PROVIDING FLEXIBILITY FOR DISTRICT HEATING GRIDS WITH THERMALLY ACTIVATED BUILDING STRUCTURES IN RESIDENTIAL BUILDINGS

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Abstract

For the urban housing sector's ongoing decarbonization efforts, district heating solutions stand as fundamental components. However, scaling up district heating systems presents significant challenges in grid extension and the integration of renewable heat sources. Demand peaks and generation mismatch pose operational hurdles which can be alleviated by using heat storages and demand flexibilities. This study evaluates the utilization of Thermally Activated Building Structures within residential complexes, employing model-based predictive controllers, to aid energy suppliers and grid operators in navigating operational challenges. Through a simulation study conducted for a real use case in the city of Vienna, this research demonstrates the efficacy of the proposed system in effectively mitigating grid peaks by leveraging thermal mass to offset non-shiftable demands, such as domestic hot water usage. The results show a peak load reduction of 27 % during the coldest week of the year and a 30 % reduction for an average winter week while keeping indoor comfort boundaries unviolated. The proposed technology therefore holds the potential to reserve grid capacity for additional buildings or to reduce the demand for peak load generation which is often based on fossil technologies.

Keywords: Thermally Activated Building Structures, District Heating Grids, Model Predictive Control

1. Introduction

For the ongoing decarbonization of heat supply in the urban housing sector, District Heating (DH) solutions are one of the main pillars. At the same time, major challenges for new and existing DH-systems are caused by a combination of growing grid size, more volatile renewable generation, lower temperature levels and high costs for peak load generation. This work proposes and evaluates a concept for the utilization of Thermally Activated Building Systems (TABs) to provide flexibility for grids and energy suppliers to overcome operational and system design challenges. Based on operational data from a real DH grid, and the conceptual data for a planned residential building project in the city of Vienna, Austria a simulation study is conducted to answer the following question.

How can TABs employing advanced Demand Side Management (DSM) strategies through Model Predictive Control (MPC) be optimized to support DH grid expansion by mitigating demand peaks, particularly by compensating for non-shiftable Domestic Hot Water (DHW) demand peaks, thereby ensuring new buildings are grid-supportive?

2. State of the art

Reynders et al. (2013) stated that the load shifting potential increases with the thermal mass of a building. This refers to the ability of materials within the structure to store heat. Studies indicate that in-floor heating, which directly utilizes the floor slab as thermal mass, offers a higher peak shaving potential compared to traditional radiators. However, it is crucial to acknowledge the potential trade-off between increased thermal mass activation and overall energy efficiency. While activating thermal mass enhances load shifting capabilities, it may also lead to higher energy consumption. Therefore, optimizing the utilization of thermal mass is essential to minimize unnecessary energy losses.

While Rijksen et al. (2010) have demonstrated a 50% reduction in peak cooling capacity for office buildings using concrete core activation, these results cannot be directly extrapolated to residential settings with heating systems.

Le Dreau and Heiselberg (2016) have shown that low-energy houses offer significant potential for load shifting, a strategy for managing energy demand by strategically moving consumption to off-peak periods. However, achieving this benefit requires robust control systems to prevent overheating issues. The effectiveness of load shifting in these houses is heavily influenced by the level of insulation. Buildings with good insulation have a reduced modulation potential, yet they offer an extended time frame for adjusting heat demand, which can surpass 24 hours. Simulations

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indicate that load shifting can be an effective strategy in single-family low-energy homes for managing electricity consumption.

The literature review delivers evidence that the desired results for grid operation can be achieved with TABs. However, a multifamily residential building with TABs has not been used for load shifting to the benefit of a thermal grid in any of the sources.

