Towards smart electric heaters for homes in-line with EN-ISO 52120 Standard

Hang Yin¹, Mohamed Hamdy¹
¹Norwegian University of Science and Technology (NTNU), Trondheim, Norway

Abstract
An advanced control system is needed for residential buildings according to the EN ISO 52120-1 standard, which requires to have a re-setting temperature setpoint considering variant load and occupancy pattern. Simple on-off control with a resetting setpoint normally has higher offset and worse setpoint tracking. In this paper, a PID controller was developed for residential heaters. The thermal performance was evaluated by IDA ICE-python co-simulation, and compared to on-off control. Results indicated the PID control saved 12.9%–18.8% energy use in high-insulated buildings. While it can save 28.5%–31.6% in poor-insulated buildings but need preheating or larger size of heaters due to the high heating demand.

Highlights
• Propose a PID control with re-setting temperature setpoint for residential electric heaters.
• Compare the performance of the proposed PID control against a traditional on-off control by co-simulation.
• Two techniques are proposed for adjusting PID control based on building characteristics and weather conditions.

Practical implications
The co-simulation work was conducted in collaboration with Mill International AS to develop a new generation of smart heaters for residential buildings, providing the company with valuable insights and data on how the smart heater can be implemented more efficiently.

Introduction
In Norway, the buildings sector accounts for 34% of total energy consumption, with over 75% being used for space heating (IEA, 2022). Norway has substantially electrified its buildings sector, and now over 84% of residential building energy consumption is supplied by direct or indirect electricity, with most buildings equipped with electric heaters (IEA, 2022). Consequently, the efficiency of electric heaters and their associated control systems is a significant concern that affects both energy costs and comfort. To reduce the energy consumption and maintain thermal comfort, the EN ISO 52120-1 standard suggests implementing Building Automation and Control Systems (BACS) in residential buildings with demand-controlled HVAC systems (EN ISO 52120-1, 2022). Towards achieving A efficiency class of BACS in the heating control system, the use of a variable setpoint with demand response and occupancy detection is recommended. Incorporating advanced control with resetting setpoints into smart building heating systems enables the optimization of energy consumption by reducing unnecessary heating. Additionally, it ensures a comfortable indoor environment when needed while minimizing energy wastage during unoccupied periods. These benefits contribute to a more energy-efficient, comfortable, and sustainable built environment with low carbon emissions.

The traditional on-off control with a deadband is commonly used for room temperature control in residential buildings due to its simplicity and cost-effectiveness. However, this control strategy may not be appropriate for temperature setpoints with periodic step-change resetting, as it can result in offset and poor setpoint tracking (T.Y. Chen, 2002). To address this limitation, a PID controller with a resetting temperature setpoint was proposed for smart electric heaters in residential buildings. In this paper, the proposed PID controller was developed in a Python script to provide the control signal for the electric heater in a Building Energy Model (BEM) created using IDA Indoor Climate and Energy (IDA ICE) simulation software. IDA ICE is a comprehensive building energy simulation software that can be used to analyze energy consumption and thermal comfort in buildings (Equa, 2022). The thermal performance of the electric heater equipped with the proposed PID controller was compared against a baseline on-off controller in terms of energy savings percentage and relative thermal comfort under different scenarios, such as building characteristics and weather conditions.

Methods
To evaluate the proposed PID control, a co-simulation workflow between IDA ICE and Python script is established, as illustrated in Figure 1.

A detailed BEM with an electric radiator is set up in IDA ICE 5.0 with defined weather conditions, building characteristics, and occupancy patterns. The PID controller with a resetting temperature setpoint is implemented using Python. A thermal sensor near the
electric radiator monitors the real-time air temperature in the target zone, which is transferred from IDA ICE to Python controller through an API. Then, the Python script computes the control signal based on the temperature errors between sensor temperatures and temperature setpoints, which operates the electric heater in IDA ICE model. The co-simulation was carried out for the month of January with a time resolution of 15 minutes.

