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On the forecast control of heating system as an easily applicable measure to increase energy efficiency in existing buildings: Long term field evaluation

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ABSTRACT

The priority for reaching carbon neutral buildings by 2050 is to first increase energy efficiency in existing buildings by use of easily and widely applicable measures that are verified based on long-term field research. One such solution is a forecast control of heating systems, which can be quickly and easily integrated to existing weather based controls. However, there are still no long-term field evaluation and detailed analyses of the main features of such a system, which would provide a clear picture about the system's energetical and economical features and thus increase their wide application in existing buildings. This paper provides the data from a long term field evaluation of an innovative forecast control of heating systems (forHEAT), which can be easily installed (in less than 2 h) and integrated with existing installations in millions of existing buildings in Europe and throughout the world. The energy consumption for heating was evaluated in seven residential buildings and three public office buildings before and after the installation and use of the forecast control. The resulting energy savings averaged 13.4% in the residential and 10.7% in the public buildings located in continental European climate, with very cold winters. The payback time averaged a 0.6 heating season and in most case studies does not exceed a single heating season.

1. Introduction

Since existing buildings use around 40% of final energy consumption [1] and above 60% of this amount of final energy is used for space heating [2], many plans and studies were (in the past) and still will be (in the future) dedicated to increase the energy efficiency, while securing proper indoor thermal comfort and environmental quality. In this direction, the European Commission has developed various comprehensive strategies and ambitious plans in this area, such as Green Deal [3] and REpowerEU [4], which may help to reach carbon neutral buildings by 2050.

One of the commonly used possibilities to reduce energy consumption for space heating and cooling is to decrease the energy needs, for example, by use of double-skin façades [5,6], more traditional thermal insulation techniques of the building envelope [7] and possible optimization by using BIM [8]. In this process, performing smart energy audits, which may also be facilitated by using BIM data, are helpful and may significantly speed up the renovation process of existing buildings [9]. Energy conservation measures and other efficiency measures should not be limited only on the building envelope and air tightness [10], but also include building services and technical systems [11,12].

In this light, many studies have focused on the control of heating, ventilation and cooling systems [13,14], which is a good alternative to other more complex and hardly applicable energy efficient measures [15]. In the case of integrating weather forecast for estimating the fuel consumption for heating, Anđelković and Bajatović [16] proposed specific algorithms using neuro-fuzzy inference to finally minimize the prediction error at less than 3.0% between actual energy use and calculations. A similar level of prediction accuracy for the energy consumption for heating and cooling was achieved by Ham et al. [17], who

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developed and implemented a real-time modeling approach for specific units in residential buildings. Nigitz and Göllesa [18] also improved the forecast of space heating demand by correlating the outdoor temperature and heat load, reaching a mean error of 2.9%. Jang et al. [19] used a deep-learning model for improving the heating energy forecast in buildings, achieving a mean error of only 0.6% by properly selecting input data.

Data from smart meters and outdoor parameters were used by Lumbreras et al. [20] to forecast heat consumption for space heating by using a multiple variable regression model for buildings supplied from district heating. Since weather forecast may significantly influence the accuracy of model predictive controls for space heating systems, Hou et al. [21] successfully introduced the specific error model and increased the energy savings potential of a model predictive control (MPC). In addition to the parameters of weather and occupancy, Hou et al. [22] introduced two additional parameters to account for the building's thermal mass in thermal storage and for the dynamic energy prices in the building's optimization process. Simulations were used to verify the proposed approach, reaching an estimated reduction in heating costs by 3.8%. On the other hand, the use of a MPC for a space cooling system reached significantly higher cost savings of 28% using simulations along with a Pareto multi-objective optimization approach [23].

On the basis of this literature overview, it becomes evident that most of the described forecast methods of heat consumption and/or forecast methods used for control of heating systems are validated mainly based on simulations or very short experimental research, which are not so trustful for potential investors. On the other hand, there is no long term field research that presents similar evidence with data from heating seasons before and after the installation of a forecast control to realistically evaluate the system's performance. In addition, as noted by Dermentzis et al. [24], an even more practical issue for engineers and investors is to know the possible payback time of the proposed energy efficiency measures.

In order to bridge the above-mentioned research gap, this paper provides initial long term field data that was collected from residential and public office buildings equipped with a forecast control system of heating, which may be easily applicable in other types of existing buildings with similar installations. The main objective of this paper is to investigate and assess the impact of different external and internal factors on the level of energy savings. The long term research benefits from this work are to facilitate accurate estimates of the anticipated energy savings and payback time of the initial investments.

2. Materials and methods

The research on the impact of forecast control of heating system (forHEAT) was carried out in seven multi-family buildings (R1-R7) and in three public office buildings (P1-P3) located in the Lublin province in southeast Poland. The standard climate conditions are representative of a continental European climate, with very cold winters. The heating season has 3957 heating degree-days (HDD) and lasts for 222 days per year. Table 1 summarizes the basic information of the ten case study buildings including the heated floor area, volume and number of stories. The envelopes of all analyzed buildings were subject to energy renovation before 2011 and initiation of this work. Specifically, double-glazed windows (U = 1.8 W m^{-2} K^{-1}) were installed in all buildings, while the external walls were thermally insulated to reach a U-value of 0.30 W m^{-2} K^{-1}, which were the maximum U values for the building's elements according to the national energy code in Poland in that period [25].

All the buildings are connected to the city's central district heating network and are supplied with heat through individual heating substations. The heating installation is made in a traditional way, as water based, with vertical risers that connect to convection radiators, which ensure thermal comfort in individual rooms. The standard operating conditions are 80 °C supply and 60 °C return of hot water inside the building, with an indoor temperature setting of 20 °C.

Table 1
Characteristics of the case study residential (R1-R7) and public (P1-P3) buildings.

