CONTROL OPTIMISATION OF A LATENT THERMAL ENERGY STORAGE - HEAT PUMP SYSTEM FOR SPACE HEATING IN NORDIC CLIMATE

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Abstract

This study develops a hierarchical control framework for integrating phase change material thermal energy storage (PCM-TES) with heat pump systems for residential space heating in Nordic climates. The control architecture aims to optimise charging and discharging sequences of the PCM-TES to balance thermal comfort, operational costs, and grid flexibility services. A 42 kWh PCM-TES unit coupled with an 18 kW ground source heat pump is installed at the KTH Live-in-Lab (LIL) testbed, with control algorithms processing real-time temperature measurements, heating demand signals, and electricity price data. The framework employs a supervisory high-level control layer for operational mode selection and a component low-level control layer for actuator management. Charging sequences strategically store thermal energy during low electricity price periods, while discharging sequences ensure reliable heat delivery during peak demand or high electricity price periods. The control framework provides practical strategies for flexible sector coupling in residential buildings, supporting renewable energy integration and Nordic decarbonization goals.

Keywords: thermal energy storage (TES), phase change material (PCM), heat pump (HP), control strategy, renewable energy integration, flexible sector coupling (FSC)

1. Introduction

The decarbonization of building heating systems is a critical pathway to achieving climate neutrality goals, while also providing essential flexibility services to electricity grids facing increasing renewable energy penetration. European buildings account for 40% of total energy consumption and 36% of greenhouse gas emissions (European Climate Foundation, 2022), presenting both a significant challenge and a substantial opportunity for decarbonization efforts. The building sector must achieve 60% emissions reductions by 2030 and complete decarbonization by 2050 to meet EU climate objectives (European Climate Foundation, 2022).

Sweden exemplifies the potential for building sector flexibility provision within Nordic climate contexts. Residential structures consume 22.2% of national final energy demand, with space heating and domestic hot water representing approximately 66% of household energy usage (IEA, 2025). Similar trends are observed internationally, with space heating representing 34% of household energy use in New Zealand (Zhou et al., 2025) and over 40% of building energy consumption attributed to space heating and hot water in the UK (Olympios et al., 2022). This concentration of thermal energy consumption across different regional contexts establishes significant opportunities for implementing demand response strategies and cross-sectoral energy coordination.

Swedish renewable energy policy targets 5-10% of electricity supply from photovoltaic generation by 2040, representing 7-14 TWh annually (Swedish Energy Agency, 2023). This substantial expansion of variable solar generation and wind energy necessitates sophisticated flexibility mechanisms, particularly within the building sector where thermal storage capabilities can effectively mediate temporal mismatches between generation availability and consumption requirements (Abdur Rehman et al., 2021).

Thermal energy storage (TES) systems offer significant potential for cost reduction and load management in residential heating applications. Studies suggest that coupling heat pumps with TES could reduce operational costs by as much as 10% (Zhou et al., 2025). Furthermore, electricity peak loads of the buildings can be reduced by 25% to 45% by shifting heating and cooling loads to off-peak hours using thermal energy storage (Erdemir

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& Dincer, 2019). Among TES technologies, phase change material thermal energy storage (PCM-TES) offers enhanced capabilities for temporal energy shifting due to its high energy density characteristics and isothermal heat release properties (Tyagi & Buddhi, 2007). When integrated with heat pump systems, PCM-TES enables strategic electricity consumption during optimal renewable generation periods while maintaining continuous demand delivery through stored energy during generation deficits, being the flexibility enabler in the system. However, realising these theoretical benefits requires sophisticated control architectures capable of managing the complex thermodynamic behaviour of the storage while optimising multiple competing objectives, including energy efficiency, operation cost minimisation, and grid support strategies.

Model predictive control (MPC) strategies have shown promise for building energy systems but require accurate thermal models and significant computational resources (Drgoňa et al., 2020). Rule-based control approaches offer computational simplicity and transparent decision logic but may lack adaptability to changing conditions and optimal performance across diverse scenarios (Yasaman Balali et al., 2023). The study aims to develop a comprehensive hierarchical control framework for PCM-TES systems integrated with a heat pump in residential applications. The proposed control architecture incorporates charging and discharging sequence management with the building management system to provide seamless space heating delivery while maximising grid flexibility services. The framework is designed for implementation at the KTH Live-in-Lab (LIL) testbed and will be evaluated using actual building heating demand, using a sophisticated rule-based control discussed in the results, and then incorporating advanced control, including MPC in the future.

2. Methodology

The section provides a detailed configuration of the integrated heat pump and PCM-TES system, along with a control system architecture and method for evaluation for the control sequence.

2.1 KTH Live-in-Lab System Configuration

The chosen KTH Live-in-Lab (LIL) testbed at KTH (called Testbed KTH) provides a residential-scale platform for evaluating building energy technologies under realistic operational conditions. The presented system in this work integrates a PCM-TES unit with a nominal storage capacity of 42 kWh and a ground-source heat pump with a nominal heating capacity of 18 kW to an air-handling unit (AHU) in Testbed KTH that provides space heating for four student apartments. The PCM-TES contains 515 encapsulated PCM capsules containing RT57HC with a void fraction of 0.56. Figure 1 represents the piping and instrumentation diagram illustrating the complete system architecture and component interconnections.

