# Design and Optimization of The Conventional Heat Pump with Thermal Energy Storage for Grid-Interactive Efficient Buildings

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## ABSTRACT

Buildings, as primary electricity consumers, have significant potential to provide flexibility on the demand side through their heating, ventilation, and air-conditioning (HVAC) systems. Heat pump (HP) is the key HVAC technology for electrification and decarbonization in buildings. Combined with Thermal Energy Storage (TES) system, HP can offer demand flexibility through shifting electricity load to help alleviate grid stress at peak hours. Direct-expansion HPs are widely used in residential, and light commercial HVAC systems to directly supply conditioned air to the space. In this study, an integrated conventional heat pump-thermal energy storage (HP-TES) system is proposed. The demand flexibility potential of such system largely depends on the system design and the operational control of such a system. A Modelica-based virtual testbed was first developed for one HP-TES system. The building and HP-TES systems were then simulated in the Spawn of EnergyPlus environment, addressing buildings with various load profiles under different climatic conditions. Last, the optimal control of this HP-TES system was investigated.

As a case study, we implemented an economic model predictive control (MPC) strategy for Phase Change Material (PCM) based HP-TES system, aiming to minimize operation costs and power fluctuations while maintaining comfortable indoor temperatures. The simulation results show that the HP-TES system based on PCM thermal storage has significant potential in terms of effectiveness for the power system signal response capability and reduced operating cost. When the prediction horizon is less than 12 hours, the load shifting effect increases with the increase of the prediction horizon length, thereby reducing the system operating cost; when the prediction horizon is greater than 12 hours, the selected optimization solver cannot always guarantee the reduction of the operating cost due to the increase of the computational complexity. Based on these findings, we provide tailored recommendations for advanced control strategies applicable to conventional HP-TES systems. The established virtual testbed provides an avenue for a future extension, including explorations of state-of-art TES materials and investigations of aggregated control strategies for distributed HP-TES systems, with the objective of improving the building-to-grid integration.

## 1. INTRODUCTION

Over 70% of U.S. electricity consumption is from buildings, and about 35% of building electricity usage is due to space cooling and heating (Liu et al., 2019). Meanwhile, with the rapidly increasing adoption of intermittent renewable sources for power generation, the challenge to balance the grid is enormous. Energy efficient and flexible buildings could potentially reduce energy demand and increase demand flexibility to decrease the pressure on the grid. On the other hand, intermittent renewable energy resources started to play an important role in the power grid. Therefore, there is a growing need for demand flexibility from buildings to balance dynamic net loads from both the supply and demand sides (Lu et al., 2021). Demand flexibility in buildings equipped with heat pump (HP) and active thermal energy storage (TES) systems is an effective way to provide grid-responsive support by reducing, shifting, shedding, or modulating electrical loads. (Hwang & Chen, 2022).

Heat pumps are seen as central to the global shift to electrify and decarbonize buildings. They play a key role in significantly reducing greenhouse gas (GHG) emissions, a significant portion of which come from the energy used in buildings for heating and other needs (Bae & Nam, 2021). The use of TES provides another way for buildings to optimize their energy use by reducing loads and storing excess energy for later use. By strategically charging and discharging TES during peak and off-peak hours, energy costs can be reduced while the grid is relieved. While heat pumps have been the subject of considerable research, their integration with TES remains relatively unexplored. There is a gap in both the theoretical understanding and practical application of such combined systems in building contexts, especially in areas such as system design and optimal control methodologies.

To the author's best knowledge, most studies use simple rule-based control and do not delve into the design logic behind it, while more focus is still on the configuration of the HP-TES system. On the other hand, though the advanced control techniques such as Model Predictive Control (MPC) and Deep Reinforcement Learning (DRL) have been widely studied for building energy management, there are fewer studies focusing on HP-TES system (Gado & Hassan, 2023; Sun et al., 2023). It is easy to design and implement conventional rule-based control (RBC), but the simple RBC is not able to fully explore the maximum available benefits of the HP-TES system due to its limitation to handle the highly non-linear HP-TES system and increasing dynamics and stochastics of the environment (e.g., weather, occupancy, electricity price, etc.). On the other hand, MPC, which has been studied by both researchers and practitioners (Bechtel et al., 2020; D. Blum et al., 2022; Tarragona et al., 2021), has demonstrated its capability to handle such operation environment. Hence, in this study, we propose an MPC-based control framework to optimize the operation of the HP-TES system.

The remainder of this paper is structured as follows: Section 2 outlines the configuration of the proposed HP-TES system. Section 3 presents the optimization problem formulation, including the newly developed virtual testbed and MPC controller design. Section 4 provides a detailed discussion and analysis of the results. Finally, Section 5 offers concluding remarks.

