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In situ evaluation of thermostat setback scenarios for all-electric single-family houses in cold climate

Sébastien Jacquet[a], Célyn Le Bel[b], Danielle Monfet[a,*]

[a] Department of Construction Engineering, École de technologie supérieure, Montréal, Canada
[b] Laboratoire des Technologies de l'Énergie (LTE), Institut de Recherche d'Hydro-Quebec, Shawinigan, Canada

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A B S T R A C T

For residential customers living in a cold climate, energy savings during the heating season are often achieved through thermostat setbacks. In order to gain insight into this phenomenon, the Laboratoire des Technologies de l'Énergie (LTE) of Hydro-Québec has used its unique twin-houses test bench that consists of two all-electric single-family houses heated by baseboards individually controlled in each room by a line-voltage electronic thermostat. The objective of this paper is to evaluate and analyse three different thermostat setback scenarios of 4 °C (night, day and dual setbacks) using in-situ measurements at the LTE twin-houses facility. The results show that at the house level, savings of 10 ± 5.9% were possible for day time and night time setbacks, while being more important for dual setback scenarios. The obtained results also show that the savings and comfort conditions varied greatly from one floor to another.

1. Introduction

For residential customers living in a cold climate, energy savings during the heating season are often achieved through thermostat setbacks. However, for a market dominated by electric space heating, such as Québec where close to 70% of single-family houses uses electricity for space heating [1], the simultaneous implementation of thermostat setback strategies could lead to significant increase in peak demand. If no time-of-use pricing is in place, the consumers opt to minimize their overall energy use without having any consideration for the effect of such strategies on the demand on the electric grid. Consequently, the required installed capacity is higher, influencing the investment costs and environmental impact at the house and utility levels.

The impact of thermostat setback strategies on energy use have been evaluated mainly using simulation tools; only a few studies are based on in-situ measurements. The proposed strategies are either evaluated in terms of energy use and occupant thermal comfort at the consumers' level, or under demand control strategies for specific time-of-use pricing schedule at the utility level.

1.1. Thermostat setback strategies

The analysis of thermostat setback scenarios can be categorized in two different evaluation approaches: (1) use of numerical analysis/simulation to evaluate the potential of the proposed scenarios and (2) real-scale measurements.

1.1.1. Numerical analysis and simulation

Most numerical analysis/simulation studies have shown a strong influence of house construction and climatic conditions on the setback scenario outcomes. For example, a hybrid computer model, developed using mathematical equations that express the thermal energy flow of the entire house and the closed loop heating control system, was used to test night, day, and dual thermostat setback scenarios in a single-family house heated by a gas-fired forced air furnace for 4 US cities [2]. The comparisons were based on heating-degree days (HDD) for two temperature setback values (21.1 °C/18.3 °C and 21.1 °C/15.5 °C) and showed that the level of insulation and outdoor air conditions influenced the energy savings, which were double for dual setback [2].

Another investigation was completed using DOE2.1A for different house constructions (classified as loose, tight and very tight) and US locations, and two space heating systems: a furnace with zonal control or zonally controlled electric baseboards [3]. The performed analysis demonstrated that the benefits of the proposed setback strategies (21.1 °C/15.6 °C) might be counterproductive

* Corresponding author at: Department of Construction Engineering, École de technologie supérieure, Montréal, Canada.
E-mail addresses: danielle.monfet@etsmtl.ca, d_monfet@hotmail.com (D. Monfet).

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owing to corollary effects such as increased peak loads and degradation of the system efficiency. Similar results were obtained in a parametric analysis of setback strategies for single-family homes for two climate zones [4], where three parameters were looked at: (1) setback period; (2) set point temperature; and (3) setback temperature. The results demonstrated that during recovery time additional energy use was noted, supporting the need for additional research to identify the most promising thermostat setback scenarios.

1.1.2. Real-scale measurements

Numerical analysis and simulation provide great insight into real life phenomena; however, the results obtained might be influenced by the modeling technique and software assumptions. Therefore, various attempts have been made to evaluate thermostat control strategies in real residential buildings. For example, thermostat setback scenarios were tested for two years in a passive solar airtight residential house heated by an electric furnace and showed to be relatively ineffective [5]. The proposed setback strategies meant greater demand at the recovery time requiring a larger installed space heating capacity, resulting in financial disadvantages.

Another in-situ residential study of building performances evaluated building energy consumption and thermal performance of exterior walls [6]. The calculation of the wall temperature gradients and its impact on steady-state method to estimate energy use in buildings showed as much as 40% difference with simulated results. The results suggested that long-term data monitoring and evaluation could lead to improve prediction and provide more realistic hypothesis for the design of high performance building.