![Diagram of IDA ICE-Python co-simulation workflow](image)

**Figure 1. IDA ICE-Python co-simulation workflow.**

**Study case**

A typical residential building with a target zone and an adjacent zone is chosen as the case study, as shown in Figure 2. The ceiling and the right-side external wall of the target room are connected to the outside environment, and the floor is connected to the ground. Other three facades of the target zone are internal walls connecting to the adjacent zone. The adjacent zone has a constant room air temperature of 16°C. In the target zone, there is a window facing the south without shading system, and an electric radiator is located below the window, responsible for controlling the room air temperature.

![Illustration of the study case](image)

**Figure 2. Illustration of the study case.**

The electric radiator has the maximum heating power of 600W, surface area of 0.26m² and longwave emissivity of 0.3. A thermal sensor is located 0.5m height besides the radiator, as shown in Figure 3.

![Thermal sensor and electric radiator](image)

**Figure 3. Thermal sensor and electric radiator.**

**PID control with a resetting setpoint**

The schematic of a conventional PID controller to control the room air temperature shown as follows (R. P. Borase, 2021):

\[
u(t) = K_p e(t) + K_i \int_0^t e(\tau) + K_d \frac{de(t)}{dt}
\]  

where \(e(t)\) representing the error between temperature setpoint \((T_s)\) and measured sensor temperature \((y)\). The controller computes derivative and integral errors with respect to time, and gives the control signal \(u(t)\) to the electric radiator for zone heating process. The proportional gain \((K_p)\), integral gain \((K_i)\), and derivative gain \((K_d)\) are the PID parameters. To eliminate the unwanted windup in setpoint resetting, the controller is saturated by adding an anti-windup actuator (Max = 0.9, Min = 0) in the feedback loop.

EN ISO 52120-1 standard recommends to having a resetting heating temperature setpoint (EN ISO 52120-1, 2022), where the setpoint is shifting between three operation modes:

- **Comfort mode**: \(T_s = 22^\circ C\)
  
  \((W: 6:30-8:00, 16:00-22:00; W/E: 9:00-23:00)\)

- **Sleep mode**: \(T_s = 18^\circ C\)
  
  \((W: 0:00-6:30, 22:00-24:00; W/E: 0:00-9:00, 23:00-24:00)\)

- **Away mode**: \(T_s = 16^\circ C\)
  
  \((W: 8:00-16:00; W/E: No)\)

A weekly heating temperature setpoint is shown in Figure 4, and the time for door openings is also marked in this figure. Each time, the door is left open for 1 min when occupant leaves or enters the room.

![Weekly scheduled heating setpoint with door openings](image)

**Figure 4. Weekly scheduled heating setpoint with door openings.**

**PID controller characteristic curve.**

PID controller is well-tuned by Mill International AS (Mill, 2022). The characteristic curve of the proposed PID controller during two representative days is shown in Figure 5. The air temperature around the temperature sensor is the control variable that the PID controller aims to regulate (green line). The PID control is tuned according to the response of the sensor temperature. The
mean air temperature (red line) is also simulated, which is considered as an indicator of thermal comfort in the target zone. Using the given PID parameters, there is a steady-state offset of about -0.4°C below the desired temperature setpoint with small fluctuations of ±0.2°C. During weekends, a longer settling time is observed compared to weekdays due to the frequency of door openings and closings, which takes more time to reach the steady state. In the weekdays morning from 6:30 to 8:00, the PID control cannot reach a steady state in that short amount of time. However, from 16:00 to 23:00, it takes about 1 hour to reach the steady state with a steady-state offset of around -0.4°C.

Figure 5 also shows the mean air temperature is higher than the measured sensor temperature, with a discrepancy of around 1°C. This is because the thermal sensor is placed beside the electric radiator, so it is rarely affected by the upward warmed air flow. Another reason is that in the IDA ICE simulation model, the sensor temperature is measured as the point air temperature on the inner side of the external wall, which may be colder than the actual sensor temperature in practice. Therefore, considering the difference between the sensor temperature and mean air temperature, this steady-state error of the PID control is maintained as it was tuned.

