# Potential of cold climate air-source heat pump control strategies to mitigate the electrical demand of heating systems during high-demand periods in Canadian dwellings

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## Abstract

Space heating electrification via heat pumps can increase house-level electrical demand. Electrical demand mitigation strategies can delay the heat pump operation giving more flexibility during electrical grid's critical periods and allowing utilities to support greater adoption in Canada. Properly understanding the potential flexibility offered by heat pump systems, and assessing electrical demand mitigation strategies, is critical. Building simulation programs often use an hourly time step and focus on annual heat pump performance, neglecting short-term behaviours and impacts on electrical demand. To assess this flexibility potential, a simulation-based approach with a detailed cold-climate air-source heat pump (CCHP) model using a 2.5-min time step to represent key heat pump operational behaviours (e.g., defrost, start-up) is presented. For the analysis, a CCHP replaces a natural gas-based furnace in a two-storey house in Toronto. Four electrical demand mitigation profiles strategies are simulated and compared to two base cases, using various temperature setbacks/preheating profiles. The three main questions this paper is answering are:

1. How long can the HVAC electrical demand be delayed during defined periods critical for the grid?
2. How much will the HVAC electrical demand increase outside the defined peak periods?
3. How does the annual energy end-use and utility cost change with the mitigation profiles?

Results highlight that, depending on the mitigation profile, HVAC electrical demand can be delayed from 30 minutes to 3 hours on the coldest day in Toronto. On the coldest ambient temperatures, the HVAC electrical demand is now occurring completely outside of the defined high-demand periods for one of the four mitigation profiles. The HVAC electrical demand increases by up to 8.5 kW mainly before the morning high-demand periods. The annual energy end-use also increases ranging from 104 kWh to 312 kWh and the annual utility cost varies within $120 CDN.

## Introduction

Canada targets a reduction in greenhouse gas emissions of 40% from 2005 levels by 2030 and zero net emissions by 2050 (Environment and Climate Change Canada 2022). Heat pumps will play a great role in achieving those objectives by allowing for an efficient electrification of heating systems. Nevertheless, a large adoption of heat pumps when replacing a fossil fuel-based heating system can pose a challenge for electric grids. This is especially true in the case of air-source heat pumps (the most popular type of heat pump in Canada (Canada Energy Regulator 2018)), which often necessitate the use of electric heating auxiliary systems during cold periods to maintain comfort conditions and limit upfront costs. When these heat pump associated electrical demands coincide across many houses within the same community, it can put pressure on the electric grid, essentially placing a practical limit on the adoption of heat pumps across Canada.

Capturing those electrical peaks is essential to better propose mitigation measures and highlight their benefits to diminish electrical demand during critical periods of the year. However, many building simulation software platforms use hourly averaged non-HVAC loads and calculate the electrical demand on an hourly basis. Furthermore, the hourly timestep does not fully represent the key heat pump operation characteristics (e.g., start-up and defrost behaviours) and can flatten the HVAC electrical demand. A recent small case study in the United Kingdom (Berry et al. 2023) aimed at identifying what influences the flexibility potential of heat pumps in homes with user comfort experience of preheating and setbacks. Evaluation of the same kind of strategies is lacking in Canadian climate on residential buildings to improve knowledge on the flexibility potential of heat pumps. Some studies have focused on load reduction with a setback applied to electric baseboards and split heat pumps (Gaucher-Loksts et al. 2023) but do not use different occupancy-based non-HVAC load profiles nor different temperature setbacks and temperature ramp-up for the mitigation strategies. Using different non-HVAC load profiles is important to establish a range of variation.

This paper uses a refined simulation-based approach with a 2.5-min time step and an enhanced heat pump model in residential buildings in Toronto to evaluate the impacts of implementing mitigation profiles to assess the flexibility a heat pump can offer. First, a detailed two-storey house is used with 28 occupancy-driven non-HVAC loads implemented to consider a large set of total occupancy and

occupant behaviour to establish a range. Then a ducted cold-climate air-source heat pump (CCHP) model considering key short-term characteristics such as defrost, and start-up behaviour replaces the furnace. Finally, two temperature setpoint profiles are used as base cases, one with a constant 21°C setpoint and one with a setback of 19°C from 9pm to 7am. Four mitigation profiles with different temperature setbacks and ramp-ups are implemented to answer three main questions:

1. For how long the HVAC heating system operation can be delayed on defined periods critical for the grid?
2. How much will the HVAC electrical demand will increase outside those defined periods?
3. What are the impacts on the annual consumption and the utility bill?