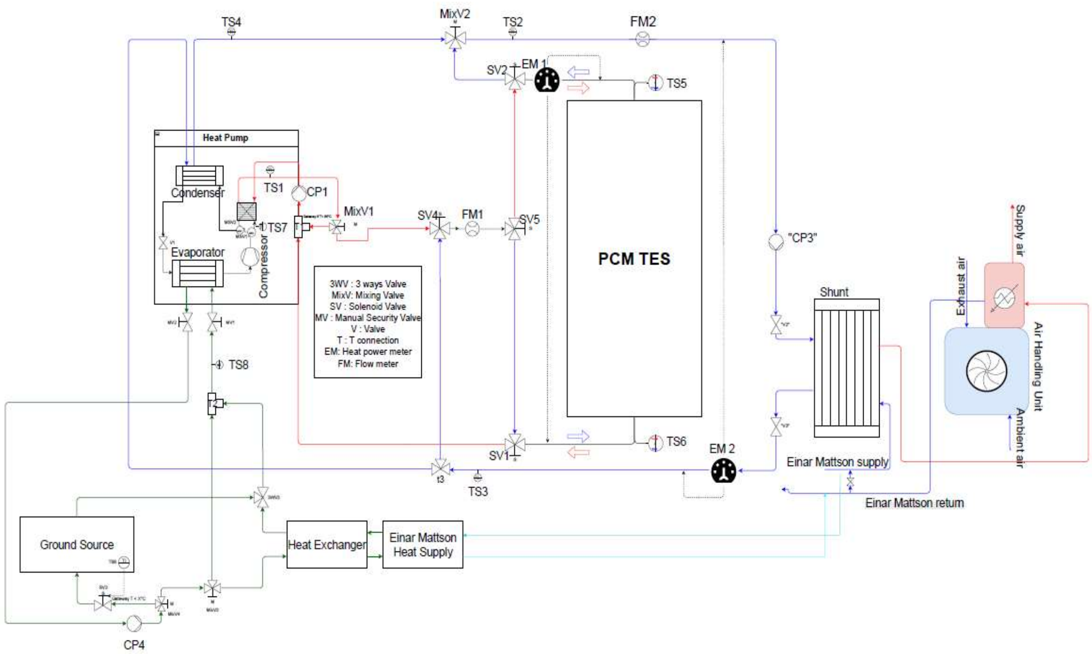

Figure 1: Detailed Piping and instrumentation diagram (P&ID) for the Testbed Live-in-lab system showing the heat pump, PCM-TES, shunt and the AHU

As shown in Figure 1, the heat pump system consists of a custom-installed desuperheater and a condenser that provide heat input to the PCM-TES and to the AHU, respectively. The heat pump circuit incorporates a desuperheater that can be activated via two solenoid valves (SV1, SV2, Figure 1) to direct high-temperature refrigerant for PCM-TES charging operations, before passing into the condenser. The PCM-TES vessel serves as the central thermal storage component, featuring inlet and outlet connections that enable bidirectional flow depending on charging (top-to-bottom) or discharging (bottom-to-top) mode. Flow direction to and from the storage is managed through mixing valves (MixV1, MixV2, Figure 1) that can route heat transfer fluid through the PCM-TES in charging or discharging.

The AHU provides space heating delivery through an air-water heat exchanger. Supply air is heated by the water heated by the PCM-TES and the heat pump. A shunt with a water-to-water heat exchanger is used to exchange heat with the PCM-TES and the condenser-based input, enabling temperature regulation of the supply water to the AHU heat exchanger. The Einar Mattson heating connection (bringing heat from a borehole field connected through a external heat pump) serves as a backup heat source when primary sources are insufficient or unavailable, ensuring continuous heating capability regardless of the heat pump or PCM-TES status.

Multiple circulation pumps (CP1, CP3, CP4, Figure 1) enable heat transfer fluid (HTF) movement through different circuit sections, with pump operation coordinated based on the active heating mode. Temperature sensors are strategically positioned throughout the system: TS1 measures desuperheater water outlet temperatures, TS4 measures condenser outlet temperature, TS5-TS6 track PCM storage inlet and outlet conditions, and TS2 and TS3 measure the temperature in and out of the shunt. Flow meters (FM1 & FM2) provide volumetric flow rate measurements, essential for energy calculations and control decisions. This comprehensive instrumentation enables continuous monitoring of system state and provides the measurement inputs necessary for control algorithm execution.

2.2 Control System Architecture

The proposed control framework implements a hierarchical architecture comprising high-level supervisory control and low-level component control layers. The high-level controller functions as the decision-making layer, determining operational modes based on heating demand signals, PCM-TES status, heat source availability, and external conditions such as electricity prices, as shown in Figure 2. This layer evaluates system state information and selects appropriate operating strategies to meet heating requirements while optimising for cost and flexibility objectives.

