CONTENT

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Enhancing Energy Efficiency in Existing Buildings: Overview of an Innovative Forecast Control Approach for Hydronic Heating Systems

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Abstract

Globally, there is a strong focus on using modern technologies to reduce carbon footprint and increase the energy efficiency of buildings. Achieving carbon-neutrality in EU by 2050 requires prioritizing energy efficiency improvements in current buildings through widely applicable and field-verified methods. This article describes a forecast control system that uses simple correlations with data from online weather predictions, including changes in wind speed, outdoor temperature, and solar insolation to optimize heating conditions. The presented method incorporates the building's actual energy model of the installed heating system, user behavior (preference profiles), and weather conditions forecasts. The implementation of presented in this article forecast control of heating system can result in energy savings of an average of 13.4% energy in residential buildings and 10.7% in public buildings compared to traditional systems, with a payback period of about 0.6 heating seasons. Installing this system in existing buildings takes less than 2 hours and poses no challenges for users or facility managers. Forecast control of heating systems can be particularly valuable for existing buildings due to their low cost and ease of implementation because it can be easily integrated with existing weather-based control systems.

Keywords: *forecast control, energy efficiency in buildings, space heating control, model predictive control, building heating system management, hydronic heating system*

1. Introduction

According to International Energy Agency, building operations constitute 30% of global final energy consumption and 26% of energy-related emissions [1]. The implementation of minimum performance standards and building energy codes is expanding in scope and stringency across countries. Concurrently, the adoption of efficient and renewable building technologies is accelerating. Despite these positive trends, the sector requires more rapid advancements to meet the Net Zero Emissions by 2050 (NZE) Scenario. This decade is crucial for implementing necessary measures, aiming for all new buildings and 20% of the existing building stock to be zero-carbon-ready by 2030 [2][3]. Achieving these targets is essential for aligning with global emission reduction goals.

In Europe, the vast majority of buildings are characterized as energy inefficient. Data indicate that approximately 97% of the EU's building stock requires upgrades to achieve high energy efficiency standards. Currently, less than 3% of these buildings meet the highest energy performance ratings. This highlights the critical need for extensive renovations across the EU region to enhance energy efficiency and reduce energy consumption [4][5].

In terms of energy consumption, residential buildings account for a significant share of the EU's final energy use. Buildings represent approximately 40% of the total energy consumption in the EU. Specifically, households contribute about 25-27% to the final energy use, with space heating alone comprising roughly 63% of household energy consumption [6][7]. These statistics highlight the critical importance of improving energy efficiency in buildings to meet the EU's climate and energy objectives.

Initiatives such as the EU's Renovation Wave, which aims to double the annual rate of energy renovations by 2030, are essential for achieving these goals [2].

Recent advancements in forecast control methods for heating systems have shown promising results in optimizing energy use and improving occupant comfort by leveraging predictive algorithms and weather forecasts. Model Predictive Control (MPC) has continued to gain traction as a superior approach to managing heating systems.

Miezis et al. [8] presented a methodology, which allows the creation of a multivariate constraint model, incorporating key constraints like building thermal capacity and energy prices. Using weather forecasts, the predictive control optimizes resources and anticipates outdoor temperature changes. Real-time MPC modeling has reduced energy consumption and costs. Besides by integrating weather forecasts and electricity tariffs, MPC improves heat source scheduling and achieves financial savings.

Rasku et al. [9] demonstrated the effectiveness of the open-source Backbone energy system modeling framework for simplified model-predictive control (MPC) of buildings. Hourly rolling horizon optimizations were conducted to minimize heating and cooling electricity costs for a modern Finnish house and an apartment block with ground-to-water heat pumps from 2015 to 2022. Using hourly spot electricity market prices instead of constant price signals resulted in annual cost savings of 3.1–17.5%, consistent with existing literature. The optimization horizon length did not significantly affect results beyond 36 hours. The study confirms that simplified MPC can be effectively integrated into large-scale energy system modeling frameworks, providing rational and cost-saving outcomes.