## Methodology

All the systems are modelled with TRNSYS v18 (Klein et al. 2017) using a 2.5-min time step. TRNSYS provides a high degree of flexibility in modelling key components (e.g., the heat pump). The small timestep facilitates a more complete representation of the key operating features of heat pump systems and their interaction with auxiliary heating systems. Canadian Weather for Energy Calculations (CWEC) weather files were used (Environment and Climate Change Canada 2020).

### Housing Model

This study focuses on a single-family house in Toronto. Building geometry is based on the Canadian Centre for Housing Technology (CCHT) test homes located in Ottawa, ON (Swinton et al. 2003). The house has two above-ground floors and a basement, for a total heated floor area of 284 $m^2$. The building's envelope parameters are specific to the Toronto region and are derived from the National Building Code of Canada (Canadian Commission on Building and Fire Codes 2015). The housing model was developed in TRNSYS v18 using Type 56 and has been validated with data collected from the CCHT test homes (Kegel et al. 2012).

To determine the HVAC electrical demand variations associated with the introduction of CCHPs, occupancy-based non-HVAC load profiles were generated by a load profile model with a total of 28 profiles. Those profiles have seven different occupancy behaviours and four occupancy levels. Details can be found in Mollier et al. (2023).

### Heat Pump Model

This study focuses on the replacement of natural gas furnaces with air-source heat pumps, given the prevalence of natural gas systems in new construction homes in Ontario and the Toronto region (Natural Resources Canada 2023). The heat pump is integrated in a centrally ducted configuration, distributing the air through ducts to the basement, the first floor and the second floor.

The cold-climate air-source heat pump (CCHP) has a variable capacity compressor that allows the system to modulate to meet the thermal demand and reduces on/off cycling in comparison to single stage heat pump systems. Additional cycle improvements (e.g., larger outdoor coils, improved controls) help to maintain a larger portion of its heating capacity at low ambient air temperatures. The minimum recommended operating temperature of the heat pump is below the minimum ambient air temperature of the CWEC weather file for Toronto so the heat pump can operate over the entire year.

A detailed custom developed CCHP model in TRNSYS was used for capturing key short-term behaviours such as defrost, start up, and cycling (Breton et al. 2019; St-Onge et al. 2018). This data-driven heat pump model uses performance files extracted from manufacturer specifications at high and low compressor speeds. The normalized capacity curves of the CCHP unit are shown on Figure 1. The sizing of the CCHP was conducted based on the option C of the NRCan *Air-Source Heat Pump Sizing and Selection Toolkit* (2021), where the heat pump capacity is selected to meet the building load at -8.3°C. This balance point temperature is also within the range of recommended balance point temperature for CCHP sizing in Toronto based on Lachance and Tamasauskas (2023). The CCHP's characteristics are detailed in Table 1.

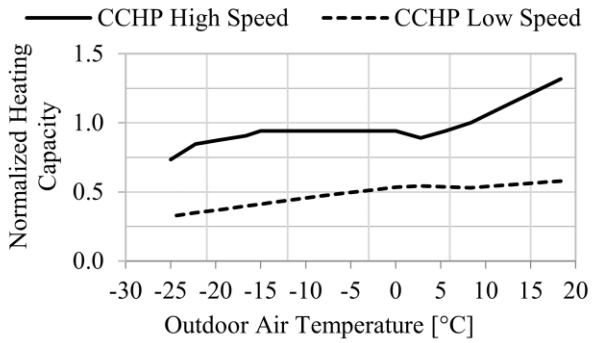


*Figure 1. Normalized Capacity Curves of the CCHP*

*Table 1. Characteristics of the CCHP unit*

| Parameter | CCHP |
|---|---|
| Heating Capacity* | 7.6 kW |
| Heating COP* | 3.8 |
| Heating COP* (Min Speed) | 5.3 |
| Min/Max Heating Capacity Ratio | 0.25 |
| HSPF2 Region V | 7.2 |
| Minimum Recommended Operating Temperature in Heating Mode | -25°C |
| % Capacity at Minimum Recommended Operating Temperature (Max Speed) | 73% |

*Based on AHRI rating conditions (i.e., nominal capacity at ambient air temperature of 8.3°C).

