Winter Demand Response Using Baseboard Heaters: Achieving Substantial Demand Reduction Without Sacrificing Comfort

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ABSTRACT

While smart thermostats have been around for a few years for HVAC central systems, their equivalent for the control of electric baseboard heaters have just hit the market and have yet to demonstrate their benefit for winter demand response (DR). This paper describes the use of such thermostats in fully instrumented research houses to study DR strategies for preserving occupants' comfort while providing substantial load reduction.

The first study focusses on the advantage of preheating and setpoint ramping to create an advanced setpoint modulation strategy. This strategy is compared to a simpler step up/down strategy. The advanced setpoint modulation of ±1°C (1.8°F) resulted in significant demand reductions during the morning and afternoon events, though slightly lower than for the simpler 2°C (3.6°F) step down strategy. Based on the ASHRAE Standard 55-2013 local thermal discomfort requirements, the advanced strategy also resulted in more comfortable conditions.

The second study consists of controlling only a fraction of the installed baseboards. The load reductions achieved for several fraction levels are given and insights on the selection of the most appropriate baseboards to control are discussed.

Introduction

Programmable communicating thermostats and smart thermostats for the control of HVAC central systems, in cooling and heating conditions, have been around for a few years. Such thermostats can deliver significant energy savings and allow automated setpoint adjustments to reduce peak demand (York et al. 2015).

Line-Voltage Communicating Thermostats (LVCTs) for electric baseboard heaters, have only recently hit the market (Sinopé 2016, Stelpro 2016). Some, incorporating an energy meter, provide valuable feedback on heating energy use on a per room basis. During winter, they can also contribute to reduce peak demand where baseboard heating is prevalent. They offer an alternative to load control modules which could be used to cycle baseboard heaters. That latter option, used by Puget Sound Energy, proved disappointing since cycled baseboards were found to contribute relatively little to demand reduction (PSE 2012). LVCTs, in replacement of existing wall thermostats, make possible the use of setpoint modulation strategies for baseboard heaters, hopefully leading to more consistent load sheds.

Modern digital line-voltage thermostats make use of proportional control and power electronics allowing multiple switching per minute, resulting in a quasi-continuous modulation of the heating output. Moreover, when in accordance to the energy performance standard CAN/CSA-C828 (CSA 2013), room temperature fluctuations for steady setpoint are less than 0.5°C (0.9°F), which goes unnoticed. Conversely, forced air systems are either on or off over longer periods, commonly controlled according to a temperature deadband to limit the number of on-off cycles and decrease the wear of their mechanical components. Starts and stops can be felt either because of air drafts, sudden temperature change or sound level. Comfort expectations for occupants of baseboard heaters equipped dwellings are thus likely higher than those with forced air systems. Hence, thermal comfort should be a prime concern when implementing DR strategies in homes heated with baseboards.

This paper describes two studies making use of LVCTs in fully instrumented research houses to assess occupants' comfort and demand reduction under setpoint modulation strategies. To our knowledge, no field study of such strategies for load shedding of baseboard heaters has been publicly released.

The first study assesses the advantages of preheating and setpoint ramping to create an advanced setpoint modulation strategy and is discussed in terms of load shed and local thermal discomfort. While step up/down simple strategies could be used, they would not take advantage of the finer control made possible by digital line voltage thermostats. Through simulation, the use of ramps, in place of step increases of setpoint, was previously found to reduce the maximum heating demand (Fournier and Leduc 2014).

The second study investigates the shedding potential occurring when only a fraction of the thermostats are contributive, hence possibly limiting the number of existing thermostats to be replaced with more costly LVCTs. This is made possible since the heating of each room is controlled individually by its own thermostat in a baseboard heater equipped dwelling. For dwellings equipped with HVAC systems, no more than a few thermal zones, hence thermostats, are typically found.

The following section describes the experimental test bench, the methodology as well as the criteria used for comparison. The results are presented and discussed for each study.

Methodology

Description of the test bench

The studies were performed in the "Maisons d'Expérimentation en Énergétique du Bâtiment" (MEEB 2016), located in Shawinigan, Quebec. They consist of twin two-storey detached homes (Figure 1, House #1-H1, House #2-H2) with excavated basements, each with a 60 m^2 (646 ft^2) footprint. The single attached garage is excluded from the tests and analysis. The houses are typical light wood framed constructions with insulation levels that were corresponding to applicable regulation at the time of construction (2011), i.e. wall insulation 3.52 RSI (R-20) and roof insulation 5.28 RSI (R-30). The basements' poured-in-place concrete walls are partly insulated while the exposed slabs are not, which was also common in the marketplace at that time.