Joe et al. [10] introduced a smart operation strategy using model predictive control (MPC) to optimize hydronic radiant floor systems in office buildings, with results from real implementation. The MPC approach used dynamic estimates of zone loads, temperatures, weather conditions, and HVAC system models to minimize energy use and costs while ensuring comfort. Data-driven building models were validated with real data, and the optimizer employed constraint linear/quadratic programming for a global minimum. The results showed 34% cost savings during cooling and 16% energy reduction during heating compared to baseline control.

Brown and Beausoleil-Morrison [11] reports on a 182-day implementation of a model predictive controller (MPC) for managing hydronic floor heating and cooling in a highly glazed test house in Ottawa, Canada. The MPC aimed to minimize energy use while keeping indoor temperatures within a set range, achieving success 71% of the time.

Pedersen et al. [12] investigates the impact of incorporating nonlinear dynamics of hydronic radiators in model predictive control (MPC) schemes for demand response (DR) in space heating. Results show that nonlinear thermal effects have minimal impact on DR performance compared to simpler linear models for convective heaters, with cost savings of around 5% for existing buildings and 18% for retrofitted buildings. These findings suggest that linear models are suitable for MPC in buildings with hydronic systems, and that a practical two-level control scheme could be effectively applied in real-world applications.

Prívara et al. [13] discusses the application of a model predictive controller (MPC) for temperature control in a real building, addressing limitations of conventional strategies like weather-compensated control, which often fail to leverage solar gain and can lead to underheating. The MPC integrates weather forecasts and a thermal model of the building to optimize energy consumption and maintain desired indoor temperatures regardless of external conditions. During one heating season, the controller was tested in a large university building, resulting in energy savings of 17–24% compared to the existing control system.

This short literature review demonstrated a significant amount of work on the use of model predictive control (MPC) in predictive control of heating systems. Numerous studies and implementations have focused on integrating MPC with installations involving heat pumps, highlighting its effectiveness and efficiency. However, there is a notable gap in the literature regarding the application of forecast control to traditional hydronic heating systems, indicating an area for further research and development. This paper describes a cost-effective, easy-to-install, and user-friendly system, alongside a simplified method for forecast control of heating systems in existing buildings with hydronic heating installations, which was developed by authors. The proposed method integrates the building's actual energy model and the installed heating system, (represented as an equivalent outdoor temperature), user behavior and user preference profiles, (expressed as an equivalent indoor temperature), and weather parameter forecasts.

2. Materials and Methods

The described forecast control method has been invented and described in a series of articles authored by Cholewa et al.[14][15][16][17], and the following article is an overview of the research presented in the mentioned literature.

The studies on forecast control of heating systems were conducted in multi-family residential buildings and public office buildings located in the Lublin province, south-eastern Poland. This region experiences a continental European climate characterized by very cold winters. The heating season comprises 3957 heating degree-days (HDD) and lasts 222 days annually. Prior to the initiation of this research in 2011, the building envelopes underwent energy renovations. Specifically, double-glazed windows with a U-value of 1.8 [W/m²K] were installed, and external walls were thermally insulated to achieve a U-value of 0.30 [W/m²K], aligning with the maximum allowable U-values for building elements under the Polish national energy code of that period.

All tested buildings are integrated into the city's central district heating network, with heat supplied through individual heating substations. The heating installations are traditional water-based systems featuring vertical risers connected to convection radiators, ensuring thermal comfort in the heated rooms.

The standard operating conditions include a supply water temperature of 80°C and a return water temperature of 60°C, with an indoor temperature setting maintained at 20°C.

All the surveyed buildings are equipped with weather-based controllers. This type of regulation of heating systems is achieved through qualitative control, which adjusts the supply medium temperature in response to variations in outdoor temperature, while maintaining a constant flow of the system medium. The weather regulator operates by measuring the outdoor temperature and calculating the necessary temperature for the medium supplied to the heating circuit, based on a predetermined heating curve.