3. Methodology

The methodology of this study revolves around evaluating the feasibility of shifting heating demand to smooth the overall load curve of a district heating grid, particularly in scenarios where non-shiftable assets like DHW constitute a significant portion of the delivered energy and contribute to load peaks. Two distinct variants, as outlined in Tab. 1, are defined for analysis, including a baseline variant featuring rule-based control with ambient temperature dependent heating curves and one system variant which is dynamically optimized by Model Predictive Control (MPC). The simulation experiments are conducted for the complete heating season and results are focused on the coldest week of the year (Feb 12th to Feb 18th) and one average winter week (March 18th to March 24th) within an ASHRAE sample climate for the city of Vienna, Austria. Evaluation methods such as comparison of duration diagrams for heat demand, and time series data of occurring room temperatures including deviations are employed to compare the simulation variants. To assess the model fidelity of the used MPC method a residual analysis for room temperature predictions is used.

Tab. 1: Simulation variants

Name	Technologies	Explanation
Standard control	TABs; Return temperature control; Individual zone temperature control; Ambient temp. dependent feed temperatures	This variant serves as a baseline showing how a conventional control system would affect the heat demand of the TABs system in the examined building.
MPC	TABs; Return temperature control; Individual zone temperature control; Ambient temp. dependent feed temperatures; MPC	The standard control of the building is extended by a supervisory MPC control which can manipulate room temperature setpoints and can set aggregated heating power for the building by manipulating the feed temperatures. The MPC is utilizing knowledge of future external boundary conditions like weather, DHW and household electricity demand and has the objective to reduce heat demand peaks of the building including the DHW demand.

The core of the used method is a comprehensive energy simulation conducted on the sample building via the software IDA ICE by EQUA (2023). This building model was first implemented by Stipsits (2024) based on planning data for the residential housing project in the city of Vienna, Austria. A 3-D Depiction of the building geometry can be found in Fig. 1.

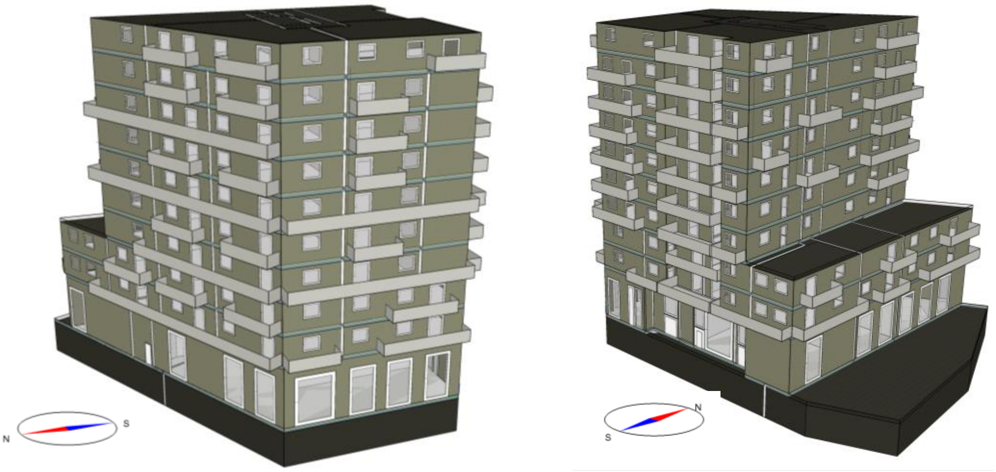

Fig. 1: 3-D views of the examined planned residential Building (left: view from northwest, right: view from southeast) (Source: Stipsits (2024))

For the applied MPC and Moving Horizon Estimation (MHE) a semi-physical model was initially devised for the application in a prior study, as outlined in Putz et al. (2023). Expanding upon this model, the proposed system incorporates a district heating connection and is displayed in its RC-equivalent form in Fig. 2 and the associated symbol description in Tab. 2. The control objective is to reduce heat demand peaks of the building including the DHW demand which is implemented by using a power dependent heat tariff. Subsequently, a co-simulation is conducted, coupling the model-based control method with the highly detailed building and system model within IDA ICE. This co-simulation involves optimizing daily load shifting tasks for the building through MPC control, while concurrently executing MHE operations to perform classical parameter estimation based on dynamic data from the IDA ICE simulation. Additionally, a state observer is employed within the controller to estimate the building structural temperature. Furthermore, the IDA ICE simulation provides essential data regarding thermal zone comfort and the hydronic system, including TABS return temperature and heat flux. The MPC Framework is implemented using the dynamic modelling and optimization package GEKKO in Python (Beal et al., 2018; Hedengren et al., 2014).