### Heat Pump Control

The heat pump model includes a 5-minute defrost cycle occurring once every 2.5 hours of operation when ambient

temperatures are below 5°C. The cooling delivered to the indoor space during defrost cycles is accounted. Also, upon startup or recovery after a defrost, the compressor frequency immediately goes to maximum to deliver heat more quickly, as noted while testing heat pumps at the CanmetENERGY facility (Kegel et al. 2017).

The heat pump is controlled by a single thermostat located on the first floor of the home, as it is common in most heat pump installations. The CCHP will change its compressor speed to maintain the first-floor temperature to the desired setpoint temperature. The auxiliary heating system has a setpoint below the first-floor temperature setpoint. The auxiliary heating system will turn on its two 2.5 kW stages depending on how far the first-floor temperature is below the auxiliary setpoint. The first and the second 2.5 kW stages turn on when the first-floor temperature is 1°C and 2°C below the setpoint respectively so that auxiliary and heat pump heating systems work in parallel. When the CCHP goes in defrost mode, the auxiliary will operate the two auxiliary stages for a total of 5 kW to minimize drops in indoor temperature.

**Base Case and Mitigation Strategies**

In this study two base cases are compared with four mitigation profiles, each setpoint profile is presented in Figure 2. The two base cases used in this study are:

- BC1 where the first-floor temperature setpoint is 21°C all day and all night.
- BC2 where the occupant will have a setback at 19°C from 9pm to 7am.

The proposed mitigation profiles named MP1 to MP4 are based on previous studies (Déry et al. 2020; Tamasauskas et al. 2023; Mollier et al. 2023). Their setbacks go from 19°C to 16°C and they use the thermal capacitance of the house to prevent HVAC systems from operating during the high-demand periods. The mitigation profiles are the same each day of the heating season in Toronto and for each of the 28 non-HVAC load profiles. The morning and evening high-demand periods considered for the study are shown in grey in Figure 2 and are based on Toronto Hydro (2024b) *On-Peak* periods: 7am to 11am and 5pm to 7pm. For the purposes of this study, a morning high-demand period of 7am to 9am was considered.

At 7am, to reach 22°C even on the coldest day of the year in Toronto, the slope of the morning ramp-up and the length of the plateau were adjusted. If the setpoint is not reached by 6am, auxiliary heating supplements the heat pump to achieve it.

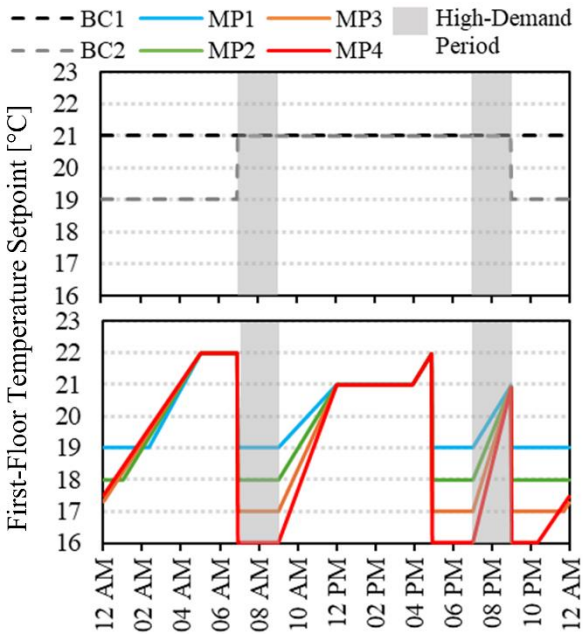


*Figure 2. First-floor setpoint profiles*

## Results and Discussion

**HVAC Electrical Demand Delay**

This section focuses on estimating the length of time that the HVAC heating system operation can be delayed on defined periods critical for the grid. The HVAC electrical demand is calculated on averaged 15-minute periods as typically done by utilities (Toronto Hydro 2024a).