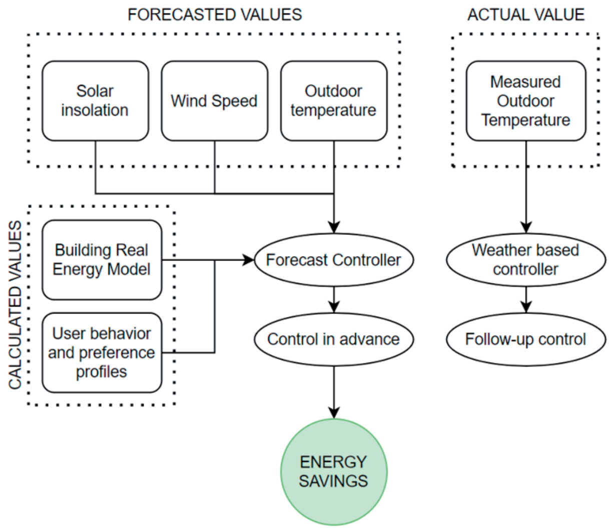

Fig. 1. Differences between the key characteristics of weather-based control and forecast-based control for heating systems.

The differences between the forecast control system and weather based control of heating system are presented in **Fig. 1**.

The process of implementing the forecast control in the building (**Fig.2**) comprises four primary stages, which involve:

1) setup of the proposed forecast control system in the building (refer to section 2.1);
2) constructing the energy model of the building (refer to section 2.2);
3) specifying the configurations for the forecast control systems (refer to section 2.3);
4) operating the proposed system in examples (refer to section 3).

2.1. Setup of Forecast System in Existing Buildings

To enable the operation of a forecast control system for heating installations in buildings, two options should be considered: installing a predictive module that collaborates with the existing weather controller, or mounting a forecast controller in place of the existing weather controller or as a new device in a building being put into use.

The installation of a forecast module in an existing building takes less than 2 hours and involves connecting the existing outdoor temperature sensor to the forecast module, and then connecting the forecast module to the existing weather-based controller.

For monitoring the heat delivered to the heating system, it is recommended to connect the forecast module to the existing heat meter or use a flow meter in the heating system circuit along with two temperature sensors. If there is no need for additional wiring, the entire installation process takes no more than 1 hour and does not require technical documentation of the building or heating installation.

However, it is worth noting that the proposed predictive control system is best suited for buildings with a single water heating system with convective radiators, supplied from risers or bottom-top from distributors. Conversely, in buildings where heat is delivered through heating-ventilation appliances or air conditioning units, the effectiveness of prediction may be limited due to the diversity of external and internal factors and their impact on heating systems.

For existing buildings, the forecast module is recommended due to its simplicity and cost-effectiveness, while the forecast controller is better suited for new constructions or comprehensive renovations.

Both options enable real-time energy modeling, facilitating informed decision-making regarding heating system optimization. They can easily interface with existing heat meters or flow meters, providing accurate data on heat consumption for space heating purposes. This integration typically takes about an hour, ensuring minimal disruption to building operations. Communication and data transfer are efficiently managed through Global System for Mobile Communications (GSM) technology, enabling remote management and adjustment of settings via a cloud-based IT system. This feature enhances the system's versatility and ease of use, allowing for seamless integration into existing building management processes.

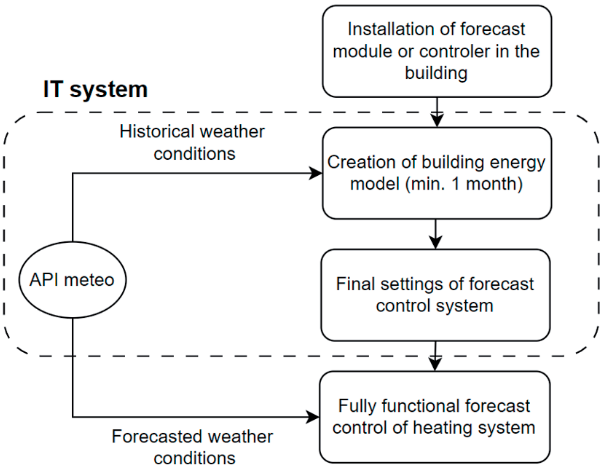

Fig. 2. The process of implementing the forecast control in the building

2.2. Creation of Building Energy Model

Immediately following the installation of the forecast control system (either version 1: the predictive module, or version 2: the predictive controller) and its connection to the central IT system, the automatic process of data collection begins.