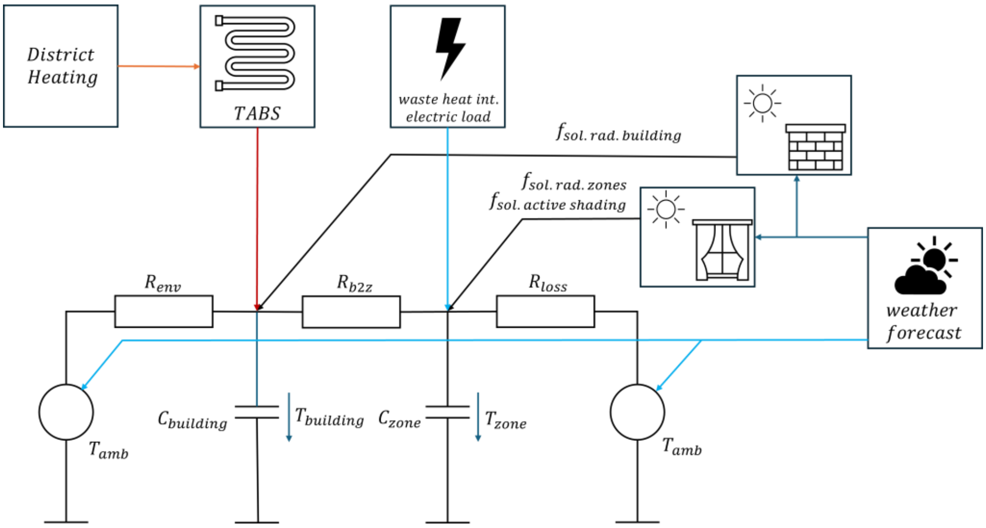

Fig. 2: RC-representation of the semi physical building model used in MPC and MHE

Tab. 2: Description of parameter symbols for the semi physical building model used in MPC and MHE

Parameter	Description
$T_{building}$	Average temperature of building masses
T_{zone}	Average air temperature of building zones
T_{amb}	Ambient air temperature
R_{env}	Thermal resistance of the building envelope part 1
R_{loss}	Thermal resistance of the building envelope part 2 and other leaks
R_{b2z}	Thermal resistance from the building structure to the thermal zone
C_{zone}	Aggregated thermal capacity of the thermal zones
$C_{building}$	Thermal capacity of the building structure
$f_{sol.rad.building}$	Multiplication factor to estimate heat flux into building structure based on solar radiation
$f_{sol.rad.zones}$	Multiplication factor to estimate heat flux into building zones based on solar radiation
$f_{sol.active\ shading}$	Time dependent multiplication factor to estimate impact of active window shading on the heat flux into building zones based on solar radiation

4. Results

In this study, the analysis of results is presented in two distinct sections to capture the variability in weather conditions during the winter season. The first section focuses on the coldest week of the year, characterized by extreme temperatures, which allows for an examination of the effects on the highest expectable peak loads. The second section presents data from an average winter week, providing a baseline for comparison and highlighting the typical conditions experienced during the season.

The coldest week of the simulated year is Feb 12th to Feb 18th. For the implemented standard control, the lowest occurring outdoor temperature of -14.6 °C leads to a space heating peak demand of 140 kW. Fig. 3 shows that using MPC for load shifting under consideration of the DHW demand, leads to lower and time shifted peaks. The total heat demand of the building is the sum of the heating power used in the TABS for space heating and the heat demand for DHW consumption plotted in Fig. 4. The total heat demand in this week is compared for the standard control and MPC in the duration diagrams in Fig. 5. It is shown that the highest occurring demand peak can be reduced by 27 % which is a significant decrease considering that this is the coldest week of the year. Comparing sum of shifted energy from times of high demand to times with lower demand, it can be observed, that lowering the peak demand comes at the cost of overall higher energy consumption. This increase amounts to 12.7 % for the coldest week scenario and 6.3 % for the average winter week. This significant increase is mainly cause by two effects. First, by comparing the achieved room temperatures for the variant with standard control (Fig. 6) and the variant with MPC based load