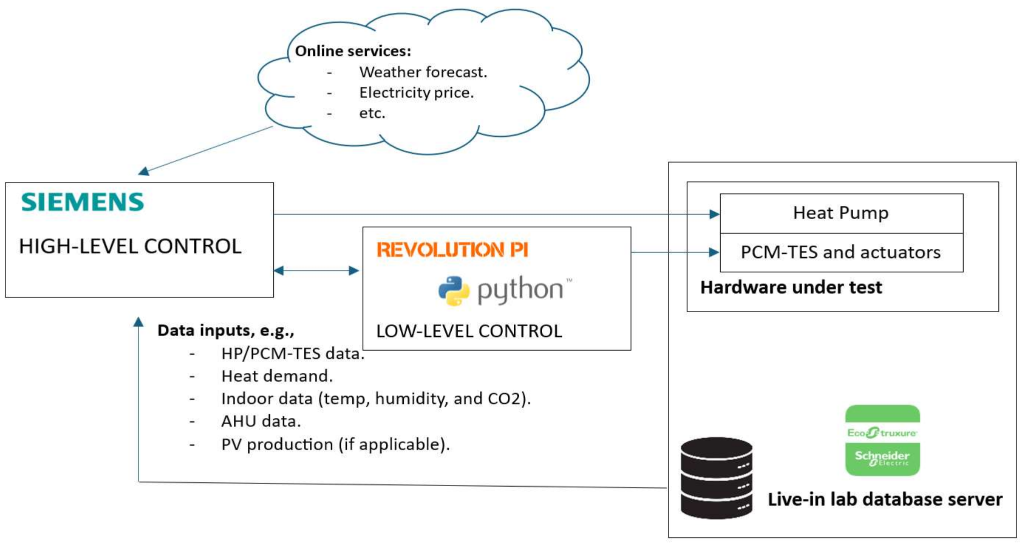

Figure 2: Control system architecture framework

The low-level control layer translates high-level mode decisions into specific actuator commands and setpoint values. This layer manages valve positions (mixing valves, solenoid valves, three-way valves), the operation of circulation pumps (including on/off states and flow rate changes through frequency modulation), and temperature setpoints for different system components. The low-level controller executes the detailed sequences required to implement charging and discharging operations.

Control objectives encompass multiple priorities that must be balanced during operation. Primary objectives include maintaining indoor thermal comfort by ensuring adequate space heating delivery and responding promptly to changes in heating demand. Secondary objectives focus on economic optimisation by preferentially utilising low-cost electricity periods for charging PCM-TES while meeting heating requirements in high-cost periods by discharging the PCM-TES, enabling peak shaving. Tertiary objectives address grid flexibility by shifting electricity consumption away from peak demand periods and maximising the use of renewable electricity when excess is available on the grid.

The control framework processes multiple input signals to inform decision-making. Temperature measurements from sensors throughout the system combined with the HTF flow measurements provide continuous state information about heat pump operation, storage conditions, and building heating demand. A key characteristic of the storage conditions used in this control process is the State-of-Charge of the PCM-TES. Heating demand signals from the building management system (BMS) indicate when space heating is required and at what intensity. External inputs, including electricity price signals (obtained from e.g. (Vattenfall, 2025) and weather data enable demand response functionality. The framework outputs control signals to actuators, including valve position commands, pump control signals, and operational mode selections for the heat pump system.

2.3 Proposed Control Sequences

Two primary control sequences form the core of the proposed framework: charging and discharging. The charging sequence manages thermal energy transfer from the heat pump to the PCM storage during favourable conditions, such as low electricity prices. The discharging sequence governs prioritized energy extraction from storage to meet building heating demands while maintaining adequate supply temperatures as well as limited to no operation of the heat pump. Each sequence incorporates decision pathways, sensor monitoring, actuator control, and transition criteria. Detailed control logic flowcharts and operational descriptions are formulated considering all possible input/output conditions, which are presented in the results section.

The control framework evaluation utilises historical heating demand data from the Testbed KTH in KTH LIL facility spanning three years of operation (2022-2025). This dataset captures realistic residential heating patterns, including daily variations, weekly cycles, and seasonal changes characteristic of Nordic climate conditions, as seen in Figure 3. The demand profiles exhibit peak heating requirements during winter months, reduced loads during intermediate seasons, and minimal heating needs during summer periods. Figure 3 also shows the price volatility alongside slight changes in demand on that particular day, which is essential when the objective is to achieve peak price shaving; hence, it becomes important to choose some days where we see variability in both demand and price, unlike in this graph, where the demand does not show any significant changes.

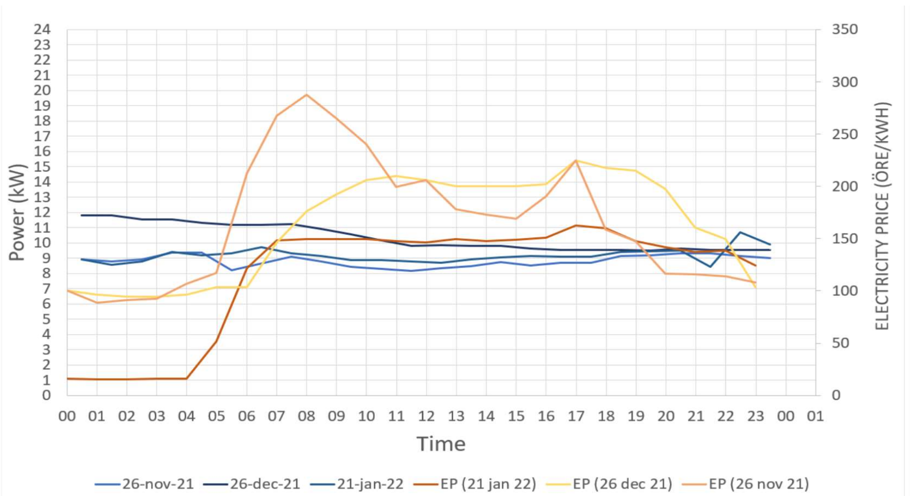

Figure 3: Electricity price and demand variation for some chosen days

Electricity price data is integrated to evaluate the control framework's economic optimisation capabilities. Hourly electricity prices reflecting Nordic market conditions are used to identify favourable charging periods and quantify potential cost savings through strategic thermal storage utilisation. Price variations throughout the day create opportunities for load shifting where thermal energy storage charging occurs during low-price periods and discharging serves heating demands during high-price periods. Electricity prices used in the analysis are spot prices, exclusive of the taxes, which include a VAT (fixed to 25%) and an energy tax. VAT and energy tax comprise of 40% of the total electricity costs in the Swedish state (Vattenfall, 2025).