This system records measurement data, including at least the outdoor temperature and the supply and return temperatures. The system archives key data for each building at high resolution (every 15 minutes), which is uncommon in similar heating monitoring systems that usually record data every 30 or 60 minutes. Additionally, these are real-time values sampled at 1-minute intervals, greatly enhancing the accuracy and value of the archived data.

After the control system is installed in the building, the heating system operates in weather regulation mode for at least one month (preferably an entire heating season), gathering the necessary data to build the building's energy model. This energy model also accounts for the actual efficiency of the existing heating system.

The data transmitted from each building can be used to create a reliable energy model, incorporating the actual efficiency of the heating system, in the form of an equivalent outdoor temperature (T_e^{eq}). This model adjusts the outdoor temperature based on wind speed (V_{wind}) and solar insolation (I_{nsol}).

Developing a building's energy model requires local meteorological data, including solar isolation and wind speed. Since not all buildings have on-site weather stations, historical data is retrieved from the meteo API integrated into forecast module, accessing data from the nearest meteorological station using the building's coordinates.

Within the IT system, users can adjust the hourly data range for a specific building to refine the outdoor temperature corrections for the energy model. During the data collection period, the heating system operates with a weather-based controller. Once the energy model is developed, the operating mode of the controller can be remotely adjusted through the IT system.

Universal computational algorithms have been developed to create the building energy model (building and heating system).

This model is expressed in terms of an equivalent outdoor temperature T_e^{eq} that accounts for the effects of wind speed and solar radiation (see Equation 1). This is crucial for forecasting the heating power demand and for efficiently controlling heat supply, which can lead to energy savings while maintaining thermal comfort for the occupants. Therefore, **Eq. (1)**, which defines the equivalent outdoor temperature T_e^{eq} for a given, will include adjustments for wind speed T_V^{rev} and solar insolation T_{insol}^{rev}.

$$T_e^{eq} = T_e - T_V^{rev} + T_{insol}^{rev} \quad [°C] \qquad (1)$$

The corrections for wind speed and solar insolation are derived from a dataset of suitably selected observations, using a regression equation that should exhibit a high coefficient of determination (R^2).

To calculate the corrections of outdoor temperature due to wind speed, an universal algorithm was developed to compute outdoor temperature corrections based on wind speed, aiming for a minimum coefficient of determination of 0.85 for each building. Initial parameter identification aimed to minimize confounding factors such as sunlight and users activity.

The relationship between heating power and outdoor temperature was assessed across wind speeds ranging from 1 [m/s] to over 10 [m/s], considering average and maximum hourly wind speeds during different daily periods. The highest coefficients of determination were observed during night time hours (23:00-4:00) for both maximum and average wind speeds, attributed to minimized external and internal factors. Consequently, the data from these night time periods were utilized for a sample to ensure precise corrections. Regression equations specific to each wind speed were preferred over using wind speed ranges, facilitating more accurate adjustments.

Using these regression equations, heating power was calculated as a function of external temperature (-20°C to +10°C). Logical data ranges were selected, demonstrating an increase in heating power with wind speed. The preliminary correction value of external temperature due to wind speed was determined to align with heating power values at different wind speeds. These dependencies necessitate individual determination for each building due to varied responses to wind speed.