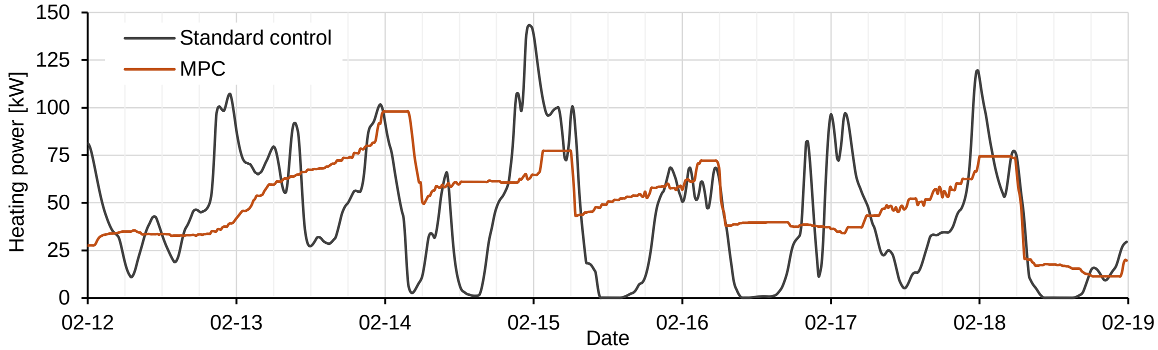

Fig. 3: Heating power of the TABs system in comparison for standard control and MPC during the coldest week of the year.

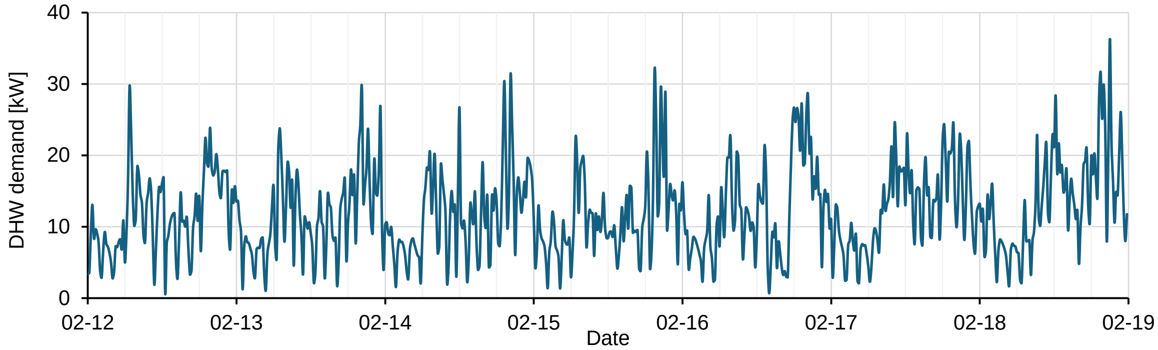

Fig. 4: Defined DHW demand of the building during the coldest week of the year.