Figure 3 shows load duration curves for our defined 2-hour high-demand periods. These graphs show the number of hours that HVAC electrical demand is above a certain level for each of the 28 non-HVAC load profiles and setpoint profiles. It focuses on the heating season with temperatures below the sizing balance point temperature of -8.3°C. This temperature was selected to represent the coldest periods of the year when HVAC electrical demand in heating is likely to be higher. It is immediately noticeable that the deeper the setback of the mitigation profile, the longer the HVAC electrical demand is close to zero. With MP4, heating system operation is now delayed for more than 2 hours. However, with lesser decreases in setpoint temperature, the HVAC electrical system operation is not delayed sufficiently to cover the 2-hour defined high-demand periods. The temperature of the first floor will reach the setback temperature sooner, and thus the heat pump and the auxiliary will turn on earlier.

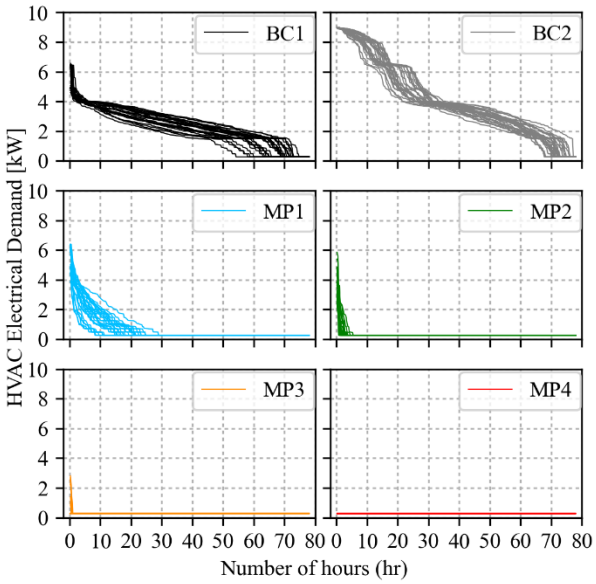


*Figure 3. HVAC electrical demand on the high-demand periods for ambient temperatures below -8.3°C*

Figure 4 represents the HVAC electrical demand and the first-floor temperature variations during the morning and the evening high-demand periods on the coldest day in Toronto (December 20th) for one of the 28 non-HVAC load profiles. The graphs of the 28 different non-HVAC load profiles were analysed to have a range of how long the HVAC heating system operation can be delayed on the coldest day of the year. Results are shown in Figure 5.

Figure 4 highlights that BC1 HVAC electrical demand and first-floor temperature are stable since it has a constant setpoint throughout the day. The same behaviour is highlighted with BC2 during the evening period only. During the morning, BC2 experiences a peak in HVAC electrical demand since the setpoint temperature of the first floor has increased.

Figure 5 shows that with MP1, MP2, MP3 and MP4, the HVAC electrical demand delay ranges from 30 minutes to 3 hours in the morning and by 1 hour to 3 hours in the evening. The deeper the setback, the longer the delay in HVAC electrical demand but also the lower the first-floor temperature. Figure 4 shows that MP3 and MP4 reach a temperature of 17°C and 17.5°C respectively on the morning period before the temperature increases, potentially reducing occupant thermal comfort.

It is interesting to note that MP4 offers HVAC electrical demand delays greater than 2 hours. For MP4, at the end of the 2-hour period, the first-floor temperature is still 1°C above the minimum setpoint temperature. Since a ramp is applied to the temperature setpoint during the recovery period, heat pump and auxiliary heating do not activate immediately after the 2-hour high-demand period. In this case study, it takes an extra 45 minutes before the indoor air temperature falls below the defined temperature setpoint, increasing the flexibility offered.