To calculate the outdoor temperature corrections due to solar insolation, a universal computational algorithm was developed, crucial for accurately predicting heating energy consumption in buildings. This algorithm considers external air temperature, wind speed, and either sunlight or cloudiness as influential factors. Parameters were meticulously defined to minimize the influence of confounding variables, such as wind speed and user activities, and ascertain the most reliable parameter for analysis: sunlight or cloudiness. The relationship between heating power and external temperature was analyzed for various sunlight ranges and cloudiness levels, considering different wind speeds and time periods (6:00-18:00 and 10:00-14:00).

Data analysis revealed that reliable results were obtained for wind speeds below 3 [m/s], indicating a minimal impact of wind on heating power and highlighting the effect of solar radiation. Consequently, to determine external temperature corrections due to solar radiation, data from periods with wind speeds below 3 [m/s], specifically between 10:00-14:00 on weekdays or weekends, were considered.

While logical results were not obtained for cloudiness analyses, logical relationships were observed for sunlight under wind speeds below 3 [m/s]. Sunlight was identified as a more reliable parameter compared to cloudiness, given its higher coefficients of determination and the limitations associated with estimating cloudiness without instruments. The algorithm for determining external temperature corrections due to solar insolation mirrors that for wind speed, emphasizing the importance of considering specific time periods and wind speeds to accurately capture the impact of sunlight on heating power demand while minimizing the influence of other factors.

Regression equations were developed for each sunlight range and wind speeds below 3 [m/s] to calculate heating power based on external temperature. Preliminary external temperature corrections due to sunlight were computed, and an average correction for each sunlight range was determined, facilitating the creation of a scatter plot of outdoor temperature correction versus sunlight to further refine the algorithm.

This comprehensive approach enables precise adjustments for solar radiation effects on heating power demand, enhancing the accuracy of predictive heating energy consumption models for buildings.

Additional research efforts were aimed at determining the impact of user behaviors and preferences on the heat consumption within buildings/facilities. This endeavor sought to develop universal, intelligent computational algorithms for the purpose of determining and subsequently selecting (individually for each building) an appropriate profile of equivalent indoor temperature. This profile accounts for the user-related aspect in predicting heat consumption. To develop profiles of equivalent indoor temperature, a methodology was developed to determine the heat loss coefficient, H [kW/K], for each building empirically. Utilizing an equation along with historical data of real heat consumption during night time periods (23:00-4:00), the coefficient was calculated, considering variations in user behavior. This approach, while contrasted with deriving H from design documentation or energy audits, ensures an accurate reflection of the building's thermal dynamics. Computation of H for each day and hour throughout the heating season is advised, with an average calculated from night time hours during the peak heating season (January to March), accounting for users behavior.

The average heat loss coefficient should be updated following any building modernization to reflect alterations in design heat load and heating power requirements. Hourly values of equivalent indoor temperature are derived from the determined H, facilitating the estimation and consideration of user behavior and internal heat gains affecting heating power demand in predictive control. An hourly profile, crucial for predicting heating power demand, is developed, considering potential variations in user preferences and behaviors. Four profile cases were considered, each tailored to minimize discrepancies between predicted and actual heat consumption.

The selection of the appropriate profile is automated using computational algorithms integrated into the Information System (NSI) for predicting heat consumption, ensuring accurate predictions for the upcoming week.

The entire computational process for determining the building's energy model (including its heating system) as an equivalent outdoor temperature is carried out independently for each building within the framework of the Supervisory Information System (NSI). The scope of input data for building the model can be individually tailored for each building using the NSI. After one month (minimum 1 month, but a full heating season is recommended) from the installation of the control system in the building, the actual energy model of the building can be determined as an equivalent outdoor temperature. The entire computational process for one building takes up to 10 seconds, and the computation can be initiated manually by the user or automatically after prior scheduling.

2.3. Configuration of the Forecast Control System

The creation of the building's energy model necessitates local meteorological data, such as solar insolation and wind speed.