## 2. HEAT PUMP-THERMAL ENERGY STORAGE SYSTEM

### 2.1 System Configuration Description

This study focuses on the HP-TES system applicable to new and retrofitted residential buildings with an air system compatible with a conventional direct expansion heat pump unit. The design of the configuration determines how the heat pump and thermal energy storage are integrated to provide energy services in the building. An optimally designed HP-TES system can realize its full potential, resulting in significant energy cost reductions and enhanced grid service capabilities. Efficiently managing how energy is stored and charged/discharge can help take the full advantage of lower electricity rates during off-peak hours and reduce reliance on the grid during peak hours.

Existing studies have discussed various series and parallel HP-TES system configurations (Jia et al., 2023). The parallel arrangement facilitates load sharing or shifting, where demands can be split or switched between the heat pump and thermal energy storage unit. This capability is particularly useful for managing peak load conditions, increasing system efficiency, and potentially reducing energy costs. In addition, the use of a latent heat storage such as Phase Change Material (PCM) is more common and effective than a sensible heat storage in advanced configurations (Tarragona et al., 2021). Because they can be charged or discharged at a nearly constant temperature and typically have a high heat capacity, PCM materials are often considered ideal for thermal energy storage for advanced cooling applications, such as building temperature regulation and electronics cooling.

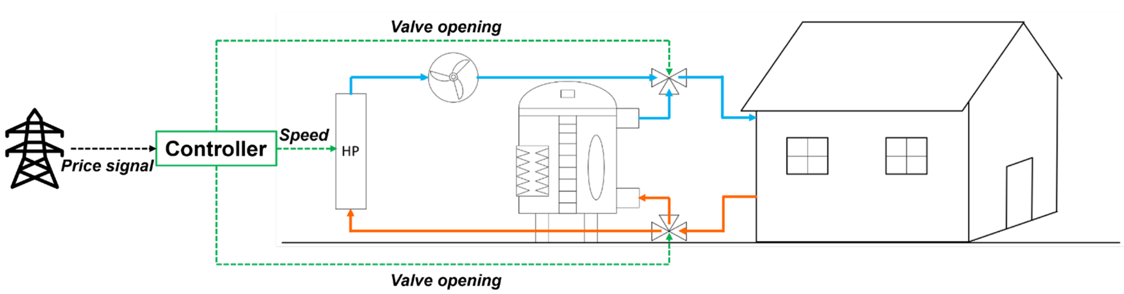



**Figure 1.** Schematic of the proposed HP-TES integration for residential buildings (Jia et al., 2023).

Therefore, we focus on an HP-TES system using a water-to-air heat pump in parallel with a PCM-based thermal storage to explore their synergistic effects on energy efficiency, operational flexibility, and grid responsiveness. The system schematic is shown in Figure 1. Taking the cooling operation as an example, by adjusting the valve opening/closing, the system can achieve three operating modes: heat pump cooling, TES charging (by heat pump), and TES discharging (cooling). This study only focuses on how to improve the demand flexibility by the switch among these modes to follow real-time building load demand and energy prices.

# 3. METHODOLOGY

## 3.1 MPC-based Operational Optimization

To optimize the operation of the proposed HP-TES system, an economic MPC control strategy is investigated. MPC is an advanced control strategy that uses a model of the system to predict future states and make optimal control decisions over a predefined future time horizon (Drgoňa et al., 2020). MPC works by solving an online optimization problem that minimizes a cost function that typically includes factors such as energy consumption, operating costs, and system performance. The optimization complies constraints and future input forecasts, ensuring that all system operations remain within established safety and operational limits. In building energy system control, MPC can be used to optimize operating costs while maintaining comfort by predicting loads and economically managing resources such as HVAC systems (D. H. Blum & Wetter, 2017; Finck et al., 2019; Fu et al., 2023).

We developed a MPC-based optimization framework to optimize the performance of various HP-TES integrations in response to external disturbances such as weather, occupancy changes, and dynamic price signals, as shown in Figure 2. The core of the MPC controller is a control-oriented model that predicts future system states, an objective function that defines the optimization objectives, and an optimizer that computes the best control actions within physical constraints. The MPC controller is developed using Julia (Bezanson et al., 2017) for high performance computational efficiency and supports different optimization solvers and is designed to enable field deployment. The virtual testbed is a simulation environment (i.e., Spawn of EnergyPlus) that co-simulates high-fidelity models of heat pumps and thermal storage unit in Modelica and building envelopes in EnergyPlus (Michael Wetter et al., 2021). Such co-simulation enables accurate and efficient model of the system's response to various operating scenarios. The interaction between Julia based controller and Spawn of EnergyPlus is implemented using Functional Mock-Up Interface (FMI), which allows for the integration between different tools (Enge-Rosenblatt et al., 2011).

