Intelligent management of baseboard heaters to level peak demand: evaluation of peak shift strategies

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Publisher's version / Version de l'éditeur:
https://doi.org/10.1109/EPEC.2016.7771730
Proceedings: 2016 IEEE Canada Electrical Power and Energy Conference (EPEC 2016), 2016

Intelligent Management of Baseboard Heaters to Level Peak Demand

Evaluation of Peak Shift Strategies

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***Abstract*— This paper presents results from an evaluation of a demand response (DR) strategy applied to residential electric baseboard heating loads. The underlying principle is based on storing electricity as thermal energy in the building envelope and household contents before the peak period and then discharging that stored energy to maintain conditions for thermal comfort during the peak period. Five different variations of the strategy were tested at the twin houses of Canadian Centre for Housing Technology (CCHT) for a four weeks period in the winter of 2015 using a side-by-side comparative assessment. The tests showed that a load shift up to 4 kW for the first 30 minutes and a total shift up to 5.7 kWh during the 2-hour period was possible, depending on the outdoor temperature. The approach holds significant potential for shifting peaks loads in locations where electricity is a major source of energy for space heating.**

Keywords—demand response; electrical thermal storage; load shift; space heating; smart thermostats

I. Introduction

In New Brunswick, 61 % of electricity use is for space heating & cooling and a further 22 % is for electric water heating. Winter peaks typically occur during the morning, as people wake up, turn up heating, have showers, turn on lights and cook breakfast, with a secondary peak in the early evening, when people get home from work, turn up heating, turn on lights, cook dinner, and use numerous appliances. These peaks are emphasized on the coldest days when demand for heating is at its highest. As such, with a predominantly supply-side approach, the electric utility NB Power, must be able to deliver peak winter demand of about 3100 MW for only a few hours on a few days of the year. With demand for electricity generally increasing over time, there may be the need to build a new power station to meet the higher long-term demand, at great expense. Effective Demand Response (DR) control strategies will help NB Power to curtail household electrical loads and thus to effectively reduce system-wide winter peak demand and accommodate more renewables (with their variable generation) on the grid. DR control involves a utility company curtailing high household electrical loads during the peak period by sending a demand curtailment signal over the communication infrastructure. This is expected to result in electricity cost benefits for customers, help realize sustainability goals, and increase grid stability.

Eastern coastal provinces have an opportunity to tap into abundant wind power but the intermittent nature of the energy source demands an economical method to store energy when surplus electricity is available and then used when generation is unable to keep pace with the demand.

As a part of due diligence prior to making a large investment in pilot studies and full-scale roll out, an investigation was deemed necessary to determine how much electrical energy can be stored in the thermal mass of a building by pre-heating interior spaces prior to the peak period. Thermal energy stored in the building envelope and contents during the pre-heat phase should enable operation of electrical heaters on reduced duty cycle during the critical peak period while allowing thermal comfort conditions to be maintained during the peak period.

Over the winter of 2015, a series of experiments were conducted in the twin house facility at the Canadian Centre for Housing Technology (CCHT) (www.ccht-cctr.gc.ca) to evaluate the load shift achieved through electrical thermal storage in the mass of the building. Built in 1998, the CCHT is jointly operated by National Research Council (NRC), Natural Resources Canada (NRCan), and Canada Mortgage and Housing Corporation (CMHC). These side-by-side test houses are fully instrumented and are unoccupied. The technology to be tested is installed in one house that is referred to as the "Test House" and its performance is compared to that of its twin, with the base technology, referred to as the "Reference House". To simulate the normal internal heat gains of lived-in houses, these houses feature identical 'simulated occupancies'. The effect on energy consumption of a new technology or a new strategy is derived by using side by side comparison of the test house energy performance with the technology against the baseline house without the technology.

II. Summary of Related Past Studies

Programs and pilot studies involving residential winter electric space heating DR have been conducted elsewhere.

Some studies have engaged electric furnaces [e.g. 1], heat pumps [e.g. 9], or radiators [e.g. 4]; for brevity, we limit our review in this paper to studies specifically engaging electric resistance baseboard heaters.

Lempereur & Bobker [6] and Huang [3] controlled baseboard heaters in apartments in New York. The first phase involved 169 apartments in three buildings, at an average supplemental equipment cost of $1644 per apartment (payback 5-7 years). The initial focus was energy savings via central control of maximum setpoints and night-time setback, but peak load was reduced by up to 0.63 kW/apartment. Later the same system served as a platform for DR across 1100 apartments in multiple buildings. Events typically lasted 1-1.5 hours, with setpoint lowered by 1.1 ^{o}C with no preheat. A typical average reduction was around 0.3 kW/apartment, with no reported complaints from occupants.