However, not all buildings have on-site weather stations. Consequently, historical data of this nature is acquired from the meteo API, integrated into forecast control system to retrieve pertinent data from the nearest available meteorological station based on the building's specific coordinates. Within the IT system, users can adjust the hourly data range for a particular building to develop corrections for outdoor temperature, which are then incorporated into the building's energy model.

During the data collection phase for building energy modeling, the heating system is controlled using a weather-based controller. The operational mode of the existing weather-based controller can be remotely modified via IT system only after generating the actual energy model of the building.

The weather-based control of the heating system operates with a delay, adjusting the heating medium supply temperature settings based on the current or recent outdoor temperature values. This control method does not consider factors such as wind speed, solar radiation, or user preferences. In contrast, the primary objective of the heating system forecast control is to proactively adjust heat supply based on forecasted changes in weather parameters and user behavior. This includes considering factors like thermal inertia and the heating system's response to weather conditions.

Before transitioning from weather-based to forecast control it is essential to verify and adjust forecast control settings for each building. Key considerations include correcting outdoor temperature for wind speed and solar insolation, particularly in response to forecasted increases in outdoor temperature. Wind correction involves adjusting heating medium supply temperature to counteract increased heating loads caused by lower ambient temperatures due to wind. Solar insolation correction anticipates higher outdoor temperatures due to increased solar gains. Furthermore, the forecast control process allows for setting suitable day and night setbacks for equivalent indoor temperature.

This accounts for occupant preferences, behavior, and heat gains associated with occupancy and activities. All settings and values can be customized for each building by using the IT system to optimize energy savings while ensuring users comfort.

3. Operating of the Proposed Forecast Control System

Once the forecast control settings are input, a crucial aspect is managing the transition from predicted heat consumption (Q_{pred}) to the outdoor temperature setpoint value (T_e^N). This transition is facilitated through the forecast module, where the predicted heat consumption (Q_{pred}) is calculated using **Equation (2)**, considering factors like equivalent indoor temperature T_i^{eq}, equivalent outdoor temperature T_e^{eq} and the average heat loss coefficient for the building (k_{mean}).

$$Q_{pred}=k_{mean} \cdot (T_i^{eq} - T_e^{eq}) \quad [\mathrm{kW}] \qquad (2)$$

However, to effectively reduce heat consumption in existing buildings, preemptive action is essential to adjust to changing external and internal conditions and provide a lower heat power than the direct forecast value.

When computing Q_{pred}^{final}, it's advisable to determine $T_e^{eq\_final}$, considering adjustments made for forecast control settings. This includes not correcting outdoor temperature for wind speed if it is below 10 [m/s], factoring in previously forecasted solar insolation values from 2 hours prior for outdoor temperature correction due to solar insolation, and considering the forecasted outdoor temperature increase from 2 hours earlier.

$$T_e^N = (T_i + T_{idecrease_{day}} + T_{idecrease_{night}}) - \frac{Q_{pred}^{final}}{k_{mean}} \quad [°\mathrm{C}] \qquad (3)$$

Equation (3) is utilized to determine the outdoor temperature setpoint (T_e^N) for the upcoming 6 hours, considering hourly intervals. This approach allows for the consideration of day ($T_{i\_decrease\_day}$) and night ($T_{i\_decrease\_night}$) setbacks in indoor temperature, leading to additional energy savings. $T_{i\_decrease\_day}$ is suggested for implementation in public buildings during weekends when the building is unoccupied. Conversely, $T_{i\_decrease\_night}$ is recommended for night time use in any building type, when occupants are absent (e.g., public buildings) or asleep (e.g., residential buildings). The reduction in indoor temperature should not exceed 5°C. It is important to note that this temperature setback does not imply that indoor temperatures will drop by 5°C. Instead, applying this indoor temperature decrease (via **Equation (3)**) will raise the T_e^N, consequently lowering the supply temperature to the heating system and resulting in expected energy savings. In most multifamily and public buildings, the design indoor temperature (T_i) is typically set at 20°C.