Multiple case scenarios can be developed to demonstrate control framework functionality across diverse operating conditions. Representative scenarios include typical winter day operation showing standard charging and discharging cycles, testing system response to peak heating demands and periods with high electricity price volatility demonstrating economic optimisation capabilities and also one day in the transitional season with low demand but high price volatility . Each scenario exercises different aspects of the control logic and demonstrates the framework's adaptability to varying operational requirements.

The control framework evaluation employs three representative days with distinct demand patterns and electricity price profiles to demonstrate the system's adaptive capabilities across diverse operational conditions. These scenarios were developed in a simplified Excel-based model which uses actual data from the KTH LL facility's AHU, with heating demand calculated from measured air flow rates and the temperature differential between inlet and outlet air streams. The data for a given day's electricity prices uses the hourly spot prices for that day. For the heat input of PCM-TES real experimental data showing power delivered for a certain flow rate (0.15 m^3/h) and temperature limits (35 °C to 65 °C) is used. Condenser input is assumed to cover the whole demand when PCM-TES is not being used. The charging of PCM-TES is done by the desuperheater, whose input is assumed to be 25% of the condenser. State of charge (SOC) estimation is performed using eq. 1 , which gives instantaneous power, which can be calculated for the given time step using inlet and outlet temperatures from the PCM-TES and the flow rate. In the control logic sequence, the algorithms should also include the PCM temperatures when estimating SOC, but as the experimental data used in the simulation lacked some PCM temperatures, simplified SOC using just the HTF temperatures can be calculated, using both eq.1 and eq.2.

$$P(t) = \dot{m}(t) * c_p * (T_{outlet} - T_{inlet}) \qquad \text{(eq. 1)}$$

Where $P(t)$ = Instantaneous power (W)

$\dot{m}(t)$ = Mass flow rate of HTF (kg/s)

c_p = Specific heat capacity of HTF (J/kg*k)

$$SOC = Q_{stored}/Q_{max} \qquad \text{(eq. 2)}$$

Where Q_{stored} = Current energy stored in the PCM-TES

Q_{max}= maximum energy stored in the PCM-TES (for a given temperature limit, which in this case is 35-65 °C)

3. Results and Discussion

This section contains control logic diagrams that represent a sophisticated rule-based control system for both charging and discharging. It also includes a simulation of PCM-TES charging/discharging with heat pump operation over days across different parts of the year to capture varying heating demands and electricity prices.

3.1 Charging Control sequence

The charging control sequence implements a systematic decision logic to manage heat input from the heat pump to the PCM-TES during favourable operational conditions. The sequence initiates when multiple criteria are satisfied simultaneously: electricity prices fall below a predetermined threshold, and the PCM-TES SOC indicates an available capacity (also at a pre-set margin). The charging process utilizes the desuperheater configuration where solenoid valves SV1 and SV2 open to allow high-temperature refrigerant from the heat pump compressor to flow through the desuperheater, i.e., the dedicated heat exchanger, as illustrated in .

