EFFICIENT HEAT PUMP OPERATION: A COMPARATIVE ANALYSIS OF MODEL-PREDICTIVE AND RULE-BASED HEAT PUMP CONTROL

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Introduction & Motivation

The transition towards decentralized and renewable-based energy systems requires advanced digital solutions to exploit flexibility regarding the electricity sector in buildings and residential environments. Particularly in the heating sector – responsible for around 60% (2023) of final energy demand in the EU [1] – heat pumps, photovoltaic (PV) systems, and thermal storage play a crucial role. Their integration offers significant potential for increasing energy efficiency [2] and reducing greenhouse gas emissions, yet also introduces operational challenges due to volatile PV generation, fluctuating thermal demand, and dynamic electricity tariffs.

Heat pumps sit directly at the interface between electrical and thermal energy and are therefore highly sensitive to control strategies. Traditional rule-based approaches often fail to make full use of available flexibility or to coordinate PV generation, tariffs and heat demand effectively. Optimization-based model-predictive energy management systems (EMS) can address these challenges in principle, but thorough evaluations of the operational performance and cost improvements are still sparse in literature.

Therefore, this work discusses a comparative analysis of such control strategies compared to rule-based ones. To this end simulation studies are used to investigate the annual performance of heat pumps in different residential system configurations, comparing a supervisory model-predictive controller (MPC) with two conventional rule-based strategies, with and without consideration of PV-generation. Therefore, key performance indicators related to cost efficiency, energy efficiency, run time behaviour, and grid interaction are analysed.

Controller strategies: Model-Predictive and Optimization-Based vs. Rule-Based

The supervisory MPC controller is based on a modular, optimization-based, predictive control framework that automatically constructs and solves a mixed-integer linear programming (MILP) problem for each considered system setup [3,4]. The framework models typical components of residential energy systems–heat pumps, thermal storage, photovoltaic systems, and household electricity consumption–using linear models. These are combined into a system-wide optimization problem that determines an ideal control trajectory over a predictive horizon. The optimization integrates multiple forecast signals for the following quantities:

- electricity price (variable or fixed tariffs),
- PV generation,
- thermal demand for heating and domestic hot water,
- ambient temperature, enabling the consideration of temperature-dependent heat pump COP.

To quantify the theoretical potential of the MPC strategy forecasts within the simulations are treated as “perfect foresight”. In a real-world implementation, the same controller would operate by re-solving the optimization at regular intervals (e.g., every 15 minutes) using updated measurements and forecasts.

The rule-based control on the other hand uses threshold values for temperatures to be available at the outlets within the thermal storages. Depending on this measurement, and the heat demand the heat pump operation is chosen. Additionally, also the availability of surplus power from e.g. PV generation is considered within this approach.

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Methodology and Studied Scenarios

The study investigates multiple system configurations relevant for residential energy systems:

- a single thermal storage buffers using volumes of 500 and 1500 litres,
- a two configuration with two 300-liter buffers for separated heat- and domestic hot water,
- fixed or variable electricity tariffs,
- 10 kWp or 15 kWp PV systems,
- with or without consideration of household electricity demand.

To ensure strict comparability, both the optimization-based supervisory controller and the rule-based approaches are implemented within the same supervisory control framework. The rule-based strategies are realized by adding additional constraints to the optimization problem that enforce the rule logic and fully determine the operating trajectory. In this formulation, the optimization problem loses all remaining degrees of freedom and effectively becomes a deterministic system of equations. While this is computationally unnecessary for rule-based control, it guarantees that identical physical models, boundary conditions, and numerical handling are used for all simulations.

Input data include domestic hot water demand, space heating demand, global horizontal irradiation, room temperature, and ambient temperature, represents a typical Austrian single-family home.

Key Results: Heat Pump Performance and Energy Efficiency

The studies show that with the optimization-based model-predictive EMS annual electricity procurement costs can be reduced by up to 80% in the most flexible configurations, within this simulation study using optimal forecasting conditions, i.e. perfect foresight. The reductions are mainly caused by:

- shifting heat pump operation to low-tariff periods,
- increasing PV self-consumption,
- operating during times of higher ambient temperature, yielding improved COP.

The controller achieves a more efficient usage of renewable generation and thermal storage and supports a grid-friendly operation by smoothing peak electricity demand. While overall performance improves, the optimized strategies tend to increase annual run times of the heat pump, illustrating a classical trade-off between efficiency and mechanical wear.

Conclusion

This study demonstrates the substantial efficiency and cost-saving potential of optimization-based, model-predictive energy management for residential heat pump systems. Heat pump data and rule-based control strategies for this research have been provided by KWB Energiesysteme GmbH. The consistent execution of both strategies using the same supervisory controller framework – either as a fully predictive EMS or with rule-based behaviour implemented through additional constraints – ensures that observed differences are attributable solely to the control logic itself, showcasing the maximal potential of such systems. As the energy transition progresses, such digitalized, optimization-based EMS solutions will play a central role in managing decentralized, sector-coupled energy systems, supporting higher renewable integration, increased energy efficiency, and improved grid interaction.

References

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