Each room is equipped with its own LVCT to control its electric baseboard heater, including rooms in the basement. The thermostats are CAN/CSA-C828 compliant and allow the setpoint to be remotely adjusted by 0.1°C (0.2°F) increments. Heating demand, air temperature and mean radiant temperature for each individual room are measured over 15 minute intervals. Local meteorological data are also gathered at the same sampling rate.

During the tests, there was no occupancy, no mechanical ventilation or other internal loads; only the heating system was active. South and east facing windows were blocked with an aluminum foil to reduce solar gains. The houses are also unfurnished. The care taken in ensuring a high degree of similarity during construction enables simultaneous comparative testing between the two houses; i.e. one house can operate under reference conditions while the other performs the test alternative. As shown on Figure 2, inner doors were closed for both studies, except for those on the main floor between the Kitchen (K), Dining (DR) and Living Room (LR).

Figure 1. MEEB test bench (H1 on left, H2 on right)

The emulated winter DR events correspond to peak periods occurring twice daily between 6 and 9 am and from 4 to 8 pm. This is typical when the outside air temperature (OAT) is low (i.e. below -20°C (-4°F) in the province of Quebec).

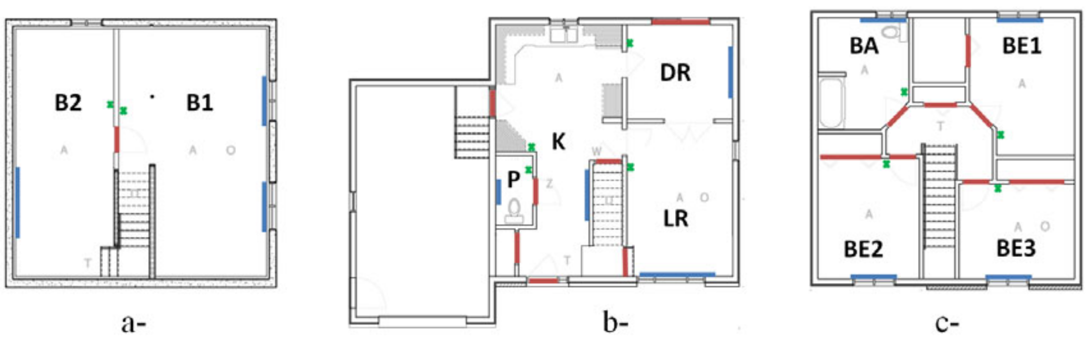

Figure 2. Room layout for a- basement, b- main and c- top floors. Closed doors are shown in red, baseboards heaters in blue and LVCTs locations in green.

Methodology for Study 1

The tested DR strategies consist of lowering the thermostat setpoints from the value that would normally prevail in the targeted rooms (set here at 21°C (69.8°F) for the main and top floor and 19°C (66.2°F) for the basement). In real-life conditions, the original setpoints are chosen by the occupant and therefore are assumed to result in acceptable reference comfort conditions.

For the first study, a simple setpoint reduction strategy is applied to one house while an advanced one is applied to the other. Figure 3 shows the applied setpoint modulation profiles for the main and top floors. The setpoint profiles applied to the basement have the same shape but are offset by 2°C (3.6°F).

In the simple strategy, the setpoint is instantaneously lowered by 2°C (3.6°F) at the beginning of the peak period and brought back to its initial value at the end of the peak period. In the advanced strategy, the setpoint follows a linear ramp starting two hours prior to the peak period to reach 22°C (71.6°F), i.e. 1°C (1.8°F) above the reference. It then remains unchanged for an hour. At the beginning of the peak period, the setpoint is progressively lowered using a linear ramp until halfway through the peak period, to reach 20°C (68°F), i.e. 1°C (1.8°F) below the reference value. At the end of the peak period, the setpoint value is raised over a one-hour period, still using a ramp, up to the reference value. The same strategy is applied for the afternoon event, with the difference that the peak period spans over four hours.

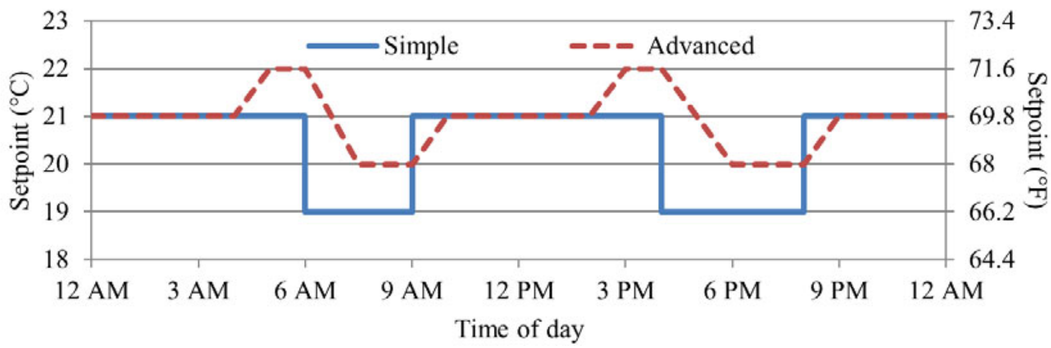

Figure 3. Simple and advanced setpoint modulation profiles for the main and top floors.