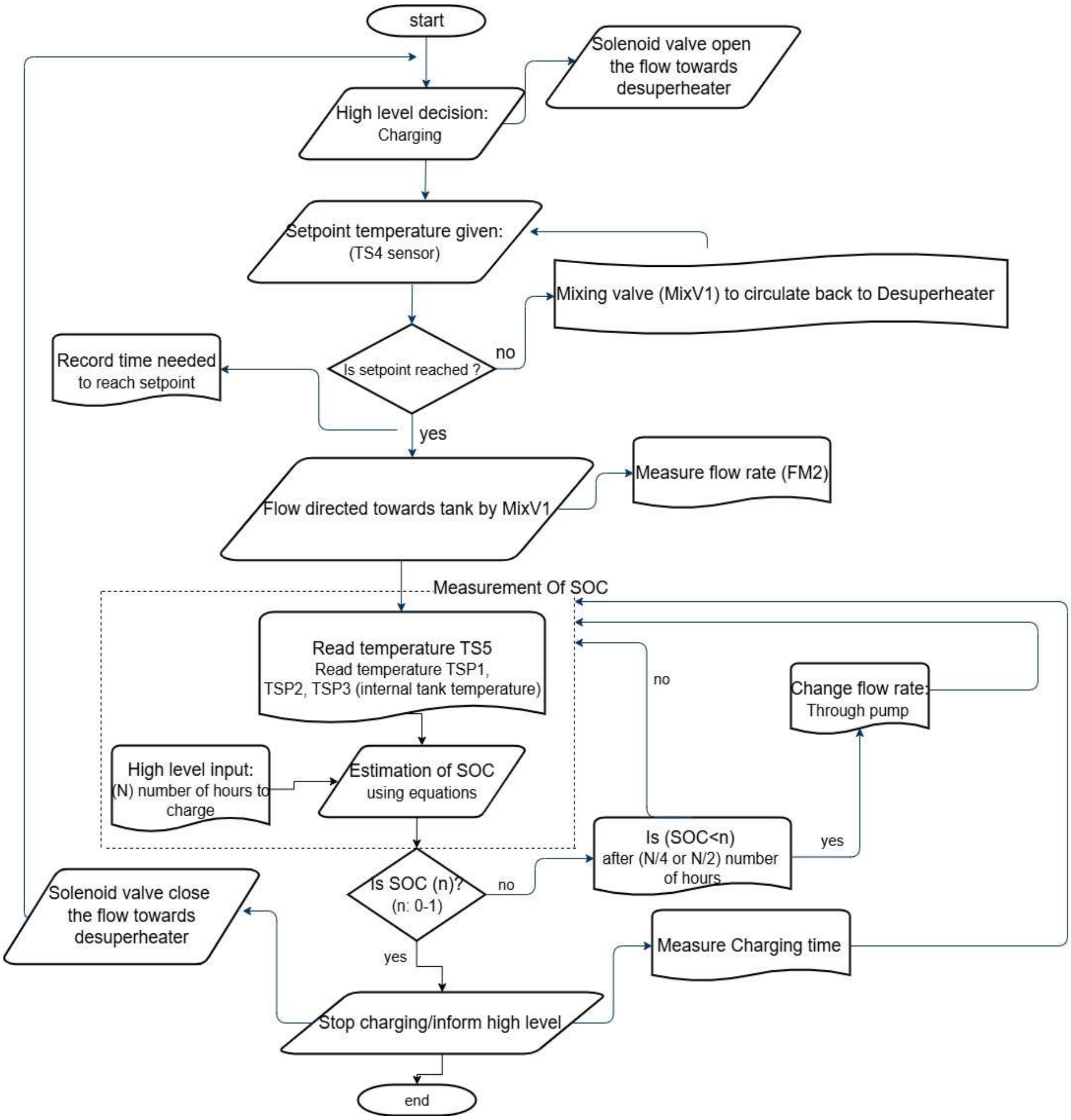

Figure 4: Charging control flowchart showing key steps and decisions

During active charging operation, the heated water from the heat exchanger outlet must meet specific temperature requirements before entering the PCM storage tank. A critical temperature control valve, positioned before the tank inlet, monitors the water temperature and permits flow into the PCM-TES only when the water temperature reaches the predetermined setpoint. This temperature regulation is essential for effective charging, as if the water temperature is too low, compared to the phase change temperature, it would not be beneficial for charging. The control valve modulates to maintain optimal inlet temperatures, typically 5-10 °C above the PCM melting point, ensuring efficient heat transfer. The system continuously monitors charging power by calculating the temperature differential between storage inlet and outlet (TS5-TS6) and by the measured flow rate from FM1, enabling real-time assessment of energy transfer rates.

The SOC estimation algorithm tracks the cumulative energy transferred to storage, accounting for the PCM's phase transition characteristics and thermal losses. SOC algorithms take into account both PCM and HTF temperatures inside the tank. The charging sequence is terminated when the SOC reaches its maximum value or when the outlet temperature is in within 1-2 °C of the inlet temperature. Post-charging procedures ensure a smooth transition to subsequent operational modes by controlling the operation of the heat pump, which involves closing solenoid valves SV1 and SV2 to bypass the desuperheater circuit.

Different charging scenarios can be developed, most of which involve setting the setpoint temperature for the MixV1 valve to open towards the PCM-TES. As mentioned before (section 2.1), the setpoint cannot be too low relative to the phase change temperature range, which is 57-60 °C. Thus, a slightly lower temperature, around 55 °C, is used to heat the system initially, as the return temperature (TS6) is too low at the start of the charging process and the set point is increased gradually when the return temperature increases. Hence, the setpoint can be set as a function of return temperature to minimise the charging time.

3.2 Discharging Control sequence

The discharging control sequence governs the extraction of stored thermal energy from the PCM-TES and the heat pump (condenser) output to meet the building heating demand while maintaining adequate supply temperatures and maximising system efficiency. Discharge initiation occurs when the BMS signals heating demand coinciding with high electricity price periods to the high-level control, provided the PCM-TES maintains a sufficient SOC. The control framework implements a hierarchical heat source selection logic that prioritises PCM-TES utilisation when adequate charge and temperature are available, followed by direct heat pump operation if electricity prices permit, and finally engages in the sequence as shown in Figure 5.

The valve positioning sequence establishes the discharge flow path by configuring MixV2 to route heat transfer fluid from the PCM-TES to the shunt, with an opening percentage maintained to achieve a specific setpoint at TS2. The high-level controller has already given a temperature setpoint for the condenser forward temperature. Both of these setpoints are key operating setpoints for the discharge scenario, as they determine the amount of heat extracted from the PCM-TES. The PCM-TES does not have a uniform temperature discharge, especially with higher temperatures in the beginning and lower temperatures towards the end. So, to reach a setpoint, it is necessary to strategically open the mixing valve and get to the required temperature needed in the shunt. The shunt enables precise supply temperature regulation by controlling the flow rate through the circulation pump CP3, which can be increased or decreased to meet the demand, helping ensure optimal heat delivery to the AHU. In conditions when PCM-TES and heat pump discharge alone cannot meet heating demands, the Einar Mattson system is used as a backup supply.

The control algorithm tracks PCM-TES SOC depletion using an energy balance approach that accounts for heat extraction rates and thermal losses using PCM and HTF temperature sensors. Supply temperature to the AHU is maintained within specified bounds through dynamic adjustment of the mixing valve opening position (MixV2) and changing the pump speed (CP3), responding to variations in return temperature (TS3) and heating demand intensity. The discharge sequence incorporates intelligent mode transition capabilities that automatically increase the forward setpoint temperature from the heat pump condenser by adjusting compressor speed when PCM-TES SOC approaches minimum thresholds or when more economical heating options become available.

Discharge termination occurs through multiple pathways: satisfaction of heating demand as signalled by the BMS, SOC reaching the minimum operational threshold, or activation of maintenance or safety override protocols such as high return temperature from the shunt. The post-discharge sequence, which is the sequence of tasks that should take place as the discharge cycle has ended, ensures orderly system reconfiguration by sequentially repositioning valves, such as solenoid valves in the desuperheater refrigerant circuit, to initiate the charging cycle.