Building	Heated area [m^2]	Volume [m^3]	Number of stories [-]
R1	970.7	2718.0	5
R2	4480.6	12545.5	5
R3	1649.3	4618.0	5
R4	2843.4	7961.5	5
R5	5995.4	16787.0	5
R6	1663.8	4658.5	4
R7	3088.8	8648.5	5
P1	2699.2	7557.8	3
P2	3951.1	11063.1	12
P3	860.7	2410.0	3

At the end of January 2021, the heating systems in the analyzed buildings were modernized and equipped with an innovative forecast control system (forHEAT) in the form of forecast modules (see Fig. 1), which were installed and connected to the existing weather based controllers. The time requirements for installing and integrating the forHEAT system with the existing heating system is very short and can be completed in less than 2 h, which has been described in detail by Cholewa et al. [26].

Specifically, a heat meter is connected to the forecasting module (via M−BUS protocol), which measures the amount of heat supplied to the heating system in a given building. The measurements include the flow

Fig. 1. View of the forecast module forHEAT integrated with the existing weather based controller.

of the heating medium and the temperature of heating medium at the supply and return from the heating system (see Fig. 2). The forecasting module is connected with the information technology (IT) system through the Internet to transfer the data. The monitored data include the outdoor temperature, heating medium flow, supply temperature, return temperature, thermal power, and heat consumption. The time interval for recording the data is a 10-minute step. As part of the IT system, archival measured data are collected and coupled with outdoor data. The local weather data (i.e. outdoor temperature, wind speed and solar radiation) are collected via the meteo API from nearby weather stations located in the vicinity of the buildings and are automatically interpolated using the building's coordinates.

The collected data are used to generate a real energy model of the building and its heating system, in the form of an equivalent outdoor temperature ($T^{eq}_{outdoor}$), which was described in detail by Cholewa et al. [27]. This also takes into account the influence of ambient conditions, e.g., wind speed and solar radiation, for each building.

Detailed data monitoring was initiated after the installation of the forecast modules in the analyzed buildings at the end of January 2021 and was carried on until April 12th, 2021. Such measured data were used to calculate the $T^{eq}_{outdoor}$, while the heating system was simply regulated using the pre-existing simple weather based control.

The second monitoring phase, from April 13th, 2021 to May 1st, 2022 that marks the end of the 2021/2022 heating season, was used to collect the data on the operation of the heating system controlled in the forecast mode. During this phase, it is possible to take into account the weather forecast with a 1 h resolution that is updated on an hourly basis. The weather forecast data is then downloaded for the next 12 h from the meteo API for the specific location of a given building. This information is then used to forecast the outdoor temperature settings for a given building for the next 6 h for estimating the equivalent indoor temperature (T^{eq}_{indoor}) in terms of user behavior profiles [28]. These temperature profiles reflect the influence of the occupants and other possible internal heat gains (e.g., from cooking, equipment and appliances) on the indoor temperature settings. Accordingly, this explains why the T^{eq}_{indoor} should not be associated with the measured value of the indoor air temperature. Fig. 3 highlights the main features for the forecast control with commonly used weather-based control systems.

The operating principle and mathematical background of the proposed forecast control is described in details in [26]. However, the main advantage of the forecast control of heating systems compared to the commonly used weather based control is that the system can consider in advance the influence of outdoor conditions (i.e. solar radiation, outdoor temperature, wind speed) and internal conditions (characterized by T^{eq}_{indoor}).

Specifically, the predicted outdoor temperature settings for a given building are provided to the forecast modules on an hourly basis for the next 6 h. This way, it is possible to take into account the variations in the forecast of the outdoor weather conditions and to derive more accurate T^{eq}_{indoor} profiles. Accordingly, the forecast module adapts the outdoor temperature settings that are then used by an existing weather based controller, as it was elaborated above and in [26]. As a result, it is possible to decrease the supply temperature of heating medium taking into account the impacts of the variable outdoor weather conditions on

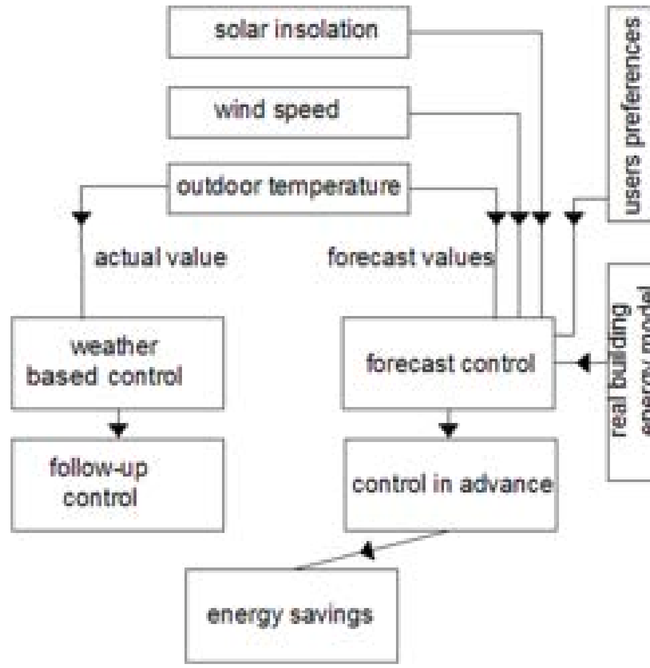

Fig. 3. Comparison of main features of weather based control and forecast control of the heating system.