Following a stabilisation period for both houses where the reference setpoints are applied, the tests were run over a three day period while alternating which house uses which strategy.

Load shed evaluation. The results are discussed in terms of demand profile impact. The average load sheds during the peak periods are computed from the average demand of each setpoint modulation strategy and the average demand that would have occurred if the reference scenario had been applied. The reference scenario's demand profile is estimated from past measurements.

Comfort evaluation. Thermal comfort is known to be affected by six factors: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity. ASHRAE Standard 55-2013 (ASHRAE 2013) was used to evaluate the effect of the setpoint modulation on thermal comfort. The Standard is applicable to occupants of residential as well as commercial buildings (ASHRAE 2014) but not to occupants who are sleeping, reclining in contact with bedding or able to adjust blankets or bedding, as might be the case in the early hours of the morning DR event. As previously mentioned, the reference conditions were assumed to be comfortable to the occupants and therefore were not evaluated according to the Standard. Local thermal discomfort requirements that assess differential conditions were evaluated, i.e. vertical air temperature difference and operative temperature drifts and ramps. ASHRAE 55 limits on temperature cycles, ramps and drifts were also used by Zhang, de Dear and Candido (2016) to study the thermal environment resulting from the cycling of an HVAC cooling system in a commercial building, as could occur under a direct load control scheme. These limits were found to be overly conservative in the context of their study.

Based on available measured temperature data points, vertical air temperature difference is computed from measured air temperatures at the center of each room at heights of 0.05 m (2 in.) and 1.8 m (72 in.), which are the nearest measurement points available to the values of 0.1 m (4 in.) and 1.7 m (67 in.) suggested by the Standard for standing occupants. According to the Standard, the difference must not exceed 3°C (5.4°F).

Operative temperature was approximated using the following equation:

$$t_o = \frac{t_a + \overline{t_r}}{2},$$

where t_o is the operative temperature, t_a the average air temperature and $\overline{t_r}$ the mean radiant temperature (from ASHRAE 55-2013, Appendix A Case 3). This approximation is valid because air speed (drafts) is less than 0.2 m/s (40 fpm, no mechanical ventilation), metabolic rates of typical occupants are likely between 1.0 and 1.3 (corresponding to quiet activities like seating), there is no direct sunlight and the difference between mean radiant temperature and the average air temperature (t_a) is less than 4°C (7°F).[1] The average air temperature and the mean radiant temperature ($\overline{t_r}$), measured using a black sphere, are both taken at the center of the rooms at 1.2 m (48 in) from the floor. Requirements for drifts and ramps are qualified for various timeframes; these are explicitly identified in Figure 9.

Methodology for Study 2

The second study looks at the demand impact of partial control within the house. Table 1 lists the controlled rooms for each tested scenario.

Table 1. Scenarios, Study 2

Rooms		Scenarios						Area
		2	3	*4ag*	*4ib*	6	10	[m²(ft^2)]
BE1	Bedroom #1			•		•	•	13.3 (143)
BE2	Bedroom #2					•	•	12.3 (132)
BE3	Bedroom #3					•	•	11.1 (119)
K	Kitchen	•	•	•	•	•	•	21.0 (226)
LR	Living room	•	•	•	•	•	•	17.7 (191)
DR	Dining room		•	•	•	•	•	11.1 (119)
BA	Bathroom						•	9.8 (105)
P	Powder room						•	3.1 (33)
B1	Basement #1				•		•	35.9 (386)
B2	Basement #2						•	25.7 (277)
	Total							161 (1 731)

The name of the scenario corresponds to the number of controlled rooms.

The setpoint profile used for controlled rooms is shown in Figure 4; unlike Study 1, it does not include progressive ramps. There are two scenarios controlling four rooms, one including only above ground rooms (4*ag*) and one that includes a portion of the basement (4*ib*). The unmarked rooms operate with a constant setpoint. The morning DR event includes a two hour preheating period while the afternoon does not. On a particular day, one scenario (for example two rooms) is applied to one of the houses while another scenario (for example three rooms) is applied to the other.

[1] This difference was calculated for each room during the test; the maximum difference was found to be 2.8°C (5°F).