The municipal utility in Madison, South Dakota has supported load control programs for more than 10 years [7]. Currently, around 343 customers have baseboard heaters under control. The control hardware involved 1-3 relays at the central breaker panel, at a cost of around $130 plus labour. A simple cycling approach is used, and a capped monthly incentive is offered. Winter peaks occur in the morning, although lower-level curtailment can persist throughout the day. The average peak reduction was estimated as 4 kW/household in January.

Leduc et al. [5] simulated baseboard DR strategies in Quebec. The simulated low-mass wood-frame house had an installed heating capacity of 21 kW, and a reference setpoint of 21 ^{o}C. Winter peak periods were defined as 6-10 am and 4-8 pm. Three basic strategies (with variants) were explored: setback only, setback with pre-heat, and limiting the power to the baseboards to a fraction of full power. Peak load reductions of up to 7 kW were demonstrated, with post-event snapbacks typically equal to, or exceeding this value. Load reductions generally declined over the four-hour event, although pre-heating strategies exhibited less decline. Pre-heat strategies had a small energy penalty and slightly worse thermal comfort parameters. Fournier & Leduc [2] applied setback strategies to only four of eight baseboard heated zones in a house, and also assumed pre-existing setback strategies. Simulations were applied to a single grid-peak day in January. Results showed peak load reductions of up to 5 kW in the first hour of an event, declining to 1 kW by the end of an event. Ramping of the setpoint reduced snapback effects substantially. There was little effect of any strategy on overall energy use.

Steele-Mosey & Steiner [10] report a pilot conducted in Washington State in 2009-2011. Baseboard cycling was engaged in 53 households. Morning peak periods were generally 6-9 am, and evening peaks periods were 4-7 pm. The estimated average load reduction was 0.18 kW. This low value was attributed to the fact that only a minority of baseboards in the house were controlled, so that when these baseboards were cycled others operated for longer periods to maintain the setpoint throughout the house. The authors suggest DR programs might target households where the residents would typically have left home by the end of the morning, to avoid potential thermal comfort problems. Overall, participant satisfaction was high, but there was dissatisfaction with the appearance and installation of the equipment. The principal motivations for participation were for altruistic and environmental reasons, and not personal financial gain. Nevertheless, many participants expected to save money on their energy bill, although this was not advertised as a benefit.

Overall, these studies suggest the following findings and lessons learned:

- A peak load reduction of up to 5 kW/house seems a reasonable average estimate of the potential for baseboard space heating DR
- Space heating DR has a greater load reduction potential per house than water heating DR
- Snapback of load after a DR event can be at least as large as the reduction during the event; pre-heating prior to heating curtailment can reduce thermal comfort problems and snapback
- Occupants generally experience few thermal comfort problems during events
- Occupants appreciate an override option for called events (though rarely use it), but successful programs have been delivered that did not offer overrides
- Overall energy use is likely unaffected by DR events
- Quality control of the DR technology and the work of the installers is very important
- It is not clear how important financial incentives are to encouraging participation
- Overall, participants in space heating pilots/programs have been satisfied with the experience
- There is little evidence on the effect of house characteristics (e.g. age) on outcomes

No prior study has been conducted that is directly analogous to the New Brunswick context, and this review supports the need for a context-specific study to inform a larger roll-out of the technology in New Brunswick in the future.

III. METHODOLOGY

A. *Load Shift Strategy*

Our strategy to shift the peak consumption is based on storing the electricity as useful thermal energy before the peak period and then discharging it during the system peak to maintain thermal comfort when baseboard heating is curtailed. This is achieved by preheating the dwellings over the normal operating indoor temperature by 1 or 2 ^{o}C before the peak period and maintaining a slightly lower than normal operating temperature during the peak. The strategy was evaluated with two variations: applied to all utility controllable thermostats of a dwelling simultaneously, or duty cycling choreographed by zones.

This study was funded by NB Power, Siemens Canada, and High Performance Building Program of National Research Council Canada

A large majority of home owners program their thermostats with nighttime temperature setbacks in winter months and most also apply setbacks for daytime hours when they are away [11, 12]. Hence the first variation of the strategy was tested without (scenario 1.1) and with (scenario 1.2) programmed setbacks.