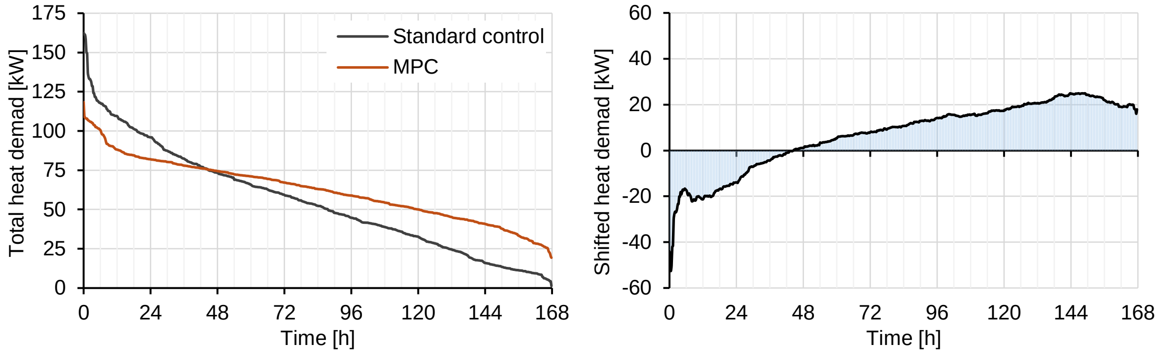

Fig. 5: Duration curves of total heat demand including TABS and DHW for standard control and MPC variant in the coldest week of the year (left). Difference between the duration curves representing the peak load reduction and the shifted energy (right).

shifting (Fig. 7) it can be seen that the MPC variant performs superior in maintaining the room temperature setpoint of 22 °C and never breaches the lower comfort limit of 21 °C. The building using standard control without predictive components struggles to maintain setpoint temperatures due to the high latencies in the thermal building dynamics. The higher energy demand of the variant with MPC is therefore caused by higher envelope losses while achieving higher temperature comfort. Secondly, the slight preheating of concrete structures raises heat losses through the building envelope and thermal bridges which can be interpreted as actual storage losses.

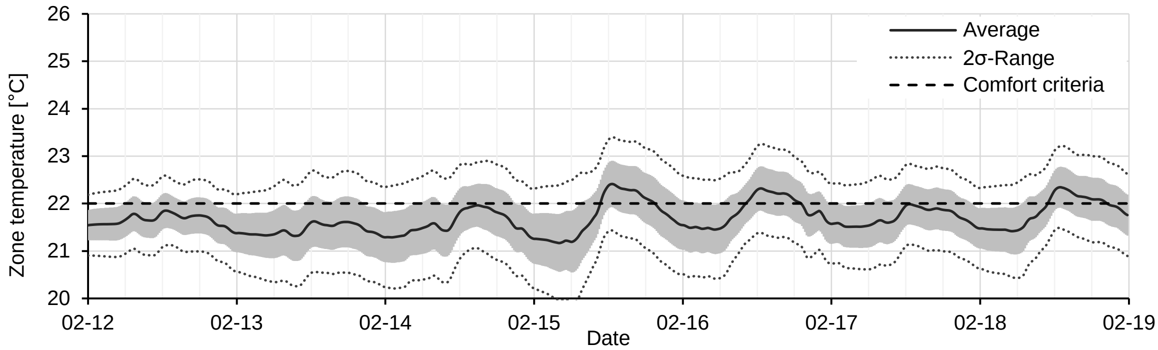

Fig. 6: Average building zone temperature and standard deviation for the coldest week of the year and standard control.

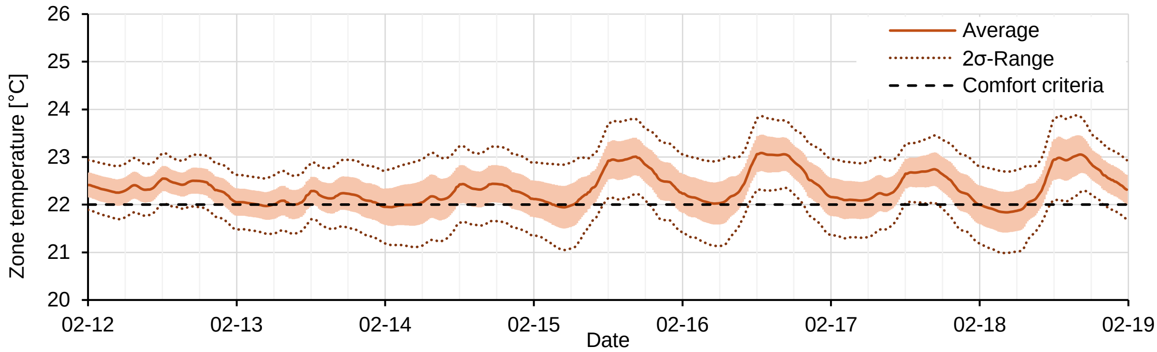

Fig. 7: Average building zone temperature and standard deviation for the coldest week of the year and MPC.