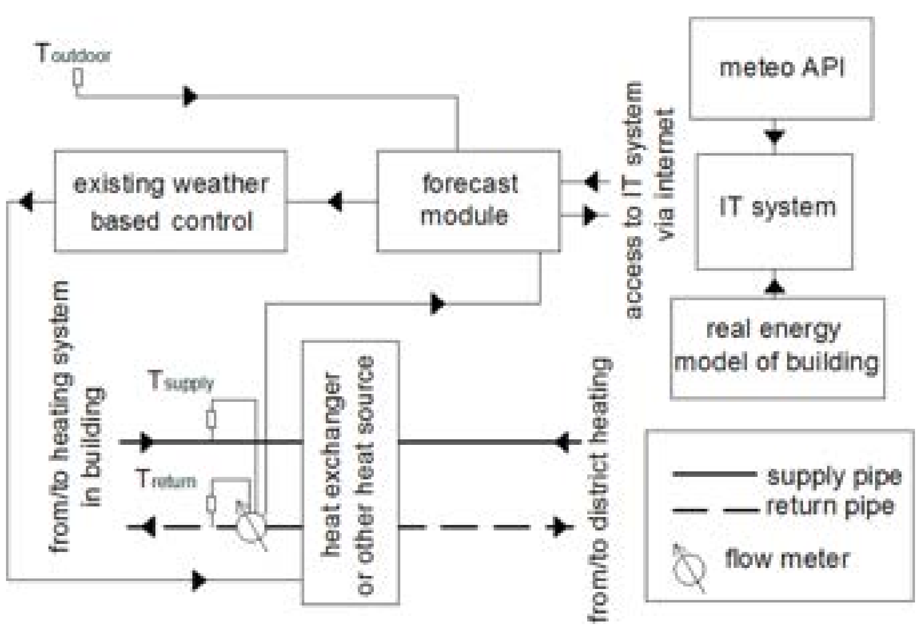

Fig. 2. Connection schema of the forecasting module forHEAT with existing heating system.

the preferences of the building occupants and the use of the heating system. Eventually, the controller can optimize the system's operating conditions and achieve significant energy savings for heating.

The initially collected data on a 10-minute time step provided a large amount of information on the heat consumption supplied to the heating system in the analyzed buildings. This data was used for the purposes of the analysis presented in section 3.1. However, the main analysis was mainly performed using aggregated data to hourly intervals. The available data that were used in this work correspond to two distinct periods. The first covers the period from 01/02/2021 to 12/04/2021, which corresponds to the period that the heating system operated in the weather based control mode. The second covers the period from 13/04/2021 to 01/05/2022, which corresponds to the period that the heating system operated in the forecast control mode.

Calibrated heat meters were used to accurately measure the heat supplied to the building for heating purposes (Q_{actual}) during the entire campaign.

In addition, the long term data was used for a broader assessment of the impacts from the use of the forecast control of the heating system on the building's heat consumption (see the analysis in section 3.2).

The data from the 2012/2013 heating season to the 2020/2021 heating season were adopted as the baseline for public buildings (buildings P1-P3), while for the multi-family residential buildings (buildings R1-R7), the data from the 2018/2019 heating season to the 2020/2021 were used. The heating season 2021/2022 was adopted as the target (final) state, because the forecast control forHEAT was already activated throughout the heating season in all the buildings.

The long term evaluation of such an efficient measure considered in the present analysis, takes into account the data from 3 (for residential buildings) or 9 (for public buildings) heating seasons before the installation of the forecast controls and 1 heating season after the installation. This is valuable information considering the lack of long term field evaluation of such a forecast control.

The actual heat consumption was normalized ($Q_{corrected}$) using the heating degree-days, by multiplying the recorded data with the ratio of the standard (HDD^{stand}) to the actual HDDs (HDD^{actual}) calculated at a base temperature of 20 °C (see **equation (1)**.

$$Q_{corrected} = Q_{actual} \cdot \frac{HDD^{stand}}{HDD^{actual}} \quad (1)$$

This method eliminates the influence of outdoor temperatures on energy consumption for heating/cooling purposes and is commonly accepted in practice for normalizing the energy use [12].

The indoor air temperature in the investigated buildings was not monitored. In part this was due to the lack of authorization by the building owners/occupants for the installation of such data loggers in the multifamily buildings. For consistency, this type of data was neither collected in the public buildings. In any event, the desirable indoor temperature was achieved since the building owners reported satisfactory indoor conditions.

During the monitoring period, no other modernizations were implemented in terms of the building envelope or the heating system, which could affect the buildings' performance or contribute to additional savings in the heat consumption. In addition, during the monitoring period, the occupants of the multifamily buildings and the type of work performed in the public buildings were not changed. To this extend, the internal heat gains and ventilation rates are not expected to have changed significantly or to an extend that they may have impacted the indoor heating demand. Direct solar gains and other weather variations, to a certain extent, they have been accounted for by the degree day normalization. Accordingly, although these parameters were not monitored in the analyzed buildings, they are not considered critical in the interpretation of the outcomes from this campaign.

As a result, one can attribute the quantified energy savings from monitoring and normalizing the heat consumption for heating for the variable weather conditions, to the forecast control of the heat supply to the heating system, which is presented in section 3.2.

3. Results and discussion

The first section (see section 3.1) presents the research results. The analysis takes into account the external factors (i.e. outdoor weather conditions like mainly outdoor temperature, solar insolation) and internal factors (i.e. occupant preferences related to the indoor temperature and the internal heat gains) on the heat supplied for heating in the analyzed buildings controlled with the use of the forHEAT forecast control system. The analysis is performed throughout the heating season, including the transition period.

Next, the analysis presents results (see section 3.2) for quantifying the energy savings obtained in the analyzed buildings as a result of installing the forecast control system and estimates the payback time. In addition, the limitations of the proposed forecast control of heating system and this study were also elaborated.

3.1. Impact of external and internal factors on the level of energy savings

Due to the thermal inertia of the building and the installed heating system, it is desirable to take into account any changes in external factors (especially the increase in outdoor temperature and the presence of solar radiation) and accordingly adjust the control process of the heating system. This control process can optimize the operating conditions and increase the energy efficiency of the heating system.