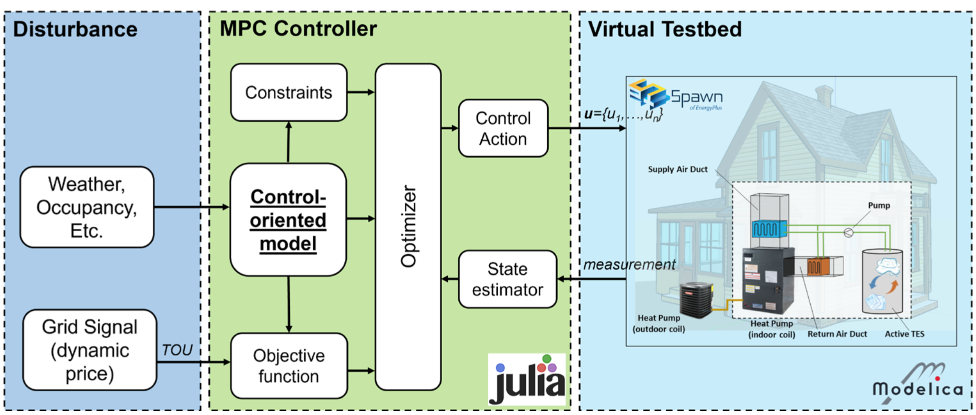



**Figure 2.** Schematic diagram of the proposed optimization framework for HP-TES system in residential buildings. A similar workflow has been also used in the literature (Shi, 2023).

Especially, to study advanced control strategies for HP-TES systems, high-fidelity models are utilized to simulate the dynamic response of the system. Since there is currently no open-source model available, we developed a reversible water-to-air heat pump model and a shell-and-tube latent heat storage tank model using the Modelica language and Buildings Library (Michael Wetter et al., 2021). Unlike existing heat pump models, the developed heat pump model uses the compressor speed as the control signal instead of the load side fluid outlet fluid temperature (Christoph et al., 2015). Our approach provides more flexibility for the control studies. The latent heat storage tank model employs the apparent heat capacity method (Mirzaei & Haghighat, 2012) and the number of transfer units (NTU) method to numerically solve the heat transfer problem in a latent TES tank. Equation (1) and (2) shows the heat exchanger effectiveness model for a tube-and-shell type storage. Furthermore, these models utilize the standard interface of the IBPSA Modelica Library (Christoph et al., 2015) and can be seamlessly integrated with other similar open-source libraries. More details of the heat pump model can be found in reference (Jia et al., 2023).

$$R_{tot} = \frac{1}{2\pi R_i L h_f} + \frac{\ln(R_0/R_i)}{(2\pi k_w L)} + \frac{\ln\{[\{\delta(R_{max}^2 - R_0^2) + R_0^2\}^{0.5}]/R_0\}}{(2\pi L k_{PCM})} \tag{1}$$

$$\varepsilon = 1 - e^{(-\frac{1}{\dot{m} c_p R_{tot}})} \tag{2}$$

## 3.2 Control-oriented Model for MPC

On-line MPC requires solving complex optimization problems through a computationally efficient approach. The control-oriented model, typically reduced-order, strikes a balance between the fidelity needed for effective control and practical considerations of the field deployment, ensuring that MPC can operate effectively in a real-world environment. Therefore, control-oriented models for all components of the proposed HP-TES system is developed.

A first-order state space model, as shown in Figure 3, is developed for the thermal dynamics of the building, which is the so-called 1R1C model. The continuous model formulation is shown in Equation (3), the state variable is zone temperature $T_z$ and disturbance includes outdoor dry bulb temperature $T_{oa}$, global horizontal solar irradiation $q_{solar}$, HVAC system output $q_{hvac}$, internal heat gain $q_{internal}$. $R_1$ and $C_1$ denote the effective thermal resistance between indoor-outdoor and effective building thermal inertia, respectively. The coefficients $a$, $b$, $c$ represents the contribution of each disturbance to the state change and need to be determined by a system identification. Using the DOE protype building model of a single-family house located in climate zone 3A, the model coefficients are identified using the results of a one-week cooling operation simulation in Atlanta. GA. Figure 4 shows the performance of the trained 1R1C model on the training and testing data sets. The Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) of the fitted model on testing data set are 1.35 and 1.64, respectively.