**Building characteristics**

The performance of the heating control system is evaluated in a case study with two different building characteristics, TEK 10 buildings and typical old Norwegian buildings (Felius, 2020). TEK 10 buildings fulfill the energy efficiency requirements of residential buildings outlined in Norwegian Building technical regulation TEK10 (TEK10, 2010). Typical old buildings represent old Norwegian residential buildings built between the 1960s and 1990s (Marit, 2009), which are known for their lower insulation and higher infiltration rate. Building envelope parameters for these two building types are summarized in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TEK10 building</th>
<th>Typical old building</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-value outer wall (W/m²K)</td>
<td>0.18</td>
<td>0.38</td>
</tr>
<tr>
<td>U-value floor (W/m²K)</td>
<td>0.10</td>
<td>0.36</td>
</tr>
<tr>
<td>U-value roof (W/m²K)</td>
<td>0.13</td>
<td>0.20</td>
</tr>
<tr>
<td>U-value windows/doors (W/m²K)</td>
<td>0.80</td>
<td>2.8</td>
</tr>
<tr>
<td>Averaged infiltration rate (1/h)</td>
<td>0.60</td>
<td>4.0*</td>
</tr>
<tr>
<td>Normalized thermal bridge (W/m²K)</td>
<td>0.05</td>
<td>0.07</td>
</tr>
</tbody>
</table>

*An additional ventilation hatch is set on the top of room’s window to reflect the high infiltration rate in this type of buildings.*

The ventilation system of TEK10 buildings complies with the minimum requirement of residence room specified in the TEK10 standard (TEK10, 2010). The target zone of TEK10 buildings is equipped with a balanced mechanical ventilation system with the supply air temperature of 16°C, and constant supply and exhaust air rates of 1.2m³/(h·m²). For typical old Norwegian buildings, the target zone relies solely on infiltration for ventilation, without the use of a mechanical ventilation system. To simulate a large infiltration in this type of buildings, in addition to setting an averaged infiltration rate of 4.0h⁻¹, an additional ventilation hatch with the area of 0.0192 m² is set to emulate the opening hole above the window. In both two cases, the adjacent zone has an exhaust ventilation with the exhaust air rate of 0.7m³/(h·m²).

Figure 6 compares the net heat inflow through the external wall, internal wall, and mechanical ventilation in the two study cases at -7°C. The heat flux through the external wall is mainly related to the infiltration rate. The heat loss from the external wall in the old building case can reach up to 120W, while for the TEK10 building case, the heat loss is around 80W. The heat loss through mechanical ventilation in TEK10 buildings can reach up to 60W when the heating temperature setpoint is set at 22°C. This heat loss is caused by supplying cold fresh air to the target zone and exhausting the warmed room air. It can also be observed that there is a heat loss through the internal wall. This can be explained that the exhaust ventilation in the adjacent zone drawing air from the target zone into the adjacent zone due to the pressure differential between the two zones. As the air in the target zone is heated by the electric heater, this air movement to the adjacent zone also carries the heat flux with it.

![Figure 6. Net heat inflow of external wall, internal wall, and mechanical ventilation in two study cases.](https://doi.org/10.26868/25222708.2023.1155)
same as the actual conditions in Oslo, Norway during the month of January, 2021.

Performance evaluation

The thermal performance of the proposed PID controller is compared to that of the baseline on-off controller during a one-month simulation period. The baseline on-off controller has a deadband of ±1°C and reacts to a constant heating setpoint of 22°C. The total heating energy consumption during the simulation period is used to evaluate the energetic performance. The percentage of energy savings ($P_{\text{Energy}}$) was calculated as:

$$P_{\text{Energy}} = \frac{E_{\text{on-off}} - E_{\text{PID}}}{E_{\text{on-off}}} \times 100\% \quad (2)$$

where $E_{\text{on-off}}$ and $E_{\text{PID}}$ (kWh) are the total heating energy consumption of baseline on-off control and PID control over one month. The thermal comfort was evaluated using the under-heating deviation degree per day (DD$_{uh}$), as calculated in Eq.(3).

$$DD_{uh} = \frac{\sum (T_a - T_s)^2}{n} \quad (3)$$

where the $T_a$ and $T_s$ represent the volume-averaged mean air temperature and the temperature setpoint, respectively, and $n$ represents the number of days during the simulation period. DD$_{uh}$ calculates the daily accumulated discrepancy values when mean air temperature is below the temperature setpoint. The decrease in the value of DD$_{uh}$ indicates an improvement in thermal comfort. The relative deviation degree (RDD$_{uh}$) is also defined by comparing the DD$_{uh}$ values of two controllers:

$$RDD_{uh} = DD_{uh \text{ on-off}} - DD_{uh \text{ PID}} \quad (4)$$

where DD$_{uh \text{ on-off}}$ and DD$_{uh \text{ PID}}$ (°C/day) are the under-heating deviation degree of baseline on-off control and PID control. The value of RDD$_{uh}$ (°C/day) is positive and larger indicates that PID control provides better thermal comfort compared to the on-off control.