The implemented semi physical building model performs sufficiently for the load shifting task and offers a coefficient of determination of 0.95 for predicting the average room air temperature in the building. The results of a residual analysis performed for the coldest week of the year are shown in Fig. 8.

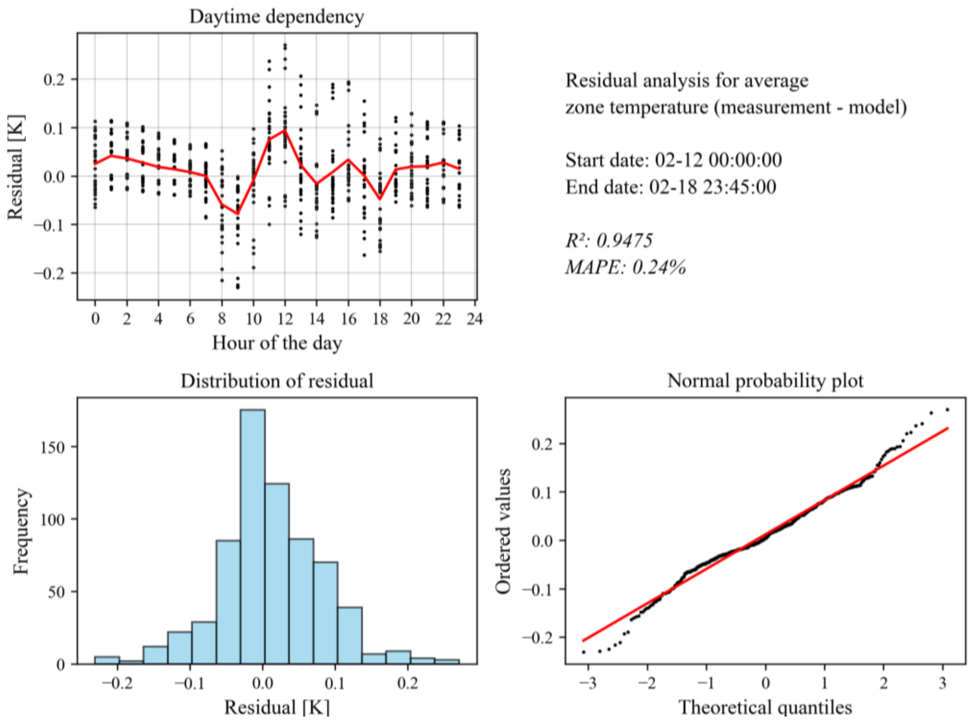

Fig. 8: Statistical evaluation of the residual of the predicted average zone temperature for the coldest week of the year.

The evaluation of results for the average winter week (March 18th to March 24th) was conducted using the same methodology as applied to the coldest week of the year. Also, in this case the use of MPC for peak load reduction is highly effective as Fig. 9 shows how the heat demand is shifted from otherwise high demand times to low demand times. Together with the heat demand for DHW consumption plotted in Fig. 10 the resulting total heat demand is calculated and shown in duration curves in Fig. 11. In this average winter week the heat demand peak can be reduced by 30 %.