$$C_1 \frac{dT_z}{dt} = \frac{T_{oa} - T_z}{R_1} + aq_{HVAC} + bq_{solar} + cq_{internal} \tag{3}$$

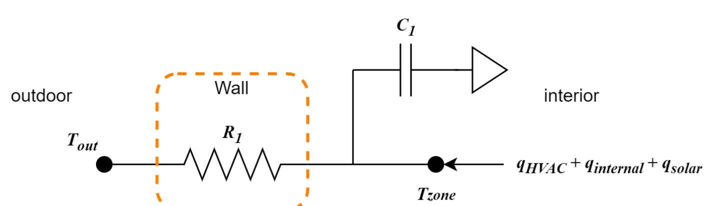



**Figure 3.** Schematic diagram of proposed 1R1C model of the building thermal model.

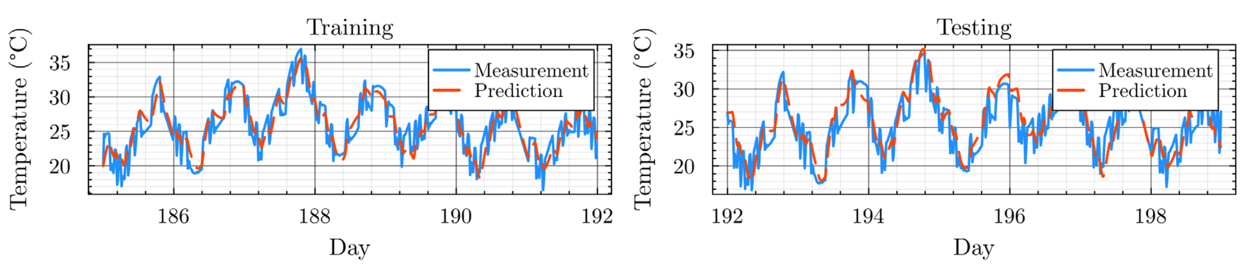



**Figure 4.** Training/testing results on the 1R1C model identification, using a two-week cooling operation data set.

For PCM based latent TES, a state space model that takes the liquid fraction as a state is developed to capture the TES dynamic response. As shown in Equation (4), the liquid fraction of TES $f_{liquid}$ is a function of PCM melting temperature $T_{melt}$, heat transfer fluid temperature $T_{htf}$, total thermal resistance between heat transfer fluid and storage material $R_{tot}$, and heat loss from storage tank to ambient $q_{loss}$. Due to the explicit modeling nature of TES, model parameters can be determined from the system design. Since only summer condition (e.g., cooling mode) is considered in this case study, the PCM material with relatively low melting point is preferred for space cooling applications. Therefore, the PCM selected here is an existing commercial product Axiotherm ATP 12 (Axiotherm GmbH, 2024); the melting point is 12 °C, fusion heat is 215 kJ/kg.

$$m_{pcm} C_{fusion} \frac{df_{liquid}}{dt} = (\frac{T_{melt} - T_{htf}}{R_{tot}} + q_{loss}) \times 100\% \tag{4}$$

The heat pump used is a 2-ton reversible water-to-air heat pump based on an existing commercial product (Trane, 2024). The heat pump operates at a constant speed with a nominal power of 1,500W and is regulated by an on/off mechanism. To reflect the impact of evaporator/condenser inlet fluid conditions on the performance, a quadratic coefficient of performance (COP) model is fitted using an open-source product data set provided by the manufacturer (Trane, 2024). The performance of fitted COP model is shown in Figure 5, with the MAE and RMSE on the testing data set being 0.34 and 0.45, respectively.