Results

TEK10 building

The total heating energy consumption and thermal comfort of the baseline on-off control and the proposed PID control in TEK10 buildings at different outdoor conditions are summarized in Table 2 and Table 3, respectively. The corresponding energy savings and improvements in thermal comfort are also calculated for different outdoor conditions. Furthermore, the variations in room air temperature and heating power during a representative week are displayed below.

<table>
<thead>
<tr>
<th>$T_o$</th>
<th>$E_{\text{on-off}}$ [kWh]</th>
<th>$E_{\text{PID}}$ [kWh]</th>
<th>$P_{\text{Energy}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7°C</td>
<td>183.9</td>
<td>149.4</td>
<td>18.8</td>
</tr>
<tr>
<td>0°C</td>
<td>134.0</td>
<td>113.6</td>
<td>15.2</td>
</tr>
</tbody>
</table>

In the case of the highly insulated TEK10 building, the proposed PID control demonstrates lower energy consumption compared to the on-off control under the same outdoor conditions. The percentage of energy savings is influenced by the outdoor air temperature, with greater energy savings achieved as the outdoor air temperature decreases. For example, at an outdoor air temperature of -7°C, the proposed PID control can achieve energy savings of up to 18.8%, while operating at 7°C results in energy savings of only 12.9%.

Table 3. Thermal comfort of baseline on-off control and PID control in TEK10 buildings.

<table>
<thead>
<tr>
<th>$T_o$</th>
<th>$DD_{uh \text{ on-off}}$ [°C/day]</th>
<th>$DD_{uh \text{ PID}}$ [°C/day]</th>
<th>$RDD_{uh}$ [°C/day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7°C</td>
<td>18.0</td>
<td>7.7</td>
<td>10.3</td>
</tr>
<tr>
<td>0°C</td>
<td>23.3</td>
<td>0.5</td>
<td>22.8</td>
</tr>
<tr>
<td>7°C</td>
<td>28.1</td>
<td>0.2</td>
<td>27.9</td>
</tr>
</tbody>
</table>

Figure 7. Baseline on-off control operated in TEK10 buildings at -7°C outdoor condition.
Typical old building

Typical old Norwegian buildings, with low-insulated envelopes and higher infiltration rates, have a greater potential for energy savings when employing the proposed PID control. Table 4 shows the total heating energy consumption of the PID control is lower than that of the baseline on-off control under the same outdoor conditions, resulting in energy savings ranging from 28.5% to 31.6%. However, it is important to consider the impact on thermal comfort performance. Table 5 reveals that when the outdoor air temperature falls below 0°C, the PID control leads to more thermal discomfort compared to the on-off control, as indicated by the relatively higher value of DDah for the PID control. Nevertheless, under outdoor condition of 7°C, the PID control provides a higher level of thermal comfort. The reason for the decrease in thermal comfort when using the PID control in cold outdoor conditions is explained in Figure 10.

Table 4. Total heating energy consumption of baseline on-off control and PID control in typical old Norwegian buildings.

<table>
<thead>
<tr>
<th>T0</th>
<th>Eon-off</th>
<th>EPID</th>
<th>PEnergy</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7°C</td>
<td>355.4</td>
<td>244.7</td>
<td>31.1</td>
</tr>
<tr>
<td>0°C</td>
<td>267.5</td>
<td>183.0</td>
<td>31.6</td>
</tr>
<tr>
<td>7°C</td>
<td>179.5</td>
<td>128.3</td>
<td>28.5</td>
</tr>
</tbody>
</table>

Table 5. Thermal comfort of baseline on-off control and PID control in typical old Norwegian buildings.