Another series of tests were conducted on real-scale residential buildings at the Canadian Centre for Housing Technology (CCHT) located in Ottawa, Canada, for different winter thermostat setback strategies [7]. The most recent study on the R-2000 houses, which are heated using a gas furnace, showed the influence of the setback scenarios and climatic conditions on the saving potentials: for outdoor air temperature higher than 4 °C, the possible energy savings were around 10% [8]. However, when the outdoor temperature is colder and the solar heat gain minimum (cloudier days), the energy savings can be as high as 21%. For the evaluated thermostat setback scenarios, the recovery time, affecting thermal comfort, was also considered and was as high as 2.25 h. Consequently, the possible savings were tainted by a decrease in thermal comfort for the occupant.

1.2. Demand response strategies

There has been an increase use of demand response strategies that try to minimize the peak energy demand or the overall energy use. In Québec, there is no time-of-use pricing in place at the residential level; consequently, the consumers opt to minimize their overall energy use without having any consideration for the effect of such strategies on increasing the peak demand at the utility level. In response to this problematic, various approaches have been proposed to evaluate the impacts of such strategy for the consumer and the utility. In Québec, the impact of thermostats setbacks for both the consumer and the utility has been initially studied, using computer simulations, on single-family all-electric houses [9]. The obtained results showed savings for the consumer that varied slightly depending on the location, the setback duration and depth and the house construction characteristics. On the utility side, the maximum demand (saturation time) was shown to depend on the characteristics of the house and of the setback. Initial attempts to experimentally assess the impact of the proposed setback scenarios were carried out using a one room experimental setup, where some discrepancies were noticed between the findings drawn from the results obtained using the simulation tools versus the actual measured savings.

Since thermostat setbacks affect the utility peak load, different control algorithms have also been developed to mitigate the peak demand without eliminating the energy savings for the consumers. One proposed solution was to use a 2 h non-linear ramp to increase the room temperature following a setback scenario [10]. Other algorithms have also been explored, such as capacity limiting algorithm and set point limiting algorithm, but have shown reduced heating capacity that could compromise the thermal comfort of the occupant [11]. Instead, scenarios based on set point modulation have been proposed [12]. The obtained results were influenced by the technology available to implement the scenarios and thermal comfort criteria. Different standards are available to assess thermal comfort, such as ISO 7730 [13] and ASHRAE 55–2013 [14], which recommend comfort ranges according to different criteria. For example, ASHRAE 55–2013 proposes the use of operative temperature, which considered the air and radiative temperatures, to evaluate comfort conditions. Only few studies have looked at these criteria (e.g. [15]) and concluded that temperature changes could influence the thermal comfort zone.

The studies presented in the literature showed a lack of experimental data to fully understand and evaluate the impact of setback scenarios in terms of energy use, peak demand and disruption of thermal comfort conditions, especially using a global approach where the dynamics of the house can be assessed. Since airtightness and envelope performance have become more stringent with recent improvements made to building codes, the impact of thermostat setback strategies in new construction needs to be evaluated in terms of thermal comfort and overall energy use, including peak demand and recovery time. In order to gain insight into this phenomenon, the Laboratoire des Technologies de l'Énergie (LTE) of Hydro-Québec, an electricity utility provider located in Québec Canada, has used a unique twin-houses test bench. The twin-houses test bench consists of two all-electric single-family houses heated by baseboards individually controlled in each room by a line-voltage electronic thermostat. The objective of this paper is to evaluate and analyse various thermostat setback scenarios (night, day and dual setbacks) using the twin-houses test bench and their impact on peak demand, peak-energy use duration, energy consumption, and indoor temperature recovery time under dynamic conditions. The novelty of the twin-houses test bench lies in its ability to allow a storey-by-storey analysis (basement, ground and second floors) as well as a whole-house analysis.

2. LTE's experimental test houses

The LTE's experimental test houses [16], located in Shawinigan Canada, consist of two identical all-electric houses representing typical residential buildings found in the province of Québec. The city of Shawinigan, QC, Canada is representative of Eastern North-American average cold-climate with approximately 5000 heating degree-days (based on 18 °C), while normal winter temperatures vary between −15 °C and −5 °C in February. The two houses are built side by side with enough space between the two to avoid cross-influence (wind, shade, etc.). A weather station recording air temperature, wind speed and direction, relative humidity as well as incident solar radiation is also installed on site.

2.1. House characteristics

Each house has 181 m^2 (1950 ft^2) of livable space, including a full basement, a kitchen, a dining room, a living room, and a half bathroom on the ground floor, and three bedrooms and a full bathroom