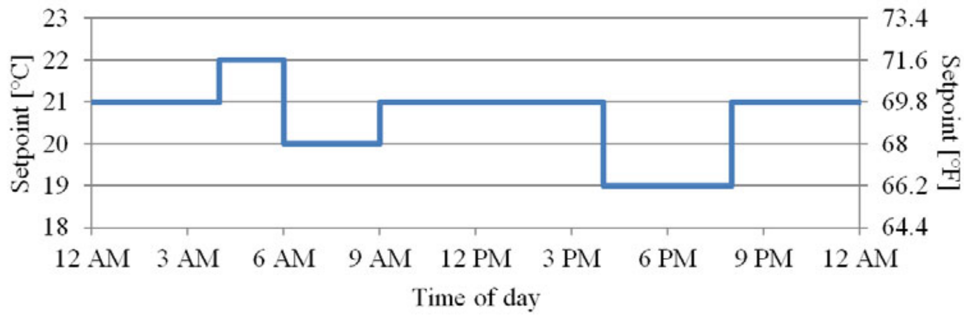

Figure 4. Setpoint modulation profiles used on the main and top floor, Study 2.

Results

Study 1

Load shed results. Similar results were observed for all tests; only the results for January 31st 2015 are presented for brevity. This was the coldest day of the three with OAT ranging from -23.8 to -13°C (-9.4 to 8.6°F). Figure 5 shows the demand profile of each house for that day and the adjusted reference demand profile (constant setpoint) from a day with similar solar radiation. One can see that the simple strategy results in sudden changes in demand. The heating demand vanishes for almost an hour at the beginning of each peak period. The heating demand then progressively resumes in the different rooms as the lowered setpoint is reached. After the peak period, the heating demand rebounds (11.6 vs 4 kW). This could be managed at the distribution level in order to avoid creating a new grid peak, for example by spreading the end time of peak periods across the population (randomization). Periods of high heating demand, however, correspond to undesirable local thermal discomfort conditions as will be discussed below.

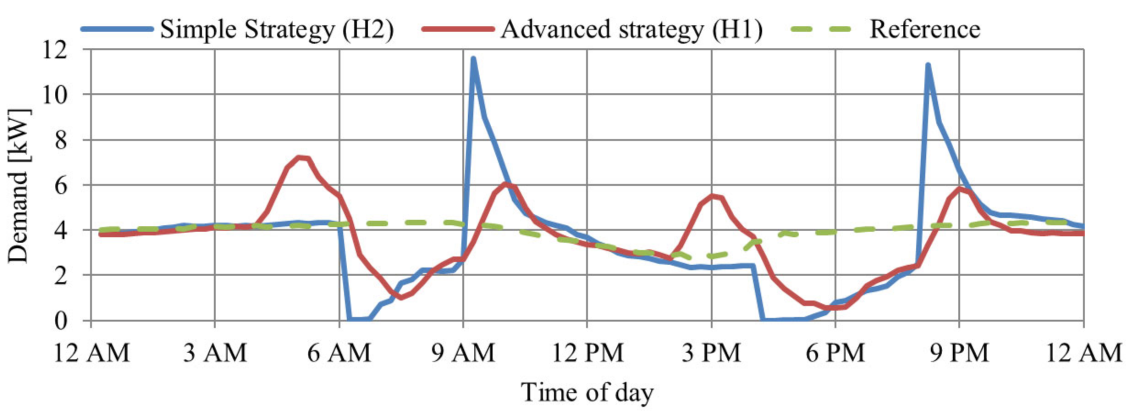

Figure 5. Houses demand profiles on January 31st, Study 1.

The advanced strategy shows a much smoother demand profile. The demand increase caused by the preheating is clearly visible but peaks about an hour ahead of the peak periods. The demand then decreases progressively to reach a minimum midway through the peak period, where the chances of occurrence of the grid fine peak are the highest. From that moment and until the end of the peak period, the demand level is comparable to the simple strategy. The demand then progressively rises until an hour after the end of the peak period.

Table 2 gives the average load shed over the peak periods for each strategy in comparison to the reference demand profile. The advanced strategy has a smaller average load shed, by 20 to 27%. This comes from the instantaneous drop in demand in the simple strategy at the beginning of the peak period. Shifting the setpoint profile of the advanced strategy by 15 minutes earlier would increase its average load shed but it would still not equal that of the simple strategy.

Table 2. Average load shed, Study 1

	AM peak period [kW]	PM peak period [kW]
H1 - Advanced	2.1	2.4
H2 - Simple	2.9	3.0
Difference	0.8 (27 %)	0.6 (20 %)

Comfort results. First, vertical air temperature differences were evaluated. For most rooms, the advanced strategy shows values well below the requirement, even during the preheating period. This is observed in Figure 6 which illustrates the conditions in Bedroom#1. Stratification closely follows the evolution of setpoint modulation trajectory. The sudden heating demand generated by the instantaneous setpoint increase creates a high vertical air temperature differential due to the convection air jet from the electric baseboard. The ramping of setpoints lowers this differential because the effective heat output is reduced resulting in an altered convection pattern.