Figure 4 and Figure 5 also highlight longer delays in the evening period than in the morning period. This is due to the solar gains helping to heat the walls and the roof of the house, the heat will then slowly dissipate. That is also the reason why the electric demand under BC1 and BC2 is lower in the evening than in the morning on Figure 4.

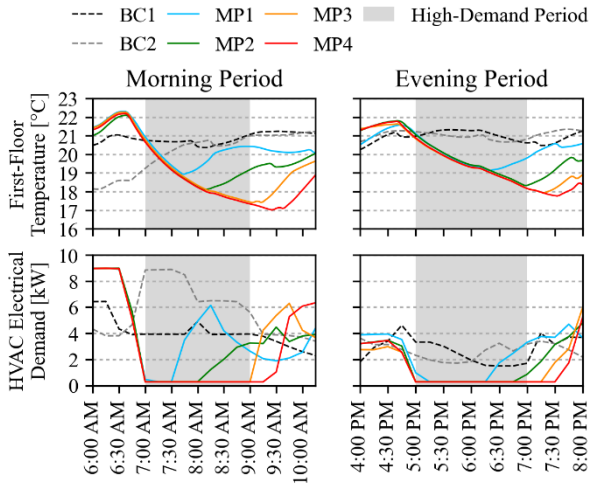


*Figure 4. HVAC electrical demand and first-floor temperature on the 20th of December for one of the 28 non-HVAC profiles*

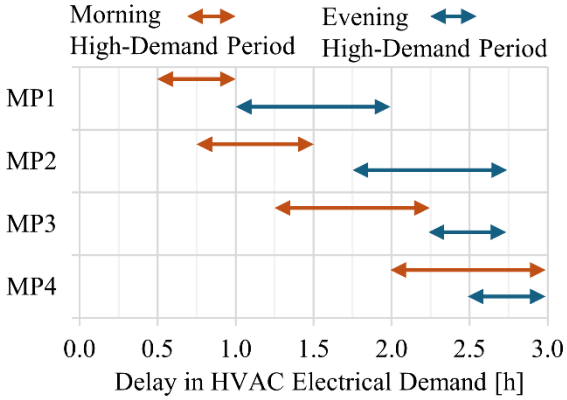


*Figure 5. Delay in HVAC electrical demand on the 20th of December*

**HVAC Electrical Demand Variation**

The previous section analysed the electric demand during the defined 2-hour high-demand periods. This section analyses the HVAC electrical demand increase outside the high-demand periods considered as there is an ultimate shift to achieve the desired flexibility. In fact, the highest HVAC electrical demands will now happen mainly before 7am when the setpoint is increased to 22°C (an increase vs. the two base cases).

Figure 6 presents load duration curves of the increase in HVAC electrical demand for each of the 28 different

non-HVAC load profiles and the different mitigation profiles compared to the two base cases. It focuses on the heating season with temperatures below -8.3°C and outside the defined high-demand periods (7am to 9am and 5pm to 7pm). It shows that HVAC electrical demand can increase by up to 7.3 kW and 8.5 kW compared to BC1 and BC2 respectively. Increases are driven using electric resistance heating in parallel with the heat pump running at maximum compressor speed as the system works to preheat the building before the high-demand periods. Thus, implementing mitigation profiles can cause higher peaks throughout the heating season, but help to reduce them during the defined high-demand periods.

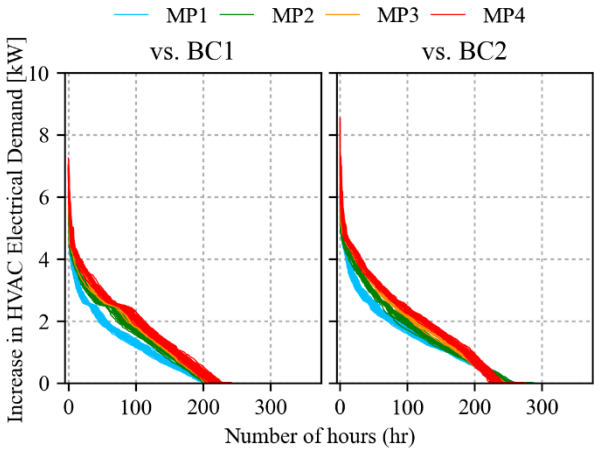


*Figure 6. Load duration curves of HVAC electrical demand increase when outdoor temperatures are below -8.3°C and outside the defined high-demand periods*