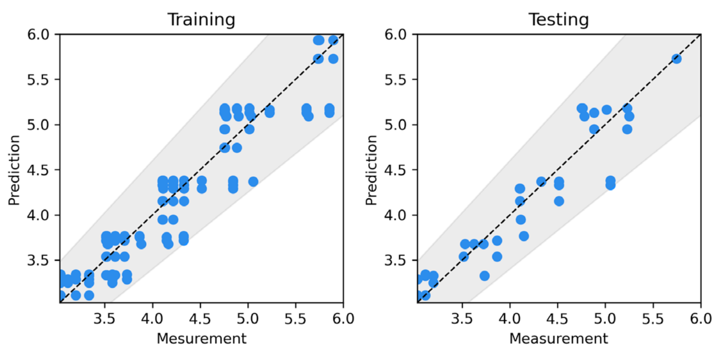



**Figure 5.** Performance of the fitted COP model, the shaded area indicates the ±15% error range.

### 3.3 MPC Problem Formulation

The objective of the MPC controller in this work is to reduce the operating cost of the HP-TES system while maintaining the thermal comfort in a single-family home. The objective function $J$ is formulated as Equation (5), which consists of three terms: operating cost, temperature deviation from the setpoint, and action slew rate. The control variable $u$ is the system operating mode: heat pump on for cooling $b_{hp,c}$, TES charging with heat pump $b_{hp,ch}$, TES discharging for cooling $b_{tes,dis}$, and idle $b_{idle}$; and the system can be in only one mode at a given time. The optimization problem is subjected to the constraints of equations (7)-(13), which correspond to the building dynamics, TES dynamics, HVAC output balance, heat pump capacity, TES heat transfer rate, liquid fraction limit, and temperature set point with slack variable for relaxation.

$$J = \min_{u^{t+k}} \sum_{k=0}^{N-1} w_1 p^{t+k} P^{t+k} \Delta t + w_2 \left\| \varepsilon_T^{t+k} \right\|^2 + w_3 \left\| \Delta u^{t+k} \right\|^2 \tag{5}$$

$$u^{t+k} = [b_{hp,c}^{t+k}, b_{hp,ch}^{t+k}, b_{tes,dis}^{t+k}, b_{idle}^{t+k}] \tag{6}$$

***s.t.***

$$T_z^{t+k+1} = RC(T_z^{t+k}, q_{HVAC}^{t+k}, q_{solar}^{t+k}, q_{internal}^{t+k}) \tag{7}$$

$$f_{liquid}^{t+k+1} = TES(f_{liquid}^{t+k}, T_z^{t+k}, b_{hp,ch}^{t+k}, b_{tes,dis}^{t+k}) \tag{8}$$

$$q_{HVAC}^{t+k} = b_{hp,c}^{t+k} q_{hp}^{t+k} + b_{hp,ch}^{t+k} q_{hp}^{t+k} + b_{tes,dis}^{t+k} q_{tes}^{t+k} \tag{9}$$

$$q_{hp}^{t+k} = g(T_w^{t+k}, T_z^{t+k}) \tag{10}$$

$$q_{tes}^{t+k} = g(T_{tes}^{t+k}, T_z^{t+k}) \tag{11}$$

$$0\% \le f_{liquid}^{t+k} \le 100\% \tag{12}$$

$$\underline{T}_z^{t+k} - \varepsilon_T^{t+k} \leq T_z^{t+k} \leq \overline{T}_z^{t+k} + \varepsilon_T^{t+k} \quad (13)$$

### 3.3 Simulation Setup

The target building is a single-family home in Atlanta, GA, located in ASHRAE Climate Zone 3A. A typical summer weather condition (June 4th) is selected to optimize the operation of the HP-TES system. The weather condition is based on Typical Meteorological Year, version 3 (TMY3) data sets. To investigate the capability of the proposed system on responding to the grid signal for demand flexibility, a three-step time-of-use (TOU) (*Xcel Energy Smart Meters And TOU Rates*, 2024) rate is used. Moreover, the internal heat gain in the single-family house is obtained from the DOE protype building EnergyPlus model. To simplify the problem, all these exogenous inputs are assumed to be perfectly known to the MPC controller, as shown in Figure 6. The indoor air temperature setpoint varies depending on whether the building is occupied or not. For the occupied period from 18:00 to 8:00, the cooling and heating setpoints are 24°C and 22 °C, respectively. The temperature setpoint is relaxed for the unoccupied period from 8:00 to 18:00, where the cooling and heating set points are 28°C and 24°C, respectively. The slack variable is set to be 1 °C. The PCM-based TES tank is designed to store a four-hour peak load with a value of around 20 kWh (Jia et al., 2023), which results in a mass of 330 kg PCM. In addition, the control step is set to be 15-min, hence there will be 96 steps in total for one day. The weight factors used in objective function are [10, 1, 10].