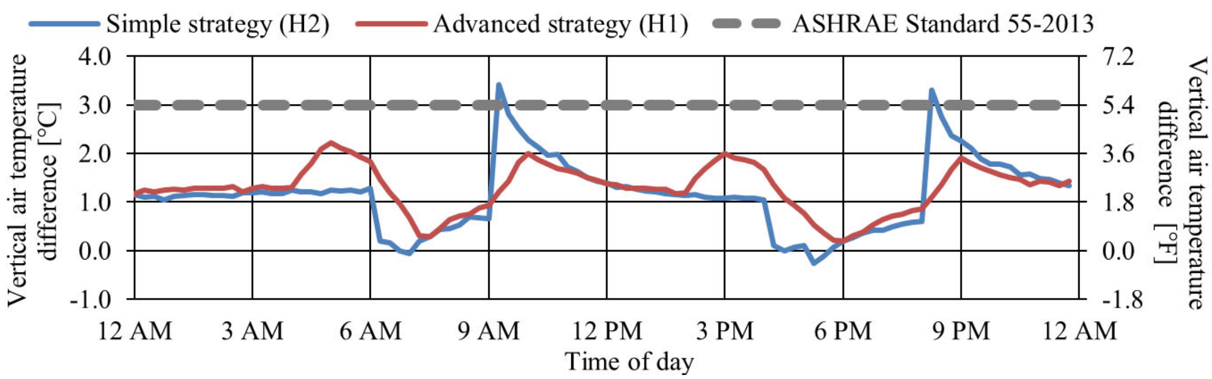

Figure 6: Vertical air temperature difference for advanced and simple strategies, Bedroom#1, Study 1.

Figure 7 illustrates the impact of the advanced strategy in Basement#1. The benefits are not as obvious for this room, which has thermal characteristics differing from the rooms above ground. Its surface area is also greater than that of the other rooms.

Based on these observations, the application of the simple strategy leads to a greater vertical air temperature gradient in above ground rooms, especially following the peak periods. This gradient is a potential source of discomfort for occupants.

Temperature drifts and ramps were also studied for the following periods: preheating, peak periods and two hours after the peak periods. Figure 8 shows operative temperature changes of Bedroom #1, for the various timeframes considered by the Standard (0.25 h, 0.5 h, 1 h, 2 h and 4 h). The simple strategy exceeds the 0.25 h and 0.5 h requirement limits almost systematically. This conclusion holds for all rooms, though it is not as important in the Kitchen where the requirement is exceeded only during the two hour period following the afternoon peak.

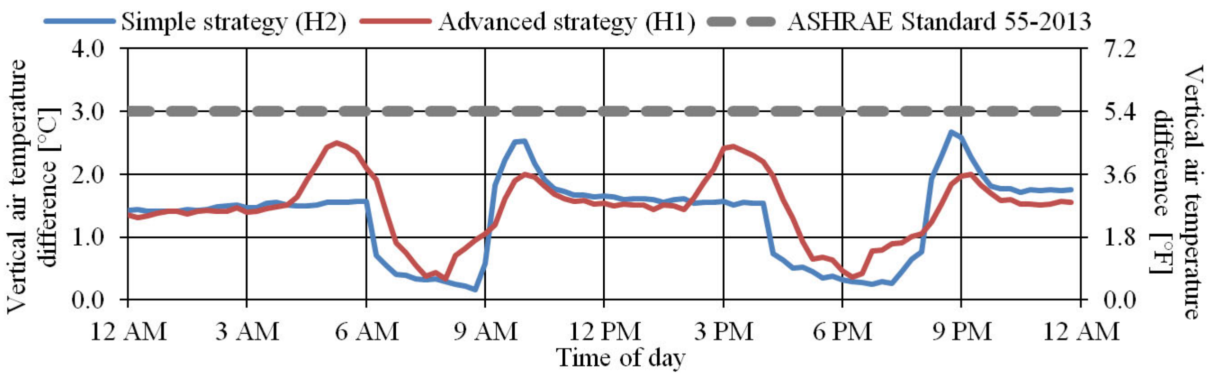

Figure 7. Vertical air temperature difference for advanced and simple strategies, Basement#1, Study 1.