In addition, the process allows for taking into account the predicted variations of the outdoor temperature (e.g., a temperature increase that will require less heating) and the influence of wind speed (e.g., higher or lower wind speed that will increase building envelope thermal losses and infiltration). Compared to a conventional weather based control that only compensates for the real time prevailing conditions, the new control process prepares the building and modulates the operating conditions of the heating system to achieve improved indoor conditions (e.g., avoid overheating) as well as optimize energy use and lower operating costs. The forecast for an increase of the heating needs as a result, for example, of higher wind speeds and lower outdoor temperature or changes in user preferences, may be of particular interest when heat storage is also utilized. This can be in the form of a buffer tank or by utilizing the building's thermal mass [29,30].

However, the impact of these external and internal factors on the thermal power supplied to the heating system should be determined individually for a given building, preferably using the actual data related to the supply of heat for heating purposes (for example, using simple methods proposed by Cholewa et al. [27] in the field of external factors and by Cholewa et al. [28] in terms of internal factors). This is important, because the calculated energy performance and the heating system used in two identically constructed and equipped buildings at the same location may have significantly different actual heating energy use profiles, as a result of different occupancy patterns and desirable user indoor conditions [31]. Similar issues have also been reported for buildings that even meet high performance design and construction standards with the same LEED label [32] or as a result of differences among the parameters of thermal envelope performance for Passivhaus certified buildings [33]. Significant deviations among actual and calculated energy savings in residential buildings have been reported from field studies as a result of energy-saving measures, for example, in The Netherlands [34] and Greece [35].

Fig. 4 (for the multi-family building R1) and Fig. 5 (for the public building P1) illustrate the actual heat consumption with the two distinct controls using the weather based and forecast control mode as a function of the outdoor temperature. For each group of data, a linear regression correlation is also included in the figures. Using these correlations for the range of the outdoor temperature during the monitoring period (from −15 °C to + 15 °C), the average energy savings as a result of the forecast control are estimated at 12.9% for the R1 building and 13.2%

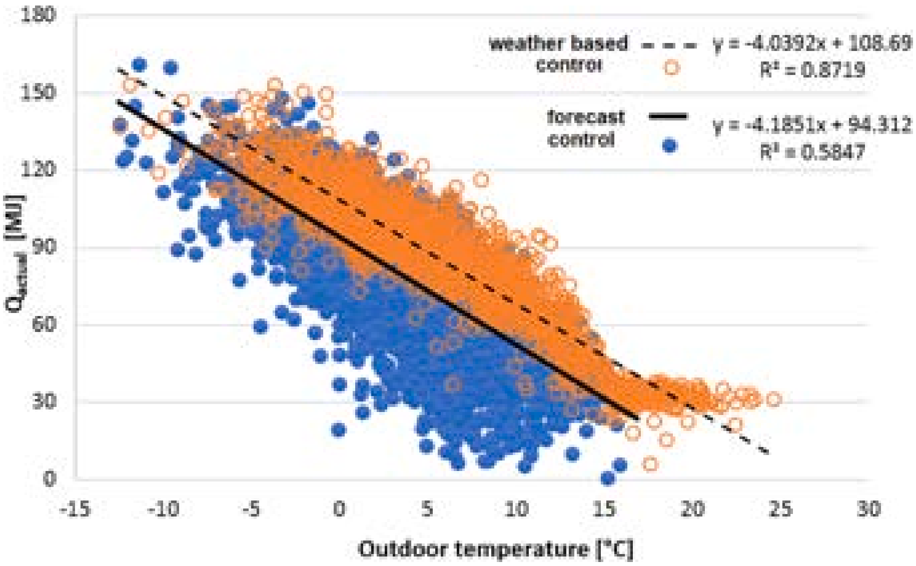

Fig. 4. Heat consumption for heating (Q_{actual}) in multi-family building R1 depending on the outdoor temperature for weather based and forecast control and 24-hour data.

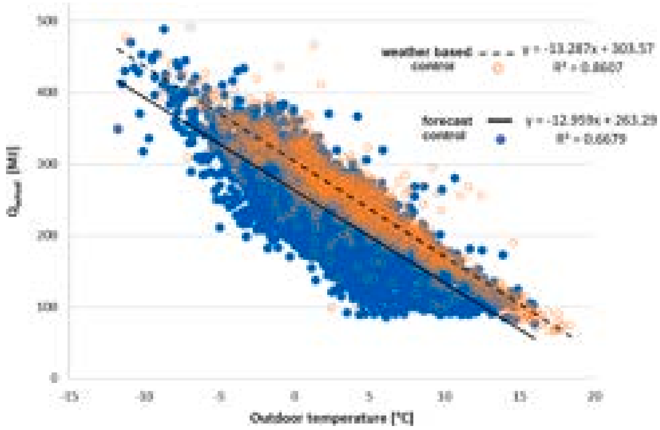

Fig. 5. Heat consumption for heating (Q_{actual}) in public building P1 depending on the outdoor temperature for weather based and forecast control and 24-hour data.

for the P1 building. These energy savings were achieved while the mean solar radiation was equal to 78 Wm^{-2} and 84 Wm^{-2} for the period with the weather-based control and the forecast control, respectively.

A more focused analysis during certain periods of the day can reveal some additional insight. For example, accounting for the availability of solar radiation during the early part of the day can have the most significant impact on the ambient air temperature. Accordingly, Fig. 6 and Fig. 7 illustrate the corresponding measured data from 7 am to 2 pm, during which the mean solar radiation was equal to 165 Wm^{-2} and 232 Wm^{-2} for the period with the weather-based control and the forecast control, respectively.

According to the results presented in Figs. 6 and 7, there is a shift to lower heat consumption during the day time periods (i.e. 7 am to 2 pm) when heat gains from solar radiation and an increase in outdoor temperature are usually expected. The average energy savings are higher by 5.4% for R1 and 0.8% for P1, compared to the data for the whole 24-h day. Therefore, higher energy savings will be expected from the use of the forecast control on the heating system by using the system during the daytime hours. This may also occur at different climate zones with higher fluctuations in outdoor conditions (especially outdoor air temperature) or favorable local microclimate conditions (the amount of available solar radiation).