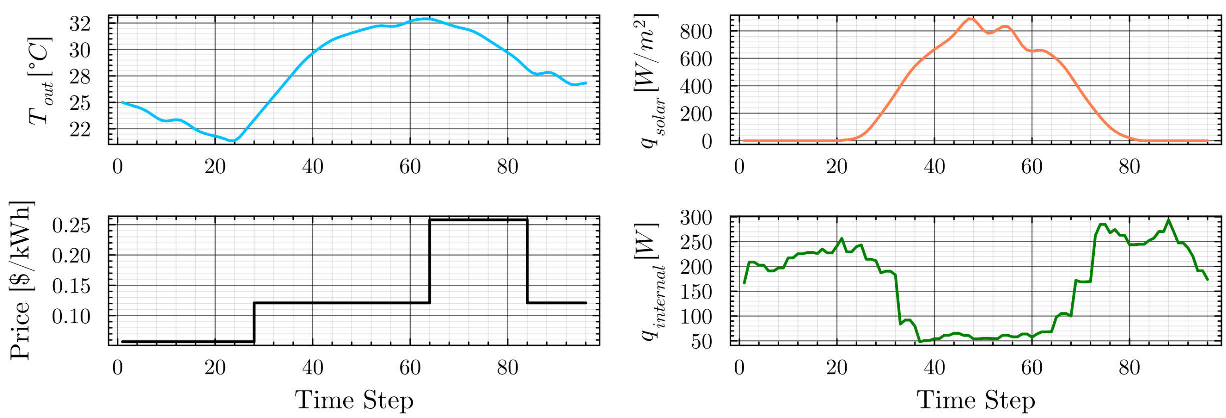
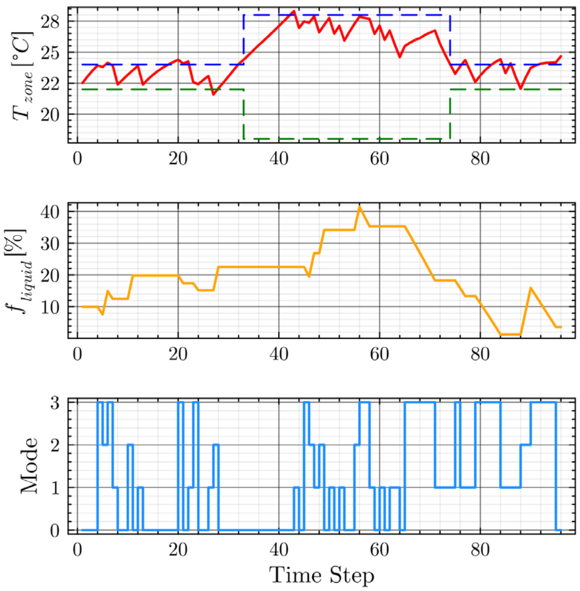