The zone choreography reduces the operating duty cycle of heaters by temperature cycling at regular intervals. All utility controllable thermostats are pre-configured to belong to certain zones of a dwelling and execute the DR event by offsetting the setpoint for the assigned period of time while the rest maintaining normal operating temperature. The load shift strategy is then rotated to another zone in the house while the former reverts back to maintaining normal operating temperatures. Though we do not expect the same level of load shift through choreography (compared to controlling all thermostats simultaneously), we expected choreography would result in a lesser drop in room temperatures during the DR event, leading to better thermal comfort conditions. Choreography was applied with (scenario 2.1) and without (scenario 2.2) preheat, and with a strategy to stagger the recovery of baseboard heater setpoint after the discharge period (scenario 2.3).

Given space constraints, it is not possible to provide details for all five scenarios evaluated at CCHT. This paper details only the results of scenario 1.2 and provides a summary of results for the rest. Scenario 1.2 was the one subsequently chosen for further evaluation in occupied homes in New Brunswick.

All thermostats in the Reference House and Test House were programmed with the schedule shown in the Table 1.

Table 1: Thermostat schedule for the Reference House.

Time interval	Programmed setpoint ° C	Period
22:00 – 06:00	18	Sleep
06:00 – 09:00	21	Wake
09:00 – 17:00	18	Leave
17:00 – 22:00	21	Return

Table 2 shows the parameters of the DR message that is only applied to the Test House. Temperature offset is the number of degrees above or below the prevailing setpoint temperature programmed in the thermostat. A utility company sends offset signals to target thermostats for DR control. By sending offsets rather than actual setpoints, the utility company does not interfere with thermostat schedule set by the occupant.

Table 2: Parameters of a DR message

Scheduled date	Scheduled time	Duration (Minutes)	Target zone	Temp offset °C
13/03/2015	3:00 AM	150	All	2
13/03/2015	5:30 AM	120	All	-1

The daily thermostat profile for the Reference House, and for Test House under scenario 1.2 are shown in Figure 1

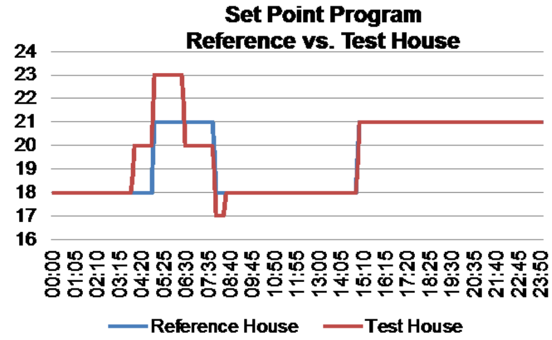

Figure 1: Thermostat temperature (°C) profile for the Test House after offsets for the DR event are applied

B. Intelligent Load Management and OpenADR Framework

An important objective of the project was to test the scheduling of DR events using automated Distributed Energy Resource (DER) control. A combination of manual and automated DER control was used to implement the various DR test scenarios. Manual DER control involved programming the thermostats directly with set points to simulate the DR event. Automated DER control was provided by the Siemens Distributed Energy Management System (DEMS) system.

For the automated DR events, dispatch files were created by the NRC that contained the DR event information. These files were input into the DEMS which then initiated the automated scheduling of the DR events with each of the connected DER devices (i.e. the thermostats) via the thermostat vendor cloud using the OpenADR2.0b standard.

For any of the five scenarios tested at CCHT the control requests were realized in the form of offsets to the current temperature set-point. In the thermostat, each of the OpenADR2.0b simple signal levels (0-3) was mapped to a corresponding offset. For example, if the current set-point was 21 degrees C and the desire was to create a 'discharge' event by turning off heaters and allowing the house to drift down to 19 degrees C, an OpenADR2.0b simple signal was sent with the signal level corresponding to a downward offset of 2 degrees. This offset was enforced for the requested duration of the event, after which the thermostat returned to its preprogrammed set-point. Telemetry, state, and registration data returned through the OpenADR2.0b requests allowed the measured data provided by the thermostat to be verified against the corresponding measured data from the sensors installed in the CCHT.