<table>
<thead>
<tr>
<th>T0</th>
<th>DDah, on-off</th>
<th>DDah, PID</th>
<th>RDDah</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7°C</td>
<td>4.4</td>
<td>64.6</td>
<td>-60.2</td>
</tr>
<tr>
<td>0°C</td>
<td>8.6</td>
<td>30.9</td>
<td>-22.3</td>
</tr>
<tr>
<td>7°C</td>
<td>13.7</td>
<td>3.5</td>
<td>10.2</td>
</tr>
</tbody>
</table>

Figure 10(a) and Figure 10(b) indicate that even with the electric heater operating at full capacity, the desired temperature setpoint cannot be achieved during the “comfort mode” period. When the outdoor temperature is 7°C, the maximum room air temperature recorded on weekdays is only about 20°C, despite the heating power being maintained at 600W. This indicates that the current heating capacity of the electric heater is insufficient to meet the heating demand in typical old Norwegian buildings with a resetting temperature setpoint.
To enhance the thermal performance in such buildings, two potential approaches are proposed:

- **Preheating-time**: Adjust the temperature setpoint schedule to allow for preheating of the room, ensuring that the room air temperature reaches the desired temperature on time.
- **Larger heater size**: Increase the heating capacity of the electric heater to provide sufficient power to meet the heating demand.

Therefore, two additional simulations for the adjusted PID control are presented below.

**Adjusted PID control with preheating time**

<table>
<thead>
<tr>
<th>$T_0$ [°C]</th>
<th>$E_{on-off}$ [kWh]</th>
<th>$E_{PID}$ [kWh]</th>
<th>$P_{Energy}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7°C</td>
<td>355.4</td>
<td>264.3</td>
<td>25.6</td>
</tr>
<tr>
<td>0°C</td>
<td>267.5</td>
<td>210.1</td>
<td>20.3</td>
</tr>
</tbody>
</table>

Table 7. Thermal comfort of baseline on-off control and preheat PID control in typical old Norwegian buildings.

<table>
<thead>
<tr>
<th>$T_0$ [°C]</th>
<th>$DD_{ah, on-off}$ [°C/day]</th>
<th>$DD_{ah, PID}$ [°C/day]</th>
<th>$RD_{ah}$ [°C/day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7°C</td>
<td>4.4</td>
<td>32.3</td>
<td>-27.9</td>
</tr>
<tr>
<td>0°C</td>
<td>8.6</td>
<td>1.7</td>
<td>6.9</td>
</tr>
<tr>
<td>7°C</td>
<td>13.7</td>
<td>0.0</td>
<td>13.7</td>
</tr>
</tbody>
</table>

Figure 11. Comparison of mean air temperature in typical old Norwegian buildings with default PID control and preheat PID control.

Adjusting the temperature setpoint schedule to initiate heating earlier is a cost-effective approach to enhance the heating performance of electric heaters with limited heating capacity in buildings with low-insulated envelopes and higher infiltration rates. To balance heating demand and energy costs, a two-hour preheating time is added to the temperature setpoint schedule when shifting from “sleep/away mode” to “comfort mode”. This modified temperature setpoint, incorporating a two-hour preheating time, is implemented in the PID control,
referred to as “preheat PID control”. The preheat PID control is evaluated under three different outdoor conditions and compared to the baseline on-off control.

Table 6 indicates that the preheat PID control still saves heating energy consumption compared to the baseline on-off control, with energy savings percentages of 25.6%, 20.2%, and 19.4% at outdoor temperatures of -7°C, 0°C, and 7°C, respectively. In terms of thermal comfort, the preheat PID control offers better thermal comfort levels while still achieving notable energy savings, although slightly lower than the default PID control.

Figure 11 illustrates the comparison of mean air temperatures in typical old Norwegian buildings using the default PID control and the preheat PID control. The results reveal that, even with the same two-hour preheating time, the desired temperature during “comfort mode” is still not achieved at -7°C outdoor condition, but is precisely achieved at 0°C. In contrast, at an outdoor temperature of 7°C outdoor condition, the preheating time proves unnecessary as the default PID control already provides sufficient heating capacity. This indicates that the importance of adjusting the preheating time based on the outdoor air temperature, where colder outdoor conditions require longer preheating durations.