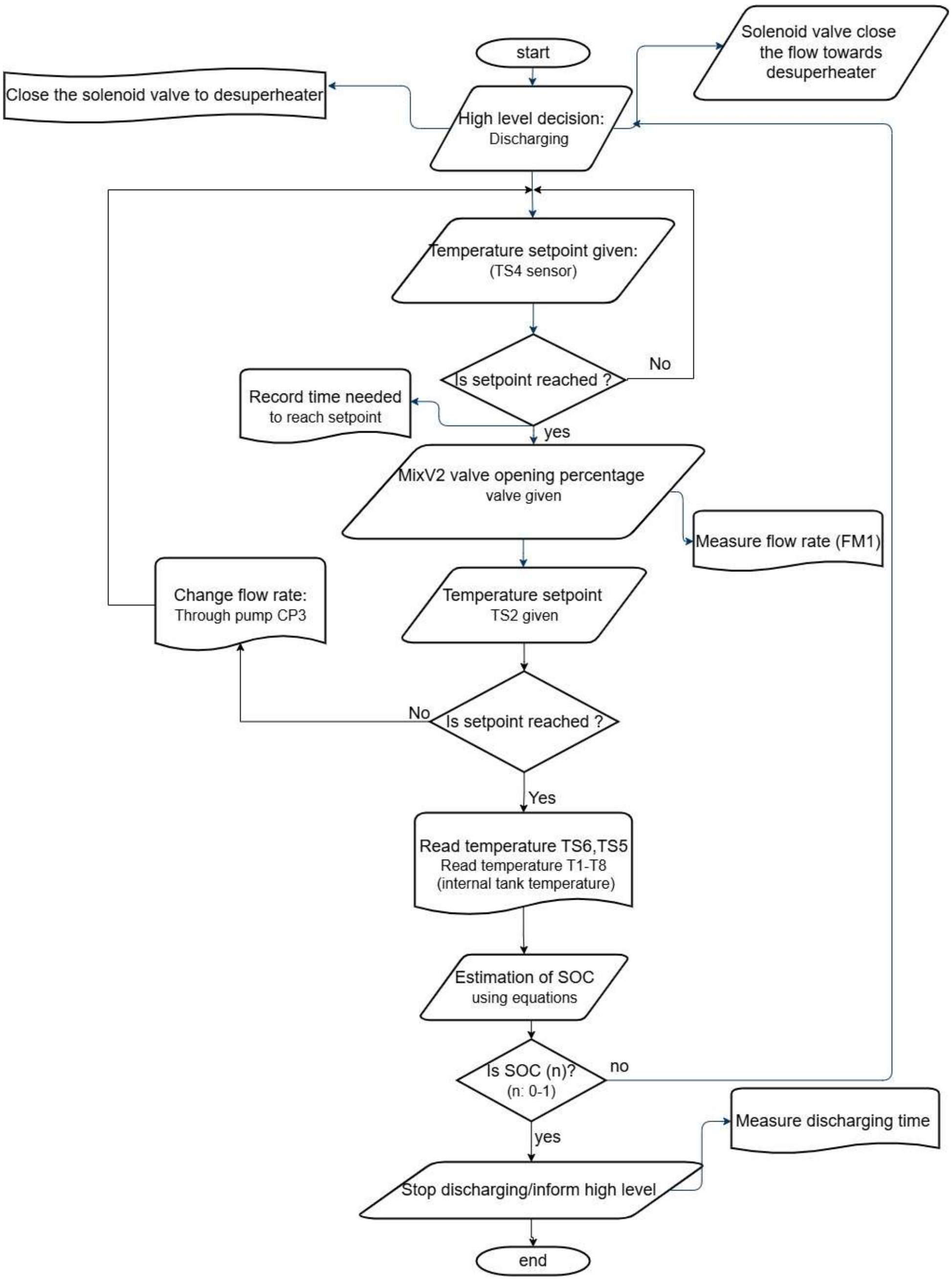

Figure 5: Discharging control flowchart showing key steps and decisions

3.3 Control Performance Analysis Across Seasonal Scenarios

Demonstrations of operation across three representative operational scenarios show its adaptive capability in managing the PCM-TES and heat pump system under varying demand and electricity price conditions. Each scenario presents unique challenges that test different aspects of the control logic, from high winter demand management to transitional season optimisation. The graphs shown below in (figure 6, figure 7, figure 8) illustrate the temporal evolution of key system parameters, including heating demand (kW), electricity price (Öre/kWh), and heat pump operation status over 24-hour periods. These graphs illustrate charging and discharging strategies that can be developed using the control framework discussed in Sections 3.1 and 3.2, along with the assumptions and equations explained in Section 2.3.

The January 7th 2024 winter scenario exhibits sustained high heating demand ranging from 5-10 kW throughout the day, with characteristic morning and evening peaks corresponding to occupancy patterns as seen in Figure 6. The execution of charging cycles should be done strategically during the morning, as the electricity prices are low from 00:00 to 12:00, which can be seen as the desuperheater input in Figure 6. In this case, interestingly, both the electricity peak and demand peak coincide, making it a perfect case for the use of PCM-TES, which can be seen between 14:00 and 20:00. The decrease in condenser heating input can also be seen in the same period, simultaneously demonstrating the supplement of heat input from PCM-TES. Many strategies can be used in this case, including shutting down the heat pump during the high-demand period and using only the PCM-TES, which would then cover only 2-3 hours of peak demand rather than supplementing the heat pump throughout the extended 6-hour period from 14:00 to 20:00. The PCM-TES starts discharging at 14:00 with a SOC of 93% and decreases to around 48% at 18:00. The total power delivered by the PCM-TES in the high-demand, high-price period is 49 % of total demand in that period (14:00-20:00)