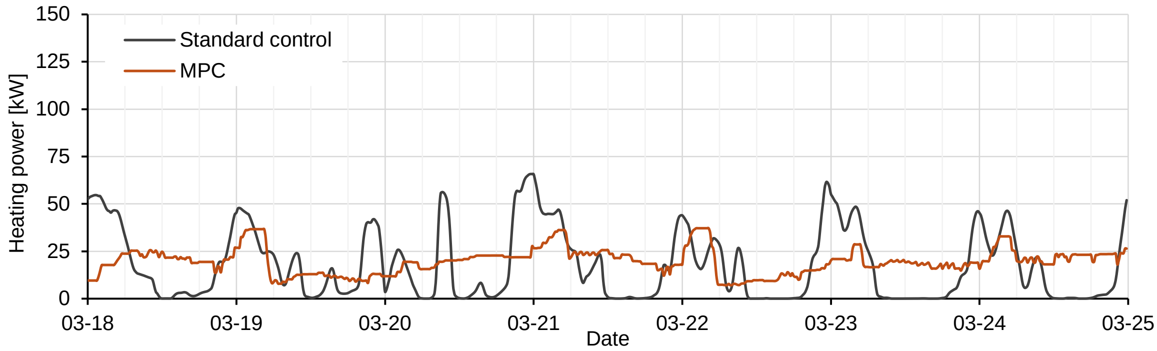

Fig. 9: Heating power of the TABs system in comparison for standard control and MPC for an average winter week.

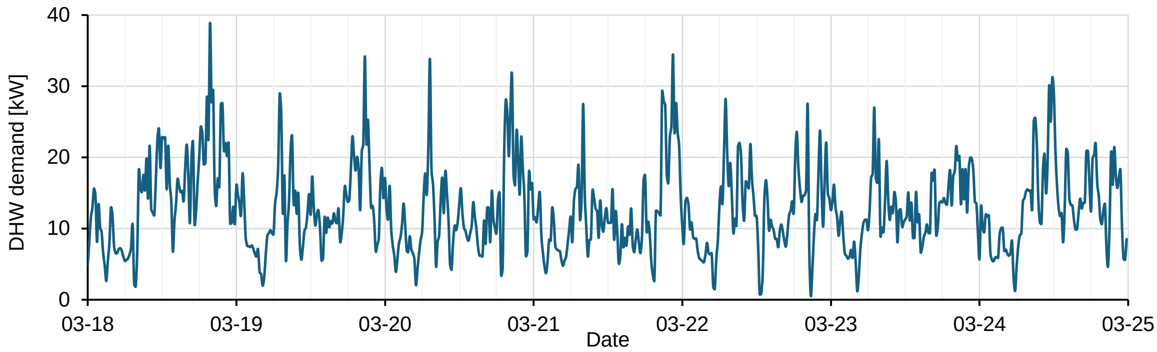

Fig. 10: Defined DHW demand of the building for an average winter week.

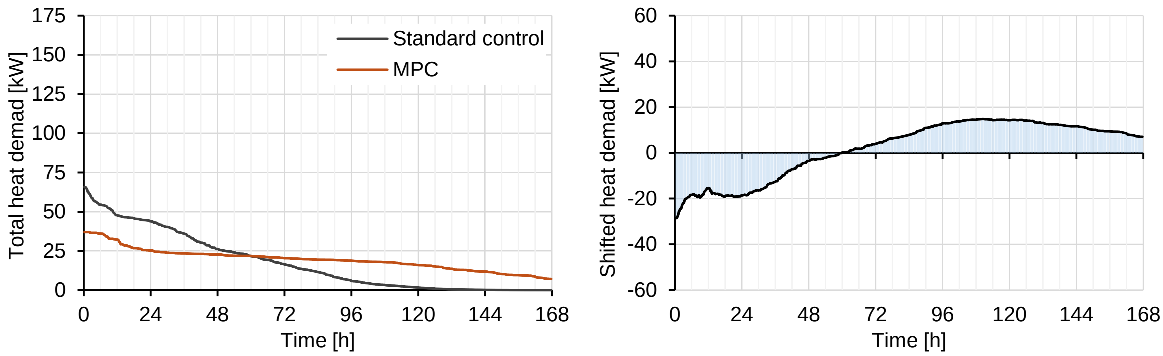

Fig. 11: Duration curves of total heat demand including TABS and DHW for standard control and MPC variant for the average winter week (left). Difference between the duration curves representing the peak load reduction and the shifted energy (right).