**Figure 6.** Exogenous inputs in the MPC problem: weather conditions, TOU rates, internal heat gain.

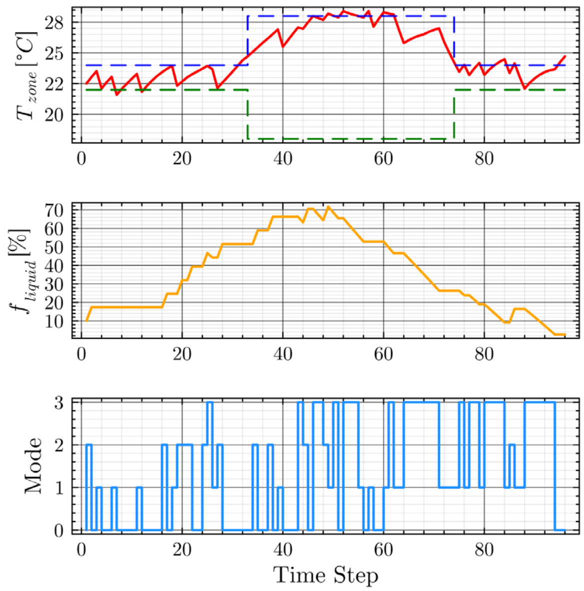
## 4. RESULTS AND DISCUSSIONS

### 4.1 Simulation Results

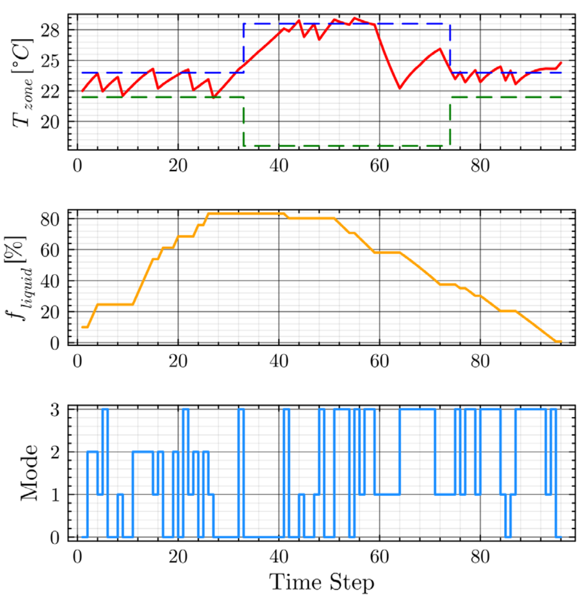
The simulation results of a one-day operation of the HP-TES system using the proposed MPC framework and virtual testbed are shown in Figure 7. To compare the influence of the prediction horizon (PH) on the MPC performance, the MPC controllers with four different PH lengths were tested under the same weather and load condition. The Figure 7 (a)-(d) shows the results using a PH of 6, 9, 12, 15 hours. The results show the zone temperature $T_{zone}$, TES liquid fraction $f_{liquid}$, and the operational mode of the system over one day. The system modes are represented by integers, where "0" means idle, "1" means heat pump for cooling, "2" means TES charging by heat pump, "3" means TES discharging for cooling. The zone temperature was well controlled in all cases, indicating the effectiveness of the MPC in maintaining comfort conditions. Minor deviations from the setpoint could be considered due to trade-offs with energy costs. Interestingly, the significant difference can be observed in the system operation mode selections, which are directly determined by the MPC controller with different PHs. The results show that the TES state of charge, as indicated by the liquid fraction, increases with the increased PH. The main reason may be that the longer PH should allow the MPC to plan for both weather and TOU rates far in advance, resulting in more efficient use of energy storage and shift the operation of the heat pump to off-peak hours to take the advantage of lower electricity rates for cost savings.



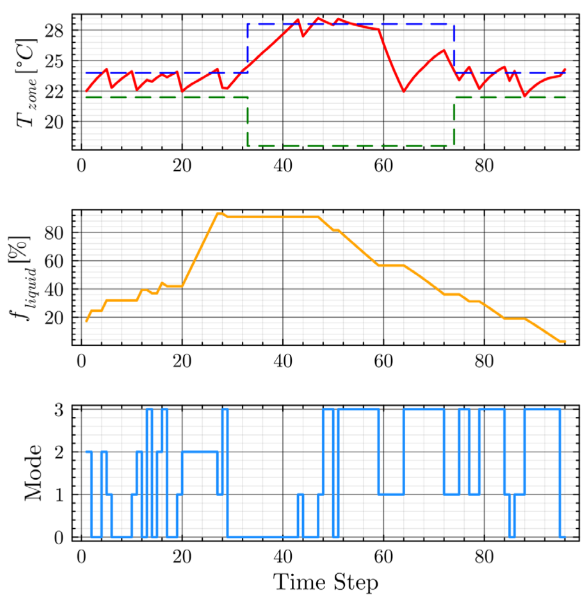

(a) Results with PH of 24 steps (6 hours)




(b) Results with PH of 36 steps (9 hours)




(c) Results with PH of 48 steps (12 hours)




(d) Results with PH of 60 steps (15 hours)

**Figure 7.** The results of a one-day simulation with a dynamic TOU rates scenario during a typical cooling period. Four cases with different prediction horizons are performed, assuming perfect prediction of ambient temperature, solar irradiation, and internal heat gains.

### 4.2 Discussions

Figure 8 shows typical performance metrics used to evaluate the control performance of the MPC controller, including thermal discomfort, maximum temperature deviation, and operating cost. This result indicates a complex relationship between the PH length and its impact on the controller performance, without straightforward correlation. PH24 appears to manage immediate thermal comfort better, but at the cost of higher operating costs. This suggests that the MPC may be using more aggressive cooling measures to maintain room air temperature, which may not be economically sustainable. PH36 and PH48 show a trade-off between the comfort and the operating cost, with PH48 achieving the lowest operating cost. This may indicate a sweet spot where the controller has enough foresight to plan for efficient energy use while still responding effectively to immediate conditions. However, PH36 shows that even within intermediate prediction horizons, slight increases in PH can degrade the comfort performance, highlighting the sensitivity of the system to the prediction horizon. While PH60 provides the best performance in controlling peak temperature deviations, it does not provide the lowest operating costs or the best overall comfort. The longer prediction horizon may allow for more efficient planning against temperature spikes, but it does not translate into overall comfort or cost improvements. This suggests diminishing returns to extending the PH length, possibly due to increased prediction uncertainty from reduced order models. Results also indicate that the MPC's performance in this study can degrade if the prediction horizon is too short due to a lack of planning, or too long due to prediction uncertainties that may undermine the control strategy's effectiveness.