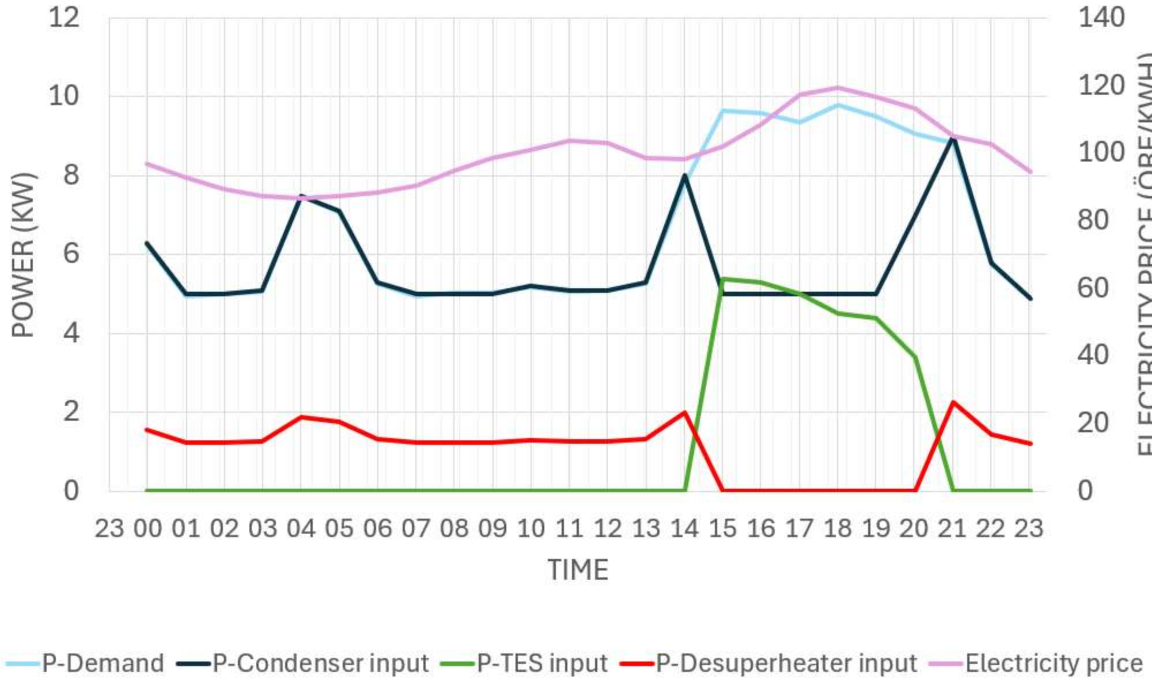

Figure 6: January 7th 2024 demand data from LIL showing strategic scenarios of charging and discharging the PCM-TES

The December 24th 2021 scenario presents regular demand patterns of around 11 kW the whole day (Figure 7) in sharp contrast of the previous case (Figure 6). Electricity prices also show heightened volatility, with extended peak periods from 14:00-17:00 and 7:00-12:00. In this case, it is advisable to determine PCM-TES discharge based on electricity prices. Therefore, implementing an aggressive charging strategy during the low-demand evening period and night period despite moderate electricity prices is interesting, as can be seen by the desuperheater input in Figure 7. The PCM-TES discharge is split into 2 phases to capture the two distinct price peaks in the day, with the heat pump input being decreased at the exact times to maximise the economic gain. Thus, 41 % of the total demand in this period is being met by the PCM-TES, which is still sufficient, as this day represents the coldest day with a high consistent demand persisting over the whole day, in 2021. This scenario truly highlights the need to strategically discharge the PCM-TES at the right time so as to maximise the advantage of having a storage.

The October 26th 2023 transitional season scenario showcases highly variable conditions with heating demand fluctuating between 4-5 kW. Electricity prices exhibit a pronounced pattern with high volatility, with low prices at night and high prices throughout the day. The control needs to capitalise on these price variations through using the PCM-TES during the high price period, 15:00 to 20:00. As this is the transitional season with the demand not being that high, the heat pump can be turned off with PCM-TES taking care of the demand itself by covering 82% of the total demand in this period and the remaining demand is fulfilled by the heat pump, as shown in Figure 8. This shows a difference in the operational approach as compared to the previous two scenarios, where PCM-TES was used as a supplement to heating rather than a replacement, where the latter was true in this case.