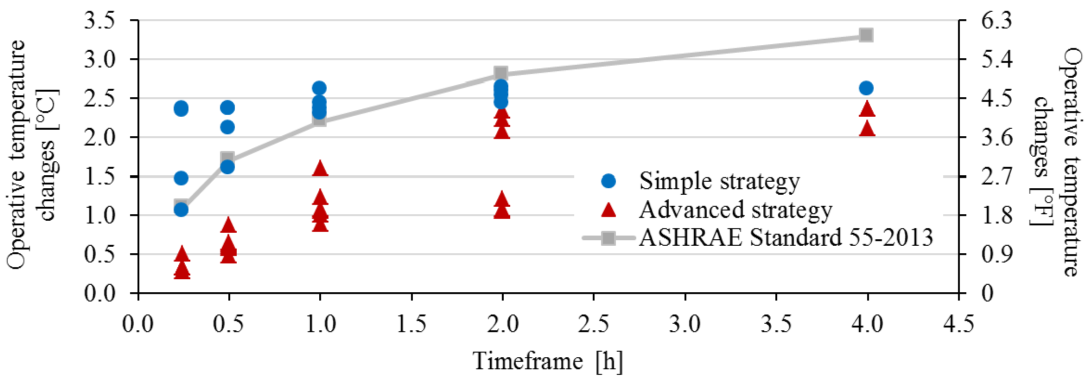

Figure 8. Operative temperature drifts and ramps, Bedroom#1, Study 1.

Overall, it appears that the simple strategy often fails to respect the Standard for both requirements. Therefore, in terms of local thermal discomfort, it seems clear that the advanced strategy would most likely generate less discomfort before, during and after DR events. Furthermore, the air temperature varies by only 1°C (1.8°F) relative to the original setpoint compared to 2°C (3.6°F) for the simple strategy. The smaller excursion from the user-selected reference setpoint would inevitably be more comfortable to the occupants.

Study 2

When comparing the impact of controlling two or three rooms, it was found to differ according to which house operated which scenario. Upon closer inspection, we found that when the main floor interior doors are open, the Kitchen baseboard of H2 often delivered more heat than H1, even if the differences in air temperatures, measured at the center of each rooms of the main floor are within measurement error. Under such conditions, the daily main floor total heating energies are still the same for both houses. This difference in the distribution of the heating source across the main floor rooms is not observed when the interior doors are closed. This suggests a convective heat flow from the Kitchen (master) to the Dining room and Living room (slaves) when the doors are left open.

In a relatively open floor plan, the impact of controlling or not a specific room depends heavily on its status (master or slave) when involved in such a dependency relationship. The control of a master room would result in a larger than expected demand impact if preheating is performed as it would also store energy in adjacent rooms. In the case of a slave room, the heating load is partially satisfied by a master room, and thus has a lower heating demand. Its control would therefore result in a lesser load shed than expected for a self-relying room. The presence of a master-slave relationship and the status held by each room, are hardly predictable as illustrated by the case of the MEEB which were built identical but still show different behaviors on the main floor. When deploying LCVTs for DR, it is therefore advisable to install and control all the thermostats of an open area space in order to eliminate the chance of relying on the control of a slave room.

The results of controlling three or more rooms are not biased from the discrepancies observed on the main floor because the interior doors of the other floors were closed and all thermostats from the main floor open area space were always controlled for these scenarios. Table 3 gives the observed load shed for the morning peak period according to the number of controlled rooms. Only the morning events are presented as those for the afternoon are highly influenced by solar radiation variations, which are difficult to rule out from one day to another. OAT ranged from -30 to -12°C (-22 to 10°F) during the morning peak periods. Up to 61% of the house total heating demand was shed over the three hour morning peak period using only ±1°C modulation around the comfort setpoint.

Table 3. Morning load shed according to the number of controlled rooms

Dates	Scenarios	Fraction of controlled area	Load shed [kW]	Reference heating demand [kW]	Heating demand shed
2015-02-03 2015-01-02 & 06	3	0.31	0.5- 0.8	3.2-4.7	13-17%
2014-12-31 2015-01-06	4ag	0.39	0.8-0.9	4.3-4.8	20%
2015-02-02	4ib	0.53	1.6	4.7	34%
2015-02-03 & 04 2015-01-02 & 03	6	0.54	1.1-1.7	3.1-4.7	23-39%
2015-01-03 2015-02-04	10	1.00	2.6	4.3-4.5	57-61%

Figure 9 suggests a linear relationship between the house total heating demand shed, expressed as a proportion of the reference heating demand, and the fraction of controlled area. No sign of saturation is visible with this independent variable.