The MPC internal semi physical building model also performs positively in this week and offers a coefficient of determination of 0.93 for predicting the average room air temperature in the building. The results of a residual analysis performed for this average winter week are shown in Fig. 12.

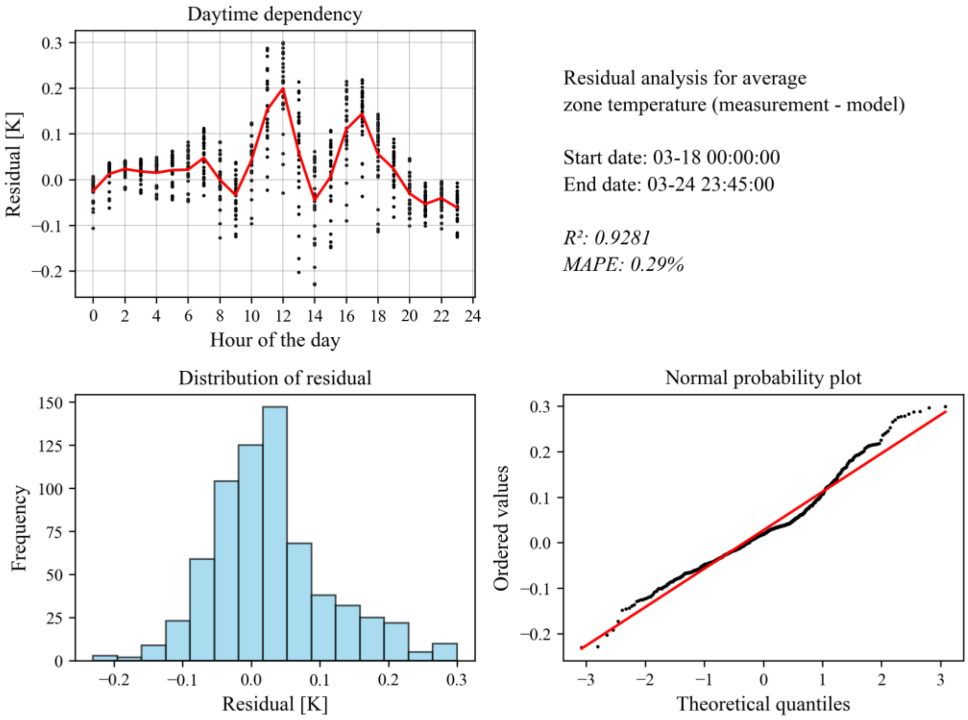

Fig. 12: Statistical evaluation of the residual of the predicted average zone temperature for the average winter week.

5. Conclusion

The study has shown that even during the coldest week of the year grid peaks can be effectively reduced. Manipulating the generally low flow temperatures of TABS together with targeted room temperature setpoint adaption enables the possibility to use the studied building for load shifting even in times of peak heat demand without compromising the tenant's thermal comfort. The utilization of supervisory MPC strategies on a building level is a key enabler for the derived results and ensures effective use of the activated thermal mass by balancing indoor comfort, heating losses and grid objectives. In the conducted simulation study this model-based control system also caused an increase in total energy consumption compared to the reference scenario which can be attributed to better compliance with temperature comfort boundaries and actual storage losses caused by the load shifting. Thus, causing overall higher energy consumption, it does so in times of lower demand which potentially can reduce the CO_2 emissions and cost. Depending on the utilized heat sources in the respective DHW grid, using more energy at times where renewable sources are available can have significant advantages over using energy from mostly fossil fuel based peak load generation.

Low order differential equation models can be sufficient to predict the thermal dynamics of large volume residential buildings sufficiently accurate to perform optimization calculations. The quality of model fitment achieved in this study can be classified with a coefficient of determination (R^2value) larger 0.9 which indicates strong correlation and is sufficient for the underlying use case. This has the potential to ease the expansion and operation of DH grids and therefore speed up the transition from fossil energy based heat supply in urban areas to more climate friendly alternatives.

6. Acknowledgments

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