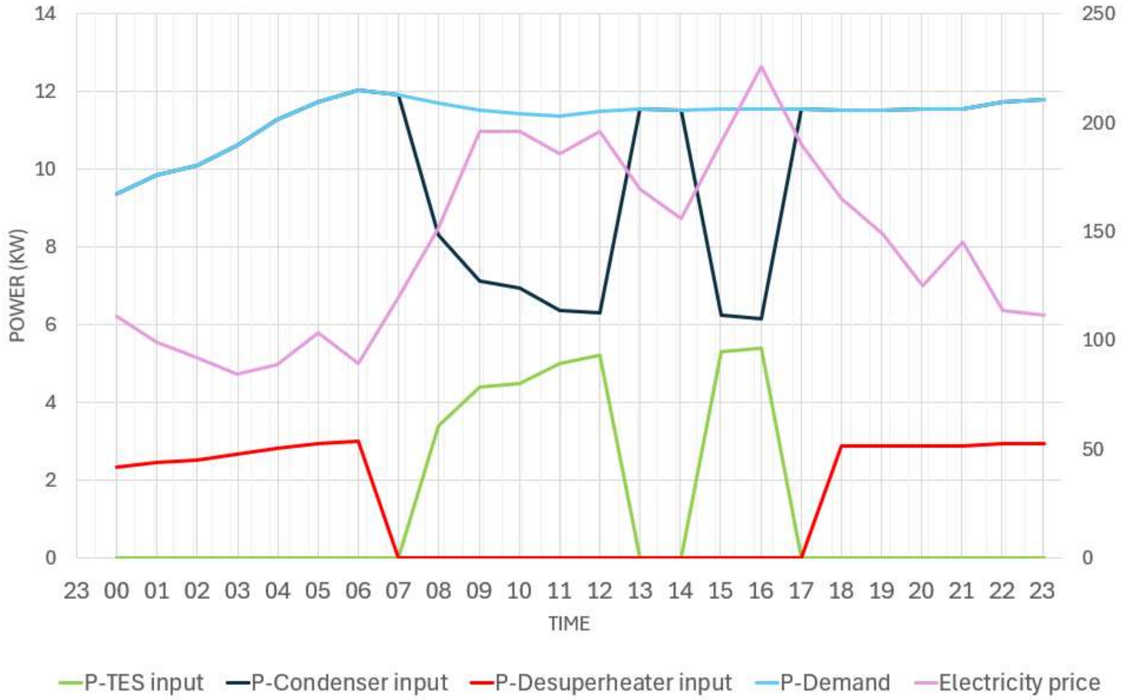

Figure 7: December 24th 2021 demand data from LIL showing strategic scenarios of charging and discharging the PCM-TES

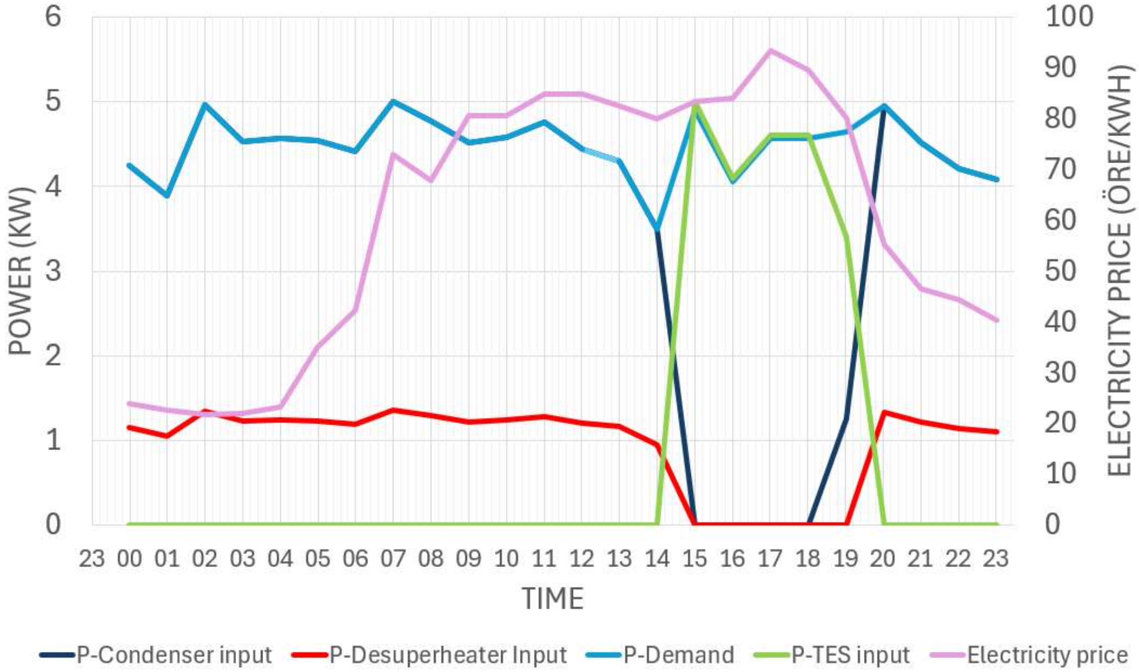

Figure 8: October 26th 2023 demand data from LIL showing strategic scenarios of charging and discharging the PCM-TES

4. Conclusions & Future work

This study developed a hierarchical control framework and operating strategies to optimise the operation of a 42 kWh PCM-TES integrated with a ground-source heat pump of 18 kW nominal heating capacity for residential space heating in Nordic climate conditions. The proposed control architecture demonstrates effective management of the complex interactions between PCM-TES, heat pump operation, and building heating demands while responding dynamically to electricity price signals and grid flexibility requirements.

The implementation of intelligent charging and discharging sequences enables strategic temporal shifting of electricity consumption, achieving significant operational cost reductions while maintaining thermal comfort standards.

The control strategies across three representative scenarios validate their robustness and adaptability to diverse operational conditions. The PCM-TES can cover e.g. up to 41 % of the demand during peak prices on the coldest days and e.g. up to 82 % in the transitional season, when the heating demand is not as high but electricity prices are volatile, making it an interesting scenario. In this analysis, taxes were not included in the electricity price, and so will be included as next steps of this analysis to provide a much deeper and realistic analysis of the cost savings.

Upcoming steps in this work include implementing and optimising the control framework in the real-life operation of this system, KTH LIL. That will be generating data that can be used for model predictive control or more sophisticated rule-based control, to be implemented on the same system for a more intuitive and automated control optimisation of this PCM-TES-Heat pump combined system operation in KTH LIL, catering to the four apartments' space heating demand cost-effectively.

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