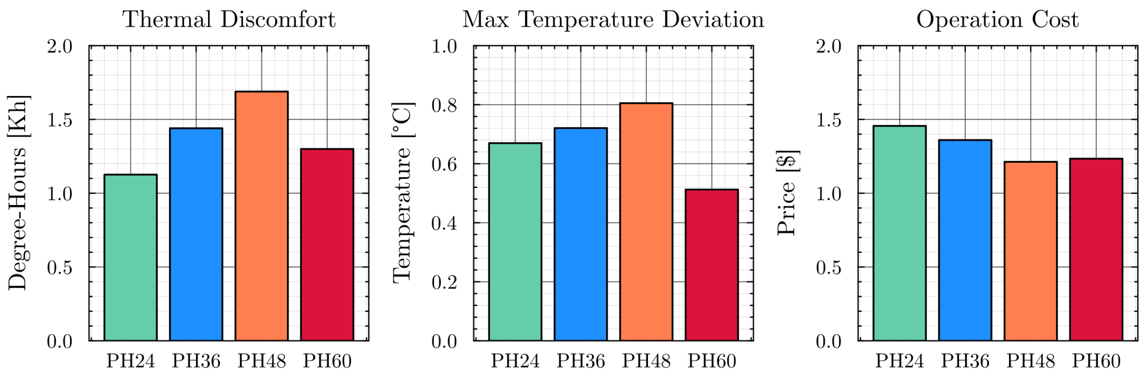



**Figure 8.** MPC control performance results for different prediction horizons.

Therefore, it is concluded that in this case, the effectiveness of an MPC strategy is highly sensitive to the choice of prediction horizon, and that there is no one-size-fits-all solution. A shorter horizon may lead to better immediate comfort but at a higher cost, while an intermediate horizon could balance cost with long-term comfort and efficiency. The longest horizon doesn't necessarily guarantee the best results, as it may introduce potential uncertainty. The optimal prediction horizon should depend on the model performance and control time step length; therefore, it must be carefully calibrated to the specific operational dynamics, the reliability of input data over different time scales, and the balance of objectives in the controller design.

## 5. CONCLUSIONS

This work focused on investigating the optimal control of one heat pump thermal energy storage (HP-TES) system. A Modelica-based simulation framework is developed for the performance evaluation of a PCM-based HP-TES system. Using the platform, a case study was set up where the building and HP-TES systems were both simulated in the Spawn of EnergyPlus environment. The economic model predictive control (MPC) technique was applied to find the economically optimal operation of the HP-TES system. The goal is to minimize operating costs while maintaining comfortable indoor temperatures. The simulation results show that the HP-TES system with PCM thermal storage is promising in terms of its effectiveness in improving the power system's signal response capabilities and reducing operating costs. Based on these results, we could provide specific suggestions for advanced control strategies that can be used in conventional HP-TES systems.

For limitations and future work, first, exogenous inputs such as outdoor temperature and solar irradiation are assumed to be perfectly predicted; however, this assumption may be difficult to achieve in real life deployment. Therefore, to deal with the uncertainties arising from the prediction of exogenous inputs, we will develop a robust algorithm that takes into account the prediction uncertainties. Second, the MPC algorithm proposed in this study has only been tested in simulation environment, how to integrate the controller into real equipment will be out next step.

## NOMENCLATURE

| | | |
|---|---|---|
| $b$ | system mode | (-) |
| $c$ | specific heat | (kJ/(kg K)) |

| | | |
|---|---|---|
| $C$ | thermal capacitance | (J/K) |
| $f$ | fraction | (%) |
| $h$ | heat transfer coefficient | (W/(m$^2$ K)) |
| $J$ | objective function | (-) |
| $k$ | thermal conductivity | (W/(m K)) |
| $L$ | tube length | (m) |
| $\dot{m}$ | mass flow rate | (kg/s) |
| $P$ | power | (W) |
| $p$ | electricity rate | ($/kWh) |
| $q$ | heat flow rate | (K/W) |
| $R$ | thermal resistance | (K/W) |
| $t$ | time | (s) |
| $T$ | temperature | (°C) |
| $u$ | control action | (-) |
| $w$ | weight factor | (-) |
| $\delta$ | phase change fraction | (-) |
| $\varepsilon$ | heat exchanger effectiveness | (-) |
| $\varepsilon_T$ | slack variable | (°C) |

**Subscript**

| | |
|---|---|
| *c* | cooling |
| *ch* | charging |
| *dis* | discharging |
| *hp* | heat pump |
| *htf* | heat transfer fluid |
| *liquid* | liquid phase |
| *oa* | outdoor air |
| *tes* | thermal energy storage |
| *w* | water |
| *z* | zone |
| *HVAC* | Heating, Ventilation, and Air Conditioning |
| *solar* | solar irradiation |
| *internal* | internal gain |

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