However, during the periods of most adverse external conditions (e.g., during the night with low outdoor temperatures), energy savings mostly depend on the internal factors. This can also be taken into account in advance, for example, in the form of different profiles for the equivalent indoor temperature (T^{eq}_{indoor}), which is elaborated in [28]. For example, the actual heat consumption during the night time periods (i.e. 11 pm to 4 pm) in 10-minute time-steps are illustrated in Fig. 8. In this process, the additional T^{eq}_{indoor} reductions that occur during the night can also be taken into account, which will further increase the heat consumption savings.

On the basis of the results presented in Fig. 8, it can be concluded that acting in advance by the control process of the heating system in terms of user preferences at night (in this case, the period was taken from 11 pm to 4 am) can result in significantly lower heating use. For the multi-family building R1, savings reach 15.7% using the forecast control of heating compared to the conventional weather based control.

The energy savings that can be achieved owing to the use of the forecast control of heating does not remain the same throughout the heating season. Actually, it depends on the range of the outdoor temperature fluctuations and the amount of available solar radiation. This is illustrated by the results presented in Figs. 9 and 10 that compare the operation of the forecast control during the full heating season (i.e. December, January February, March, with mean solar radiation equal to 185 Wm^{-2} for the period from 7 am to 2 pm) and the transition seasons (April, May, September, October, November with mean solar radiation equal to 307 Wm^{-2} for the period from 7 am to 2 pm), respectively. Fig. 9 illustrates selected data for the analyzed multi-family building R1 from 11 pm to 4 am and Fig. 10 from 7 am to 2 pm.

On the basis of the data presented in Fig. 9, it is observed that at night, there is no significant difference in the achieved level of energy savings during the operation of the forecast control of heating between the full heating season and transitional period. This corresponds to the periods where there is no available solar radiation and no significant outdoor temperature variations. This is due to the fact that the forecast control system accounts for the forecasting of internal factors in a similar way (in this case in the form of T^{eq}_{indoor}) both for the full heating season and for the transitional period.

On the other hand, when analyzing the data presented in Fig. 10, it is concluded that during the transitional season from 7 am to 2 pm, the energy savings average 18.7%, which is higher than in the full heating season. This is due, among others, to the fact that during the transitional

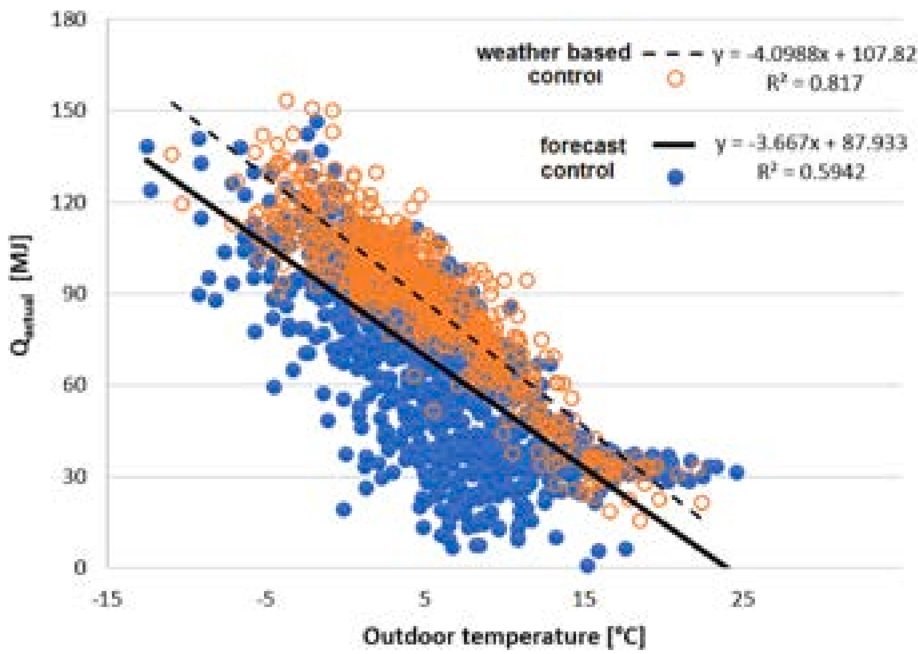

Fig. 6. Heat consumption for heating (Q_{actual}) in multi-family building R1 depending on the outdoor temperature for weather based and forecast control and data from 7 am to 2 pm.