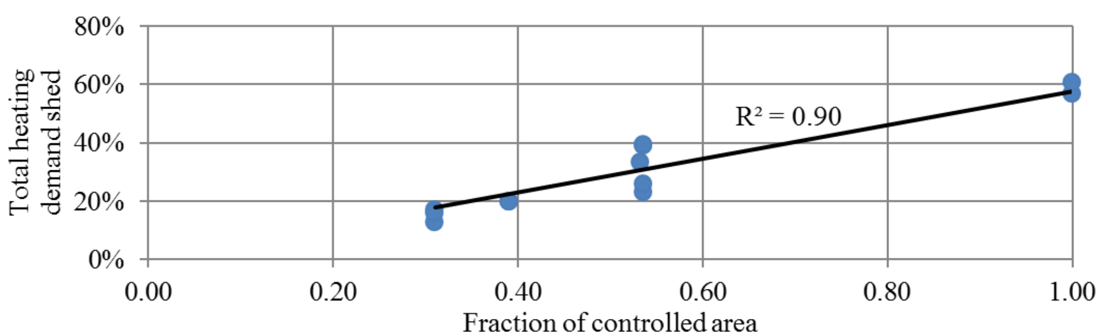

Figure 9. Total heating demand shed according to the fraction of area under control, Study 2

From the available test results, it was also possible to directly compare load sheds resulting from the control of a basement thermostat versus one on the top floor. Figure 10 shows the heating demand profiles of Bedroom#1 and Basement#1 for January 1st 2015. On that day, scenario 4*ig* was run on H1 while scenario 4*ag* was run on H2. The setpoint modulation was applied to the main floor of both houses and to an additional zone (Basement #1 for H1 or Bedroom #1 for H2). OAT was warmer on that day, averaging -7.5°C (18.5°F) which is why it was not included in Table 4. The heating demand of Bedroom #1 is slightly more than half that of Basement #1. The heating dynamic is also quite different during peak periods. While the heating resumes at 7:15 am and 5:45 pm for Bedroom#1, it delays until 8 am and the end of the afternoon peak period. This tends to show that in-ground rooms could sustain longer without heating during setback periods than those above ground. The higher thermal mass, and possibly lesser air infiltration compared to the upper floor, are likely explanations for this dissimilarity.

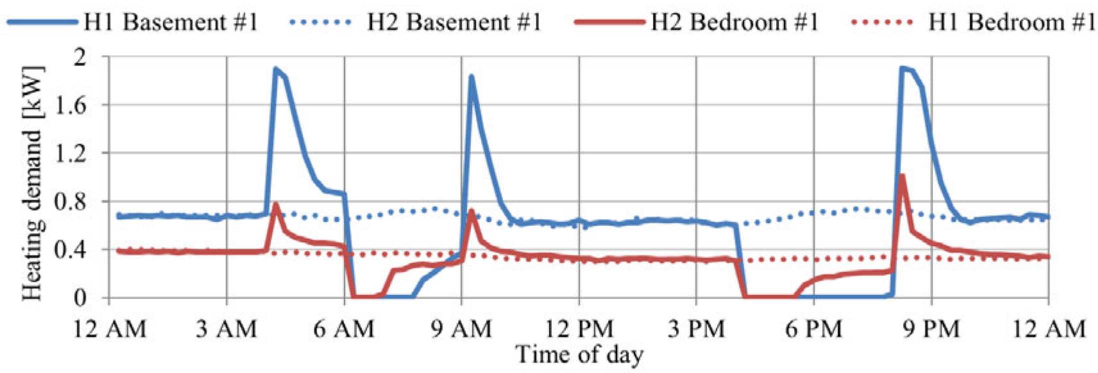

Figure 10. Heating demand profile for Bedroom #1 and Basement #1, January 1st 2015, Study 2

Table 4 presents the load sheds of both rooms during peak periods for both events of January 1st 2015. As shown in Figure 4, setpoint modulation strategies differed for the morning and afternoon events. As expected, load sheds are higher for Basement #1 than for Bedroom #1, even when expressed in terms of specific load shed. The relative basement advantage ranges from 18 to 21%. At the whole-house level, the basement advantage could be less as it is presumed that the main floor heating demand should increase to compensate the reduced incoming heat flow from the basement.

Table 4. Load shed comparison between a top floor room and a basement room

Event	Load shed		Specific load shed		Basement advantage
	Basement #1	Bedroom #1	Basement #1	Bedroom #1	
AM	0.6 kW	0.2 kW	17 W/m²	14 W/m²	21 %
PM	0.7 kW	0.2 kW	19 W/m²	16 W/m²	18 %

This second study has shown a direct relationship between the load shed and the area under control. This suggests that when deploying LVCTs for DR and only a fraction of the thermostats are to be replaced, prioritizing the rooms with the largest area should yield the most load shed. More shedding may also be expected by controlling an equivalent area of basement space to upper floor space, at least for the tested construction type, and if the basement is kept at or near comfort temperatures.