C. Side-by-side comparison

Though both houses are identical in design their base energy consumption when technology is not being evaluated is not exactly the same due to minor variations in construction, shading, appliance, and mechanical equipment operation. These small differences are quantified during benchmarking, and subsequent differences in house performance during an experiment are then attributed to the technology being assessed. The methodology for testing in the CCHT has the following four steps:

- Setup both houses with identical configurations
- Benchmark energy consumption of houses to establish a baseline
- Deploy the technology and the energy management strategy to be tested at the Test House with the base technology and operations maintained at the Reference House.
- Compute the energy effects of the technology (in this case the load shift) by comparing the time-series data from the Test House to the Reference House.

D. Set-up

The twin houses were divided into the “Living Zone” and the “Bedroom Zone”. OpenADR compliant Smart thermostats were installed in both houses to control larger baseboard heaters ranging from 1 to 2.75 kW. The remaining baseboard heaters (e.g. in washrooms, small rooms, and basement ranging from 0.3 to 1.5 kW) were connected to non-demand responsive line voltage thermostats. The demand responsive heat load made up 66% of the total heating load and Table 3 shows the total capacity of baseboard heaters for each zone. The focus on major baseboard loads reflected a desire to constrain the total installed cost of the multi-thermostat system. Note, a forced air heating system typically requires a single low voltage thermostat, whereas a typical baseboard heating system requires one thermostat in each enclosed space.

Table 3: Nominal capacities of baseboard heaters by zones in kW

Zones	Total capacity	Demand responsive	Non-demand responsive
Basement	1.5		1.5
Living	5.25	5.25	
Bedrooms	5.3	2.75	2.55
Total	12.05	8.00	4.05

E. Benchmarking

For this evaluation study, the houses were benchmarked in identical configuration at the start and end of the experiment. A sample benchmark day of hourly electrical consumption data is presented in Figure 2 for the Reference House.

The largest load in both houses is the baseboard electrical load (orange). Internal lights and appliance loads are significant, particularly in the evening, when the simulated occupants are present. The electrical load profiles for two houses are very similar, but there are small differences between them that are accounted for in the experiment analysis.

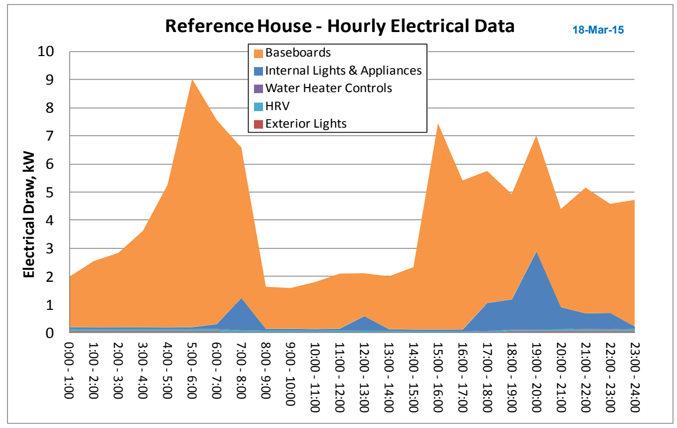

Figure 2: Hourly electrical draw for the Reference House

A daily analysis of the total heating consumption highlights the base differences between the houses. Figure 3 plots the total daily Test House heating system consumption (y-axis) against the daily Reference House heating system consumption (x-axis). Each point on this graph represents a single day of benchmarking. Were the houses identical, the benchmark points and trend line would lie on the 45-degree line. In reality, the Test House on average consumes 5.4% more heating energy than the Reference House during benchmarking. The 5.4% total daily difference is not disributed evenly across all hours of the day. The load shift results account for this difference by applying an adjustment factor that is the average of difference between the Test and Reference houses electricity usage at every two hours for all baseline days.