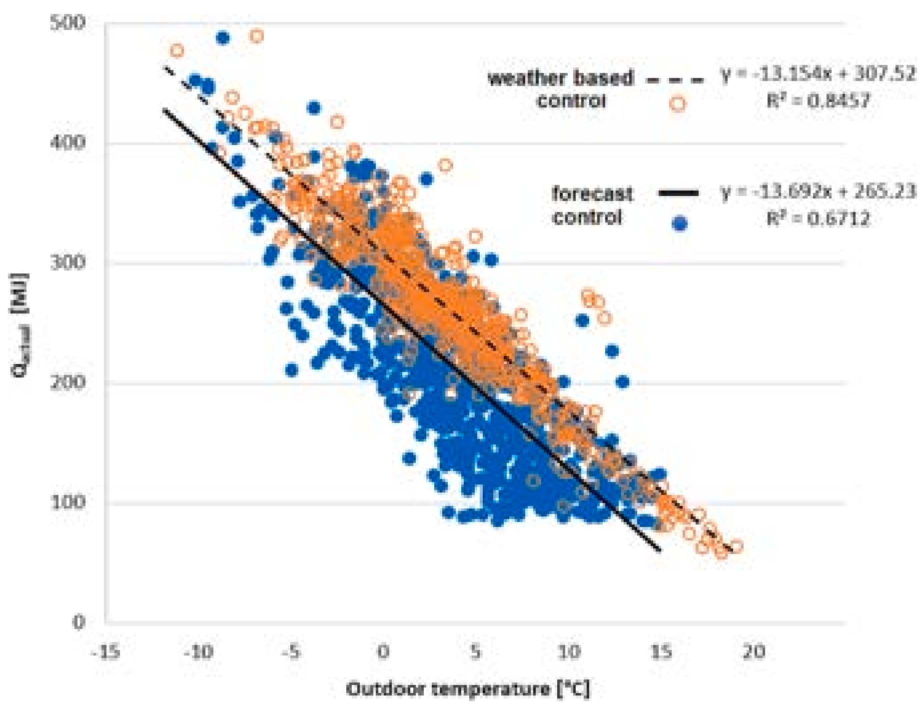

Fig. 7. Heat consumption for heating (Q_{actual}) in public building P1 depending on the outdoor temperature for weather based and forecast control and data from 7 am to 2 pm.

seasons there are more frequent and greater fluctuations of outdoor temperature and solar radiation.

The results analyzed in this section have elaborated the impact of external and internal factors on the level of energy savings achieved by the use of forecast control of the heating system. However, these results may not convince a potential investor to use the forecast control of heating in a building. Therefore, section 3.2 presents a long-term evaluation and economic assessment of the performance of forecast control system of heating.

3.2. Long term energy savings and payback time

The amount of heat delivered to the heating system in the analyzed buildings is illustrated in Fig. 11. The data correspond to the normalized heat consumption ($Q_{corrected}$) for all seven multi-family buildings (R1-R7) during the three heating seasons before and one heating season after the installation of the forecast control of the heating system. Similarly, Fig. 12 shows the corrected heat consumption ($Q_{corrected}$) for the three public buildings (P1-P3) during the nine heating seasons before and one heating season after the installation of forecast control system.

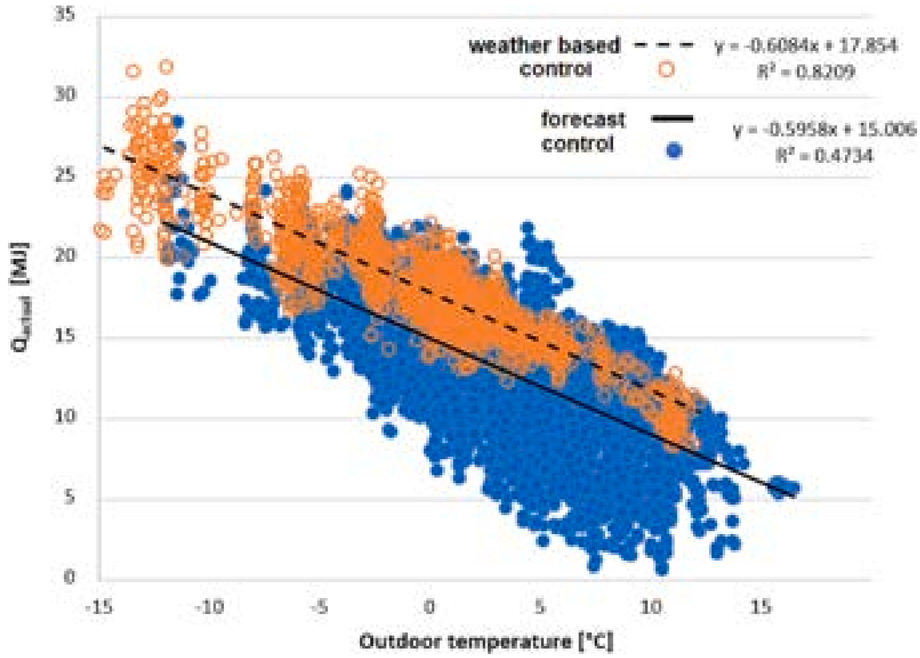

Fig. 8. Heat consumption for heating (Q_{actual}) in multi-family building R1 depending on the outdoor temperature for weather based and forecast control and data from 11 pm to 4 pm in 10 min resolution.

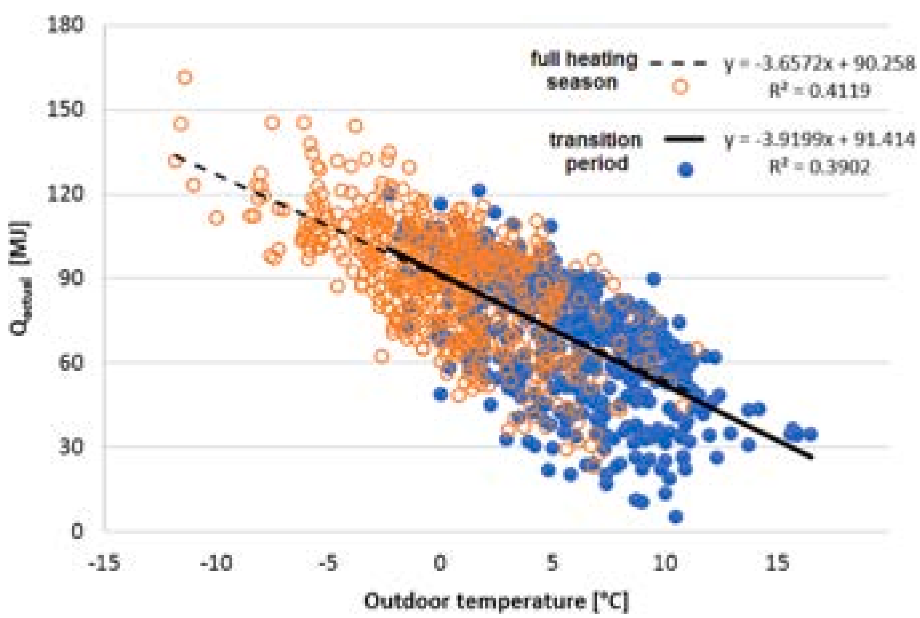

Fig. 9. Heat consumption for heating purposes (Q_{actual}) for a multi-family building R1 depending on the outdoor temperature for forecast control in the full heating season (December, January, February, March) and in the transition period (April, May, September, October, November) and selected data from 11 pm to 4 am.