The estimated T_e^N values for the next 6 hours are relayed to the forecast module (or forecast controller) within the specified building. These values are factored into the heat supply control process for heating, considering the heating curve stored in the existing weather-based controller, if it is available.

This cycle repeats hourly, with new T_e^N values recalculated and transmitted for the subsequent 6 hours, replacing the previous ones. If the T_e^N value for a given hour surpasses the current outdoor temperature measurement, the forecast module or controller integrates the T_e^N value into the control process instead of the measured T_e value. Conversely, if the hourly T_e^N value is lower than the current measured outdoor temperature, the forecast module or controller disregards the T_e^N value and uses the measured T_e value in the control process. This ensures that the heating system does not operate with a higher heating medium temperature in forecast control mode compared to its operation in simple weather-based control mode.

The implementation of forecast control in while long-term on-site assessment showed that multi-family buildings results in energy savings ranging from 11.3% to 18.9%, with an average savings of 13.4%. In the case of public utility and office buildings, energy savings ranged from 8.3% to 13.7%, averaging 10.7%. There, research cleared a trend of increased savings in larger buildings. The observed higher percentage of energy savings in larger buildings is primarily due to their substantial size and the presence of larger heating systems, which exhibit greater thermal inertia. Furthermore, the reduction in the supply temperature of the heating medium, facilitated by forecast control, is anticipated to enhance energy savings.

4. Conclusions

Long-term field research and monitoring of actual buildings have yielded valuable data for evaluating the effectiveness of implementing a forecast control system in existing residential and public utility/office buildings. This innovative forecast control system incorporates predictions of outdoor and indoor conditions, allowing for significant energy savings. Analysis of real-world long-term research data indicates that compared to traditional weather-based controllers, the forecast control system can achieve average savings of 13.4% in residential and 10.7% in public buildings. The payback period for implementing forecast control systems in existing residential and public buildings is approximately 0.6 heating seasons, on average. This duration can be notably shorter for larger buildings with higher pre-installation heat usage.

The effectiveness of the forecast control system is particularly pronounced in the regions characterized by higher daily temperature variations and extended periods of solar radiation. As such, it is highly recommended for use in climatic zones with these features, especially during transitional periods between seasons.

Installation and integration of the forecast control system are straightforward, requiring less than 2 hours and compatible with most existing weather-based control systems in buildings with hydronic heating installations. Its simplicity and independence from building documentation make it a cost-effective and time-saving solution for both existing and new buildings.

The system's predictive capabilities account for changes in external weather parameters and internal user preferences, resulting in tangible energy savings and enhanced occupant engagement in energy-efficient building operation.

With online access to operational energy data, occupants and facility managers can actively participate in optimizing heating system performance.

In conclusion, the proposed forecast control system offers a viable alternative to traditional weather-based controllers, providing an easy-to-install, cost-effective solution for improving energy efficiency in buildings. Ongoing research will further refine its performance under various operational conditions, including different building types, occupancy patterns, and climate zones, paving the way for broader implementation in buildings worldwide and also verifying the potential applicability of the developed algorithm in cooling systems.

Integrating the proposed forecast control system into buildings with diverse heating systems, such as HVAC systems, presents several challenges. One key issue is compatibility with varying control protocols and operational characteristics of these systems. HVAC systems often employ complex controls that may not seamlessly align with our predictive algorithms. Developing adaptable interfaces or hybrid control strategies may be necessary to enable effective collaboration between our system and existing HVAC controls.

Additionally, each building has unique thermal dynamics and energy usage profiles, necessitating customization of control algorithms. This could involve calibration processes that add complexity to the initial implementation phase.

Broader geographical coverage introduces challenges related to climate variability. Our current study's results, based on specific climatic conditions, need validation across different environments. Future research will focus on conducting field tests in diverse climates to gather data on extreme temperatures, humidity levels, and solar gain patterns. This will allow us to refine our algorithms, ensuring their effectiveness and adaptability in various settings. By addressing these challenges, we aim to enhance the applicability and utility of our forecast control system in a global context.

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