**Adjusted PID control with larger heater size**

To address the issue of insufficient heating capacity of the default electric heater, employing larger size of electric heaters in typical old Norwegian buildings would be a solution. The thermal performance of the baseline on-off control and the PID control are then compared when using 800W or 1000W electric heaters. Table 8 and Table 10 display the heating energy consumption of the two controls when utilizing an 800W and 1000W electric radiator, respectively. The results indicate that the PID control achieves energy savings of 23.8% to 24.8% with an 800W heater, and 17.4% to 19.1% with a 1000W heater. When considering thermal comfort, the DD$_{ah}$ values in Table 9 and Table 11 are analyzed. With a 1000W heater, the DD$_{ah}$ values for the PID control range from only 0.3°C to 6.0°C. However, when utilizing an 800W heater, the DD$_{ah}$ values for the PID control are higher, ranging 0.3°C to 24.7°C. Thus, it can be concluded that applying the PID control to electric heaters with larger sizes greatly improves thermal comfort while reducing the potential for energy savings.

Table 6. Total heating energy consumption of baseline on-off control and PID control in typical old Norwegian buildings (800W electric radiator).

<table>
<thead>
<tr>
<th>$T_o$ [°C]</th>
<th>$E_{on-off}$ [kWh]</th>
<th>$E_{PID}$ [kWh]</th>
<th>$P_{Energy}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7°C</td>
<td>347.3</td>
<td>261.5</td>
<td>24.7</td>
</tr>
<tr>
<td>0°C</td>
<td>261.0</td>
<td>196.3</td>
<td>24.8</td>
</tr>
<tr>
<td>7°C</td>
<td>175.7</td>
<td>133.8</td>
<td>23.8</td>
</tr>
</tbody>
</table>

Table 9. Thermal comfort of baseline on-off control and PID control in typical old Norwegian buildings (800W electric radiator).

<table>
<thead>
<tr>
<th>$T_o$ [°C]</th>
<th>DD$_{ah, on-off}$ [°C/day]</th>
<th>DD$_{ah, PID}$ [°C/day]</th>
<th>RDD$_{ah}$ [°C/day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7°C</td>
<td>14.8</td>
<td>24.7</td>
<td>-9.9</td>
</tr>
<tr>
<td>0°C</td>
<td>18.5</td>
<td>7.5</td>
<td>11.0</td>
</tr>
<tr>
<td>7°C</td>
<td>21.6</td>
<td>0.3</td>
<td>21.3</td>
</tr>
</tbody>
</table>

Table 10. Total heating energy consumption of baseline on-off control and PID control in typical old Norwegian buildings (1000W electric radiator).

<table>
<thead>
<tr>
<th>$T_o$ [°C]</th>
<th>DD$_{ah, on-off}$ [°C/day]</th>
<th>DD$_{ah, PID}$ [°C/day]</th>
<th>RDD$_{ah}$ [°C/day]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7°C</td>
<td>334.6</td>
<td>270.8</td>
<td>19.1</td>
</tr>
<tr>
<td>0°C</td>
<td>248.2</td>
<td>202.4</td>
<td>18.4</td>
</tr>
<tr>
<td>7°C</td>
<td>164.6</td>
<td>135.9</td>
<td>17.4</td>
</tr>
</tbody>
</table>

Table 11. Thermal comfort of baseline on-off control and PID control in typical old Norwegian buildings (1000W electric radiator).

**Figure 12.** Comparison of mean air temperature in a typical old Norwegian building heated by varied sizes of electric radiator with PID control.
Figure 12 compares the mean air temperatures in a typical old Norwegian building heated by electric heaters of different sizes, using the default PID control. In Figure 12(c), it can be observed that there is significant overshoot occurring when using a 1000W electric heater at 7°C outdoor condition during temperature setpoint changes. In addition, with larger electric heaters, the stability of the PID control is compromised when the door is opened or closed, as indicated by small disturbances when the setpoint is 22°C on weekends. In Figure 12(a), although 1000W electric radiator with the PID control can meet the heating demand at -7°C outdoor temperature, there is significant fluctuation during nighttime when the room air temperature drops to 18°C due to the heating temperature setpoint shifting from “comfort mode” to “sleep mode”. On the other hand, the control performance is more stable with the 800W electric heater, with less offset and fluctuations, although the thermal comfort of the PID control at extreme cold weather may not be guaranteed.