On the basis of the average (from 3 heating seasons for buildings R1-R7 and from 9 heating seasons for buildings P1-P2) corrected heat consumption for heating of the analyzed buildings, it was possible to estimate the level of energy savings resulting from the use of the forecast control of the heating system. The results are summarized in Table 2.

On the basis of the available data in Table 2, it can be seen that the level of energy savings achieved owing to the use of the forecast control in multi-family buildings R1-R7 ranged from 11.3% to 18.9% (averaging 13.4%) and assumed higher savings for larger buildings. On the other hand, the energy savings for public buildings P1-P3 ranged from 8.3% to 13.7% (averaging 10.7%) and also assumed higher values for larger buildings. Higher percentage energy savings in larger buildings are achieved as a result of, among others, larger size buildings and bigger heating systems, which are characterized by greater thermal inertia. In addition, when the supply temperature of the heating medium is lowered as a result of the forecast control, greater energy savings are expected.

The payback time was estimated using the average energy savings resulting from the use of the forecast control and assuming the current heat price for 1GJ from a district heating network at €20. The energy prices were assumed to have an annual increase of 5% for the following heating seasons [36]. The results are summarized in Table 2. The first cost investment for the forecast module is assumed at €800, with an installation cost and integration with an existing weather based

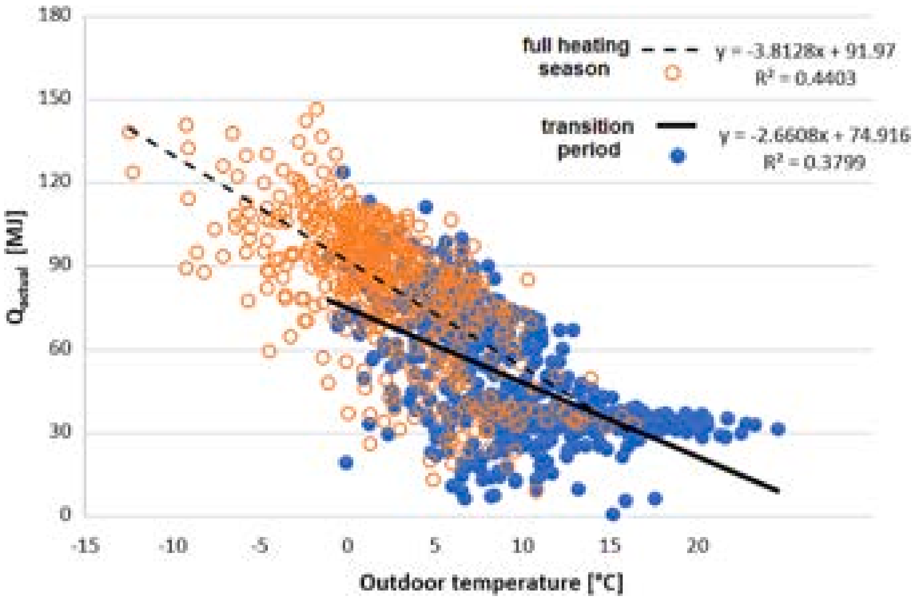

Fig. 10. Heat consumption for heating purposes (Q_{actual}) for a multi-family building R1 depending on the outdoor temperature for forecast control in the full heating season (December, January, February, March) and in the transition period (April, May, September, October, November) and selected data from 7 am to 2 pm.

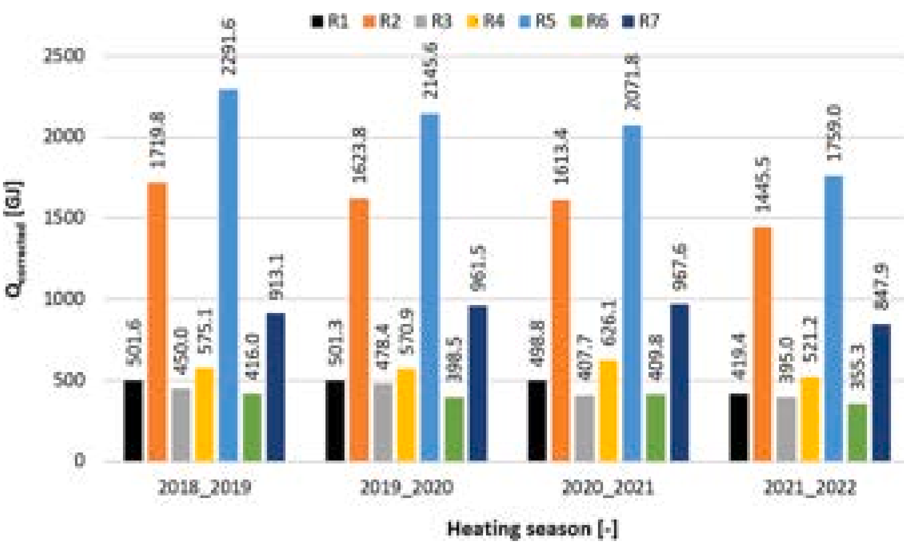

Fig. 11. Corrected heat used ($Q_{corrected}$) in residential buildings R1-R7 before (2018/2019–2020/2021) and after (2021/2022) the application of forecast control of the heating system.

controller at €200 per unit. The results are summarized in Table 2.

