October. The plots show hourly sums across the pool, providing a comprehensive view of the overall load profile. Seasonal differences between winter and transition periods are visible in the total electricity demand and PV generation.

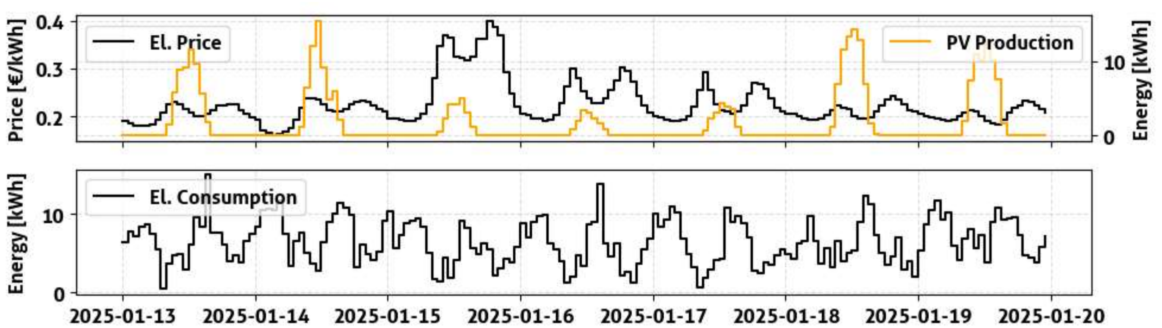

Figure 4: Electrical consumption of MPC-operated pool depending on electricity price and PV production in winter season

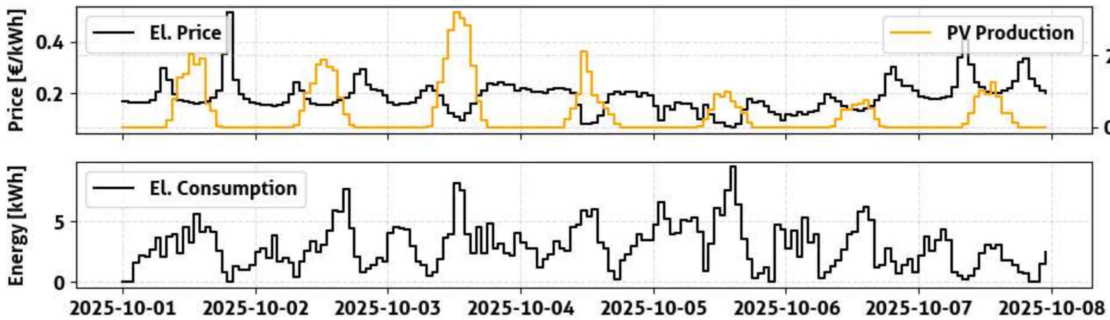

Figure 5: Electrical consumption of MPC-operated pool depending on electricity price and PV production in transitional season

The plots indicate that the MPC-controlled pool shifts electricity consumption in response to price signals, reducing demand during higher-price periods and taking advantage of low-price periods. Simultaneously, the aggregated load aligns with periods of high photovoltaic generation, increasing on-site self-consumption.

4. Conclusion and Outlook

This study demonstrates the practical feasibility and robustness of MPC for residential heat pump systems under real operating conditions. The field deployment shows that MPC can reduce electricity costs and increase renewable electricity utilization while maintaining thermal comfort. Aggregated analyses reveal that, although all systems operate independently, common responses to electricity price signals and photovoltaic generation result in load profiles that align with low-cost and high-renewable periods.

The control architecture was designed with scalability as a primary objective, relying on automated model parameterization from user input and historical operational data to keep setup and commissioning costs low. In practice, this scalability is achieved most reliably for standard hydraulic configurations, while non-standard or highly customized system layouts require additional modelling effort and therefore limit straightforward roll-out. Occasional communication delays or data losses do not critically affect performance, as model adaptation relies on long-term operational data rather than short-term measurements.

Future work aims to extend the control architecture to multi-family housing applications and more complex building configurations. In ongoing research projects, we focus on refining and extending building models, forecasting methods, and system-level performance to increase the economic and environmental benefits of MPC strategies in diverse residential and non-residential settings.

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