Conclusion

Setpoint modulation strategies of electric baseboard heating were applied in research experimentation houses to study their impact for winter demand response. These houses were unfurnished and unoccupied, solar gains were reduced and there were no other loads than space heating. The basement was partially finished. Generalisation of the results should therefore be performed with care. For example, the presence of internal heat gain could lower the absolute load shed as the overall heating demand would be reduced. The experimental setup allowed the detailed comparison of DR strategies but a real life pilot would better estimate shedding levels achievable upon DR program deployment.

Nonetheless, an advanced strategy, making use of ramps and preheating, resulted in average load shed of more than 2 kW per house using only a ±1°C (1.8°F) setpoint modulation. This was about 25% less than with a simple strategy (2°C (3.6°F) step down). The advanced strategy, however, resulted in increased comfort as demonstrated by the analysis of the local thermal discomfort requirements of the ASHRAE Standard 55-2013. It was shown to reduce the vertical air temperature gradients compared to the simple strategy because of lower effective heat output from the electric baseboards. The setpoint modulation of the advanced strategy also reduces operative temperature changes (drifts and ramps) hence lowering discomfort perceived by occupants as a result of the DR strategy. It should be noted that the simple strategy often exceeded limits of the Standard for both requirements. In this study, the advanced strategy was applied to rooms originally operating at constant setpoints. Alternate versions of the advanced strategy could be developed for thermostats operating nighttime setbacks or both daytime and nighttime setbacks, as was presented in Fournier and Leduc (2014).

The second study showed evidence of a convective heat transfer between rooms of the main floor when interior doors are open. This is hardly predictable and could significantly impact the load shed when only a fraction of the rooms are under control. It was also found that the total load shedding level versus the fraction of the house area under control showed no sign of saturation. Up to 61% of the house total heating demand was shed for a three hour morning event using only ±1°C (1.8°F) step changes around the reference temperature setpoint. Finally, the control of basement rooms resulted in higher specific load shed (per unit area) than the control of a top floor room.

If only part of the house thermostats were to be controlled for DR, the selection of the rooms with the largest heating demand should result in the best shedding level per thermostat. However, individual room heating demand is not typically known before the installation of LVCT. In such a case, and based on the above results, it seems advisable to:

- install and control LVCT in all rooms of an open area space in order to eliminate the chance of relying on the control of a slave room;
- prioritize the rooms with the largest area first;
- favour basement space over equivalent top floor space if the basement is kept at or near comfort setpoint, i.e. is used as a living space.

Other factors, such as convective heat flow between floors (through staircases, for example), may also modify the load shed when a fraction of the rooms are under control but these aspects were not investigated.

Though derived from observations made in specific conditions, taking into account these recommendations in the design of a real life pilot should improve chances of recording substantial DR load sheds. Such a pilot could also bring insights on occupant satisfaction with the use of LVCTs for DR. Perceived comfort and ease of installation and use could be evaluated. Finally, LVCTs could be adapted to natively perform ramps to alleviate discomfort associated with setpoint changes, during both application of DR events and normal operation.

Reference

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). 2013. *ANSI/ASHRAE Standard 55-2013 Thermal Environment Conditions for Human Occupancy*. Atlanta, GA: ASHRAE.

------. 2014. *Interpretation IC 55-2013-1 of ANSI/ASHRAE Standard 55-2013 Thermal Environment Conditions for Human Occupancy*. September 8th. www.ashrae.org/File%20Library/docLib/StdsInterpretations/IC55-2013-1.pdf

CSA (Canadian Standards Association). 2013. *CAN/CSA C828-13: Performance requirements for thermostats used with individual room electric space heating devices*. Mississauga, ON: CSA.

Fournier, M. and M.-A. Leduc. 2014. ″Study of Electrical Heating Setpoint Modulation Strategies for Residential Demand Response.″ eSIM 2014 Conference Proceedings. www.ibpsa.org/proceedings/eSimPapers/2014/4A.1.pdf

MEEB. Accessed May 2, 2016. www.meeb.ca

PSE (Puget Sound Energy). 2012. *2011 EM&V Report for the Puget Sound Energy Residential Demand Response Pilot Program – Final Report.* Boulder, CO: Navigant Consulting.

Sinopé. Accessed May 2, 2016. www.sinopetech.com/en/

Stelpro. Accessed May 2, 2016. www.stelpro.com/en-US/4000-w-ki-thermostat-smart-home

York, D., S. Nadel, E. Rogers, R. Cluett, S. Kwatra, H. Sachs, J. Amann, and M. Kelly. 2015. *New Horizons for Energy Efficiency: Major Opportunities to Reach Higher Electricity Savings by 2030*. Washington, DC: ACEEE. aceee.org/research-report/u1507

Zhang, F., R. de Dear, and C. Candido. 2016. ″Thermal comfort during temperature cycles induced by direct load control strategies of peak electricity demand management.″ *Building and Environment* 103: 9-20