**Annual Energy End-Use and Electric Cost**

Considering the annual energy use, the implementation of mitigation profiles can generate an increase compared to BC1 and BC2 as shown on the box plots in Figure 7. The mitigation profiles will increase the annual energy end-use from 104 kWh to 312 kWh, depending on the mitigation profile and which baseline is used. This increase can be higher with BC2 than with BC1 because BC1 has no setbacks so has a higher annual energy end-use than BC2 which has a night setback at 19°C. With the base cases, the auxiliary will work less, and the heat pump will work closer to its nominal capacity. With the mitigation profiles, the HVAC system must continually adapt to changing setpoints and will require the heat pump and the auxiliary to work for a longer period and at higher capacity to increase the indoor temperature with the different ramp-ups. Furthermore, Figure 7 shows that deeper setbacks do not result in lower annual energy end-use. The increase with MP2 and MP3 are very close with medians ranging from 155 kWh to 171 kWh vs. BC1 or BC2. MP4 and MP1 have a higher increase in annual energy end-use. For MP4, the HVAC system will have to work for a longer period and at higher capacity to increase the first-floor temperature from 16°C to 21°C and MP1 does not have a setback low enough to overcome the energy requirements for a higher pre-heat temperature. This suggests some form of setback strategy that best balances preheat, recovery, and depth of setback, which will be investigated in future work.

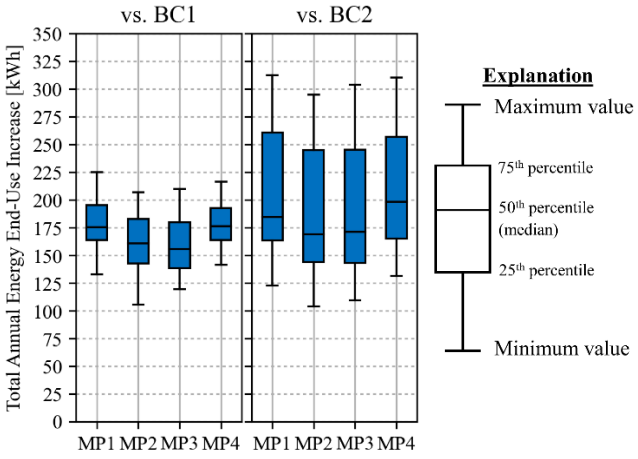


*Figure 7. Box plots of the annual energy end-use variation with mitigation profiles with box plot explanations*

Changing the setpoint profile from the base cases to the mitigation profiles will not significantly change the annual electric cost, based on the electricity rates examined in this study (Toronto Hydro rates from 2023). Toronto Hydro currently employs a time-of-use rate structure *Off-peak*, *Mid-peak* and *On-peak* periods. The annual electric cost can decrease by down to $85 CDN and can increase by up to $34 CDN. Increases are due to the use of more auxiliary to reach the 22°C before the high-demand periods. Besides, as there is a recovery period from 9am to 11am with the mitigation profiles, more electricity is used within the *On-peak* rating periods (7am to 11am) than with BC1. Decreases are due to the use of setbacks during the night and lesser consumption of electricity within the *On-peak* rating periods compared to BC2.

**Discussion**

The aim of this paper has been to compare the impact of different mitigation profiles, rather than suggest a single optimal profile. Each profile presented demonstrates a balance between electrical demand reductions during high-demand periods and resulting impacts on annual energy consumption. If the objective is to avoid any HVAC electrical demand during the defined 2-hour high-demand periods during the coldest period of the year, profiles with deeper setbacks such as MP4 appear to be preferred. MP3 offers a high degree of flexibility by delaying most of the HVAC electrical demand for more than 1h15. To allow even longer delay, MP4 can delay the HVAC heating system operation to up to 3 hours. MP1 and MP2 do not allow long enough delay in HVAC system operation. All mitigation profiles are associated with some form of annual energy use increase, although these increases appear to be smaller for

MP2 and MP3. It is also important to note that these simulations represent a sample analysis, and results may change for different building types, construction vintages and regions.