The use of a forecast control system in existing buildings gives very good economic results, with a payback time of the initial investment for an existing building ranging from 0.12 to 0.99 heating season for the analyzed multi-family buildings (R1-R7) and in the range from 0.14 to 1.09 heating season for the analyzed public buildings (P1-P3). The average payback time for all buildings was at 0.6 heating season. Shorter payback times are achieved for larger buildings that use more heat for heating purposes. In addition, taking into account the possible future increase in costs per unit energy of heat, the payback time of investment costs related to the use of forecast control of heating will continue to decrease.

Accordingly, the forecast control of heating is a highly competitive energy conservation measure that allows increasing the energy efficiency of the heating system in existing buildings in a quick, simple and consistent manner.

Regarding the limitations of the forecast control system of heating, it should be noted that it can only be used in hydronic heating systems where the heat source for heating has an existing weather based controller. Therefore, it is not recommended to use this solution in the buildings equipped with an air-conditioning system for heating and/or cooling (e.g. shopping centers).

This type of work may also be enhanced in order to quantify savings in more detail by monitoring the indoor temperature, internal heat gains, occupants' behavior, ventilation rate, and solar gains. Finally, the difference between the periods (before and after installation of forecast control) may provide uncertainty in terms of estimated energy savings and payback time.

4. Conclusions

The long term field research and monitoring of real buildings provided for the first time the data that can be used to evaluation of application of a forecast control of heating system (forHEAT) in existing

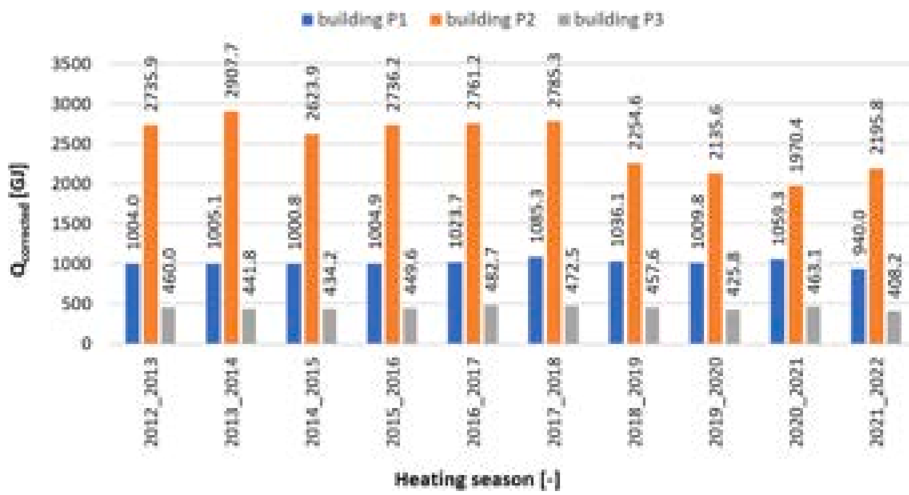

Fig. 12. Corrected heat used ($Q_{corrected}$) in public buildings P1-P3 before (2012/2013–2020/2021) and after (2021/2022) the application of forecast control of the heating system.

Table 2
Actual energy savings and payback time of application of forecast control of the heating system in the analyzed residential (R1-R7) and public (P1-P3) buildings.

Building	Mean corrected heat used before [GJ]	Mean corrected heat used after [GJ]	Mean energy savings per heating season [%]	Payback time [heating season]
R1	500.6	419.4	16.2	0.62
R2	1652.3	1445.5	12.5	0.24
R3	445.4	395.0	11.3	0.99
R4	590.7	521.2	11.8	0.72
R5	2169.7	1759.0	18.9	0.12
R6	408.1	355.3	12.9	0.95
R7	947.4	847.9	10.5	0.50
P1	1025.4	940.0	8.3	0.59
P2	2545.7	2195.8	13.7	0.14
P3	454.2	408.2	10.1	1.09

residential and public buildings. This novel control takes into account the forecast of outdoor conditions (outdoor temperature, wind speed, solar insolation) and indoor conditions (preferences of occupants in the form of profiles of T^{eq}_{indoor}), which allows achieving significant energy savings. Analysis of actual data revealed that compared to conventional weather based controllers, it is possible to average higher savings by 13.4% in residential and 10.7% in public buildings. The payback time of installation of such a forecast control of heating system in existing residential and public buildings averages 0.6 heating season. This can be shorter for large size buildings that use more heat before the application of the new control system.

As demonstrated, higher energy savings result from the use of this forecast control system when there is a higher daily amplitude of outdoor temperature and a higher number of hours with solar radiation. That is why, this control system is highly recommended in the climatic zone characterized by these features and long period of transition period between fall and winter as well as between winter and spring.

The proposed forecast control system can be easily installed and integrated in less than 2 h with commonly used weather based control systems that are available in most of existing buildings with hydronic heating system. Accordingly, it is a highly recommended and widely applicable measure to increase energy efficiency of heating systems in many of existing buildings, before transition to carbon neutral buildings.

Because of good energetic and economical results of application of the proposed forecast control in frame of heating systems in existing buildings, future research continues in the direction to check the possibilities to use of such a forecast control in cooling systems in buildings.

Future research will collect additional performance data from more installations, longer periods under different operational conditions and monitor the indoor conditions and actual occupant interactions. This will provide more insight about the system operational characteristics and actual savings in order to quantify in more detail the possible impacts of other influencing factors.

CRediT authorship contribution statement

Tomasz Cholewa: Conceptualization, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. **Alicja Siuta-Olcha:** Writing – original draft, Writing – review & editing. **Andrzej Smolarz:** Writing – review & editing. **Piotr Muryjas:** Writing – review & editing. **Piotr Wolszczak:** Writing – review & editing. **Łukasz Guz:** Writing – review & editing. **Martyna Bocian:** Writing – review & editing. **Gabriela Sadowska:** Writing – review & editing. **Wiktoria Łokczewska:** Writing – review & editing. **Constantinos A. Balaras:** Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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