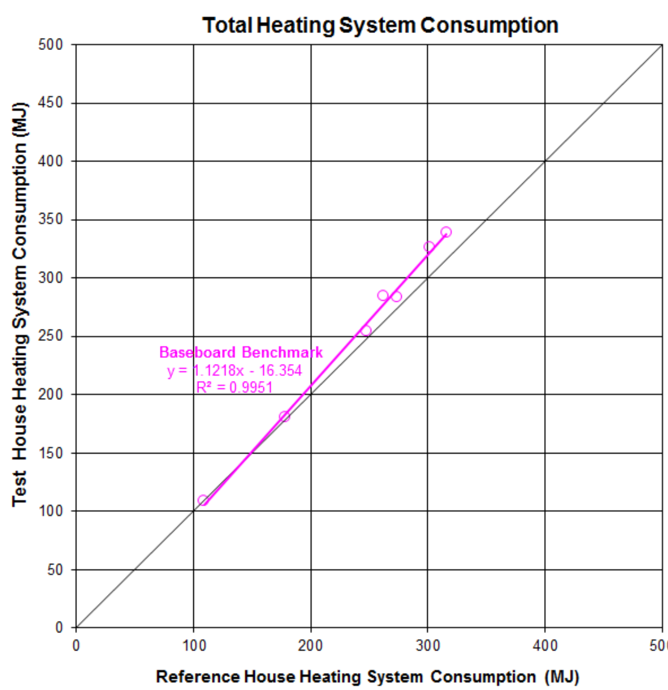

Figure 3: Linear benchmark trend line

F. *Computing the Load Shift*

The load was measured using the Key Performance Indicators (KPI) established by NB Power to measure results relative to expected Demand Side Management (DSM) program outcomes.

1) Key Performance Indicators: The primary KPI impact sought relates to a reduction or shift in energy consumption away from morning peak periods of the winter months. As such, following measureable parameters were established :

- Average power shifted in the first 30 minutes of the discharge period
- Average power shifted over the whole total 2-hour peak period

Since the peak shift strategies involved changing residential temperature set-points, it was also important to evaluate effects on the household's total energy consumption, and on room temperatures.

2) Load Shift Computation Method: The shift in load was computed by comparing the half hour power and energy data of the test House to the reference House, and then applying the baseline adjustment factor. For example, Figure 4 shows the load shift chart for 18-March-2015 which was the coldest day for Scenario 1.2.

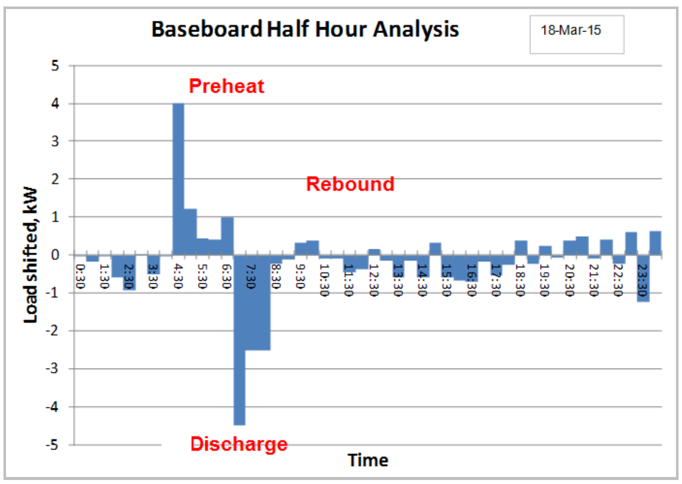

Figure 4: Load shift for scenario 1.2 for 18-Mar-15. The difference between the power draw for the Test House and Reference House yields the load shift after applying the adjustment factor.

IV. Results

The load shift is plotted in Figure 5 for all six days on which Scenario 1.2 was invoked. Generally, the power shift profile is similar for all days for this scenario except for one day (17th Mar-15) when the outdoor temperatures were very mild (as shown in Table 4).

We analyzed the thermostat data, example shown in Figure 6, of various spaces to understand preheat and discharge characteristics of various spaces by deriving the values of the following two parameters from room temperature data:

- B1: The time it takes for a space to reach the highest setpoint during the preheat period
- C1: The time it takes for a space to reach the lowest setpoint during the discharge period

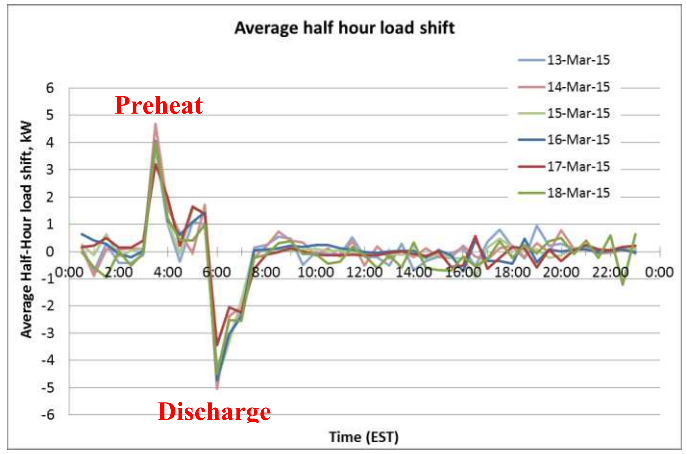

Figure 5: Average half hour power shift, all days of scenario 1.2

Table 4: Power shift for the discharge period

Date	Power shift (kW)		Outdoor temp (°C)
	First 30 min	Average for the discharge period	
13-Mar-15	-4.3	-2.3	-9.9
14-Mar-15	-5.0	-2.4	-3.7
15-Mar-15	-4.7	-2.4	-1.9
16-Mar-15	-4.7	-2.5	-6.7
17-Mar-15	-3.5	-2.0	0.8
18-Mar-15	-4.5	-2.4	-11.7