On the annual utility cost side, for all mitigation profiles the variations are quite close, and costs can change depending on the utility objective. With the current time-of-use rates in Toronto, mitigation strategies do not allow the users to save a significant amount of money considering the efforts they have to make on their potential comfort.

Other sets of mitigation profiles were developed before selecting the ones presented in this paper. Scenarios without the plateau at 22°C before the morning high-demand period or without the setpoint increase for the auxiliary system, for example. These scenarios were not able to warm up the first-floor temperature to 22°C on the coldest day of the year (December 20th) and thus were not considered in the assessment. In this paper, the mitigation profiles were defined based on the coldest day as a first attempt to assess the benefits and available flexibility of such mitigation scenarios.

## Conclusion

This paper looks at the HVAC electrical demand, the annual energy end-use and the utility cost variations when implementing electrical demand strategies in a single-family house in Toronto heated with a ducted cold-climate heat pump (CCHP). A detailed housing model and occupancy-based non-HVAC load profiles are used to better capture diversity in occupancy scenarios and number of inhabitants. A data-driven enhanced CCHP model and the use of a 2.5-minute time step are selected to represent heat pump short-term characteristics such as defrost and start-up to evaluate the HVAC electrical demand more accurately. Two setpoint profiles are used as base cases: BC1 with a constant setpoint at 21°C and BC2 with a setback to 19°C from 9pm to 7am during the heating season. Four mitigation profiles (MP1, MP2, MP3 and MP4) are compared to the base cases and have setbacks and warm-ups to delay the HVAC electrical demand using the thermal mass of the house.

This paper focused on three questions:

1. For how long the HVAC heating system operation can be delayed on defined periods critical for the grid?

Results highlight that mitigation profiles can delay the HVAC electrical demand and make them happen out of defined high-demand periods (7am to 9am and 5pm to 7pm) when warming the house up to 22°C before those periods. The HVAC electrical demand can be delayed on Toronto's coldest day by 30 minutes to 3 hours depending on the mitigation profile. MP4 can delay all the HVAC electrical demand on the coldest days out of the high-demand periods and can give up to 3 hours of delay. MP1 is the profile with the smallest delay since its setback is not deep enough during the high-demand periods.

2. How much will the HVAC electrical demand will increase outside those defined periods?

Outside the high-demand periods, on the coldest days of the year, the HVAC electrical demand can increase by up to 7.3 kW and 8.5 kW compared to BC1 and BC2 respectively. This is due to the highest HVAC electrical demand now happening mostly before the morning high-demand period when the temperature of the house increases. The auxiliary will supplement the heat pump operation to reach 22°C on the first floor and thus will increase the electrical demand compared to the base cases.

3. What are the impacts on the annual consumption and the utility bill?

Focusing of the annual impacts of those mitigation strategies is important to compare the mitigation profiles to BC1 and BC2. Depending on how the users currently operate their heat pump, annual variations will be different. Compared to BC1 and BC2 respectively, the mitigation profiles can vary:

1. The annual energy end-use from +104 kWh to +312 kWh.
2. The annual utility cost from -$85 to +$34 CDN.

The annual variations in cost are small and the user might experience slight thermal discomfort during certain periods of the day. Utilities can also change and give more benefit to the users depending on the grid's objectives.

Future work will investigate how mitigation profiles driven by occupancy and ambient air temperatures can better optimize the annual cost and energy end-use variations. Finally, a highly zoned house model will be used to implement those mitigation strategies on electric baseboards and ductless heat pump systems to assess their flexibility potential.

## Nomenclature

BC: Base Case

CCHP: Cold-Climate Air-Source Heat Pump

CCHT: Canadian Centre for Housing Technology

CWEC: Canadian Weather for Energy Calculations

HVAC: Heating, Ventilation and Air-Conditioning

MP: Mitigation Profile

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