Overall, for a low-insulated building with high heating demand, an 800W electric heater is deemed suitable when paired with the proposed PID control, which enables to balance the energy savings and thermal comfort, resulting in potential energy savings of up to 24.8% while improving thermal comfort. However, for a 1000W electric heater, further tuning of the PID control is necessary to enhance stability.

Discussion

This section discusses the cost optimality of the proposed PID control for electric heaters in residential buildings, which involves a trade-off between performance and costs. The proposed PID control has better performance than the traditional on-off control for operating the heating system in residential buildings, while the costs of implementation and operations are much higher compared to the on-off control. It is time-consuming and costly of tuning the PID parameters for achieving good response with large disturbances coming from unpredictable occupant activities and weather conditions. To limit the costs and improve the control performance, an adaptive PID control with self-tuning capabilities could be used in residential buildings (A. G. Alexandrov, 2014). The adaptive PID control adjusts its parameters dynamically, and adapts to disturbance and changes of operational conditions without experts’ involvements.

The cost optimality of preheating strategy and heater size are discussed as follows:

- **Preheating strategy**

To achieve cost optimality in preheating strategy, the relationships between performance and operational costs can be investigated under different scenarios. In our study, two-hour preheating with a step change is employed. The step-change in temperature setpoints would cause overshoot, leading to lower energy efficiency. In addition, the preheating time should be optimized by considering the outdoor temperatures and building insulation levels. Generally, poor building insulation and colder outdoor conditions require a longer preheating time for the heater, which enables indoor temperatures reaching to its desired temperatures. Overall, this simple preheating strategy implemented in this study would not enable to track the desired temperature. A more advanced controller, Model Predictive Control (MPC), could be used to eliminate the overshoot and minimize the energy cost dynamically. At each time step, the optimizer in MPC enables to find the optimal temperature setpoint that drives the predicted air temperature as close to the desired air temperature as possible. Kumar, U. et al. (U. Kumar, 2020) compares the setpoint tracking of the PID and MPC controllers and indicating that MPC has good setpoint tracking without overshoot problem, which is more efficient and reliable than PID controller. In future, MPC controller would be implemented in these two cases and compared to the proposed PID controller.

- **Heater size**

Choosing an appropriate size of electric radiators is important for cost optimality because an oversized electric radiator would result in unnecessary energy consumption and increased energy costs, while an undersized electric radiator would not be able to provide enough heat and may result in discomfort for occupants. Additionally, choosing an appropriate size of electric radiators is also important for implementing the PID control, which normally require a certain heating capacity to achieve optimal performance.

In our study, 600W electric radiator is enough to have the good thermal performance in high-insulated TEK10 buildings, while for low-insulated old Norwegian buildings, it may need 800W electric radiator with the trade-off between energy savings and thermal comfort. The value of DDₘₙ can be used as thermal comfort indicator for choosing the heater size.

Conclusion

Co-simulation is conducted to compare the proposed PID control and the baseline on-off control under different building characteristics and outdoor conditions. Main findings outlined:

- The PID control with a resetting temperature setpoint has a high potential for energy savings, particularly in Nordic residential buildings located in cold climates. It can achieve energy savings of up to 18.8% in high-insulated TEK10 buildings, and up to 31.6% in low-insulated old buildings.
- A 600W electric radiator with the proposed PID control enables to provide thermal comfort in TEK10 buildings, but it lacks sufficient heating capacity for typical old Norwegian buildings, which have higher heating demands.
Preheating can improve the thermal comfort of the PID control, but limits the potential for energy savings. It can achieve up to 25.6% energy savings in typical old Norwegian buildings.

To overcome this limitation, a larger size of the electric heater is needed for typical old Norwegian buildings. Results indicate that applying the proposed PID control on electric radiators with larger sizes can greatly improve thermal comfort but reduce the potential for energy savings. It can save 23.8% to 24.8% using an 800W heater and save 17.4% to 19.1% using a 1000W heater.

The cost optimality of preheating and heater size is discussed to provide the best trade-off between performance and costs for the proposed PID control in residential buildings, considering different scenarios.

Acknowledgement
This work was done at the Research Center on Zero Emission Neighborhoods in Smart Cities in Norway. The authors gratefully acknowledge the support of the Mill International AS.

References