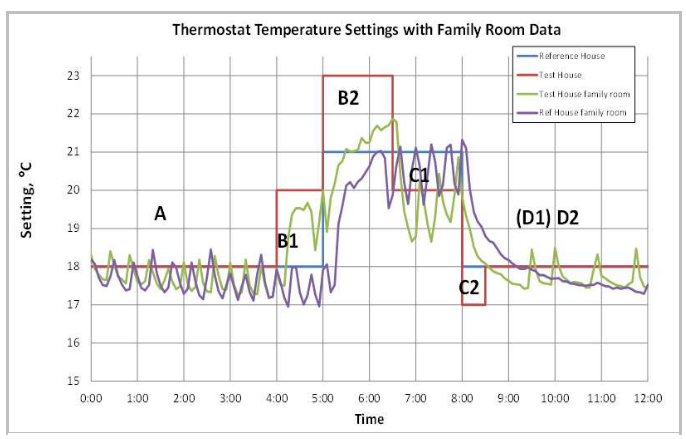

Figure 6: Thermostat settings for Reference House (blue) and Test House (red), and the actual temperature in the test house family room (green) for 18-Mar-15

For colder days the values of parameter B1 were higher and C1 lower for the spaces on the first floor as compared to that of the second floor due to the open concept layout of the houses.

The load shift results for all five scenarios are summarized in Table 5. Our evaluation of the DR strategy at the CCHT suggests that:

- There is a potential for 4 kW load shift for the first 30 minutes of DR through preheat on colder days, though the results in real occupied homes can be expected to vary depending on the total installed capacity of baseboard heaters, the ratio of utility controlled baseboard heaters to the total installed capacity, the energy efficiency of the home, and the thermostat schedule including normal operating temperatures and setbacks.
- Pre-heating increases load shift, and also reduces rebound
- There is a potential for 2 kW potential shift without preheat on milder days
- Although potential load shifts were larger on colder days, substantial load shift was observed at mild temperatures as well
- Scenarios 2.1 to 2.3 involved duty cycling of baseboard heaters through choreography and hence yielded smaller shifts for the full period than the first two scenarios though 2.1 still shifted 4.0 kW in the first 30 minutes as it involved preheating. The 30 minutes shifts for 2.2 and 2.3 were the lowest as these scenarios did not involve preheating.
- Scenario 2.3 had the maximum rebound as it involved turning baseboard heaters off for one hour period through demand response signals with -5°C temperature offset. The recovery of baseboard heaters was staggered over one hour period to constrain the rebound else it may have been larger.

Table 5: Average power shift for all scenarios during the discharge period

Discharge Scenario	Outdoor Temp (°C)	Power shift (kW) for discharge		
		First 30 min shift	Average for full period	Rebound
Scenario 1.1	-8.8	-3.5	-2.6	1.1
Scenario 1.2	-5.5	-4.5	-2.4	0.1
Scenario 2.1	-11	-4.0	-1.8	-0.3
Scenario 2.2	-4.2	-2.4	-0.6	0.4
Scenario 2.3	-6.0	-2.4	-0.8	1.6

- Preheat and discharge strategies did not result in any substantial increase in total daily heating energy consumption

Encouraged by the load shift results achieved at the CCHT, NB Power, Siemens, and NRC undertook further evaluation of the peak shift strategies in 50 occupied homes in the City of Fredericton during the winter of 2016.

ACKNOWLEDGMENT

The authors are grateful to Frank Szadkowski of Natural Resources Canada for his assistance to setup the houses for the study; Steve Kruithof (NRC) for setting up baseboards and thermostats; Heather Knudsen (NRC) for data analysis; Chantal Arsenault (NRC) for compiling the weather data; Bradley Rideout, Chris Pelkey, Dietmar Staack, Greg Robart, Jason Etter, Mark Etheridge, Terrance Cormier (Siemens Canada) for feedback on the design of the study, and scheduling DR events through Siemens DEMS System.

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