Potential of building thermal mass for energy flexibility in residential buildings: a sensitivity analysis

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Abstract: *Building thermal mass, which can be used as a thermal storage system, can provide energy flexibility potential for demand response (DR). This flexibility refers to the deviation of energy demand against normal operation of building mechanical system during a certain period, for instance, during grid peak hours. This paper assesses several key performance indicators (KPIs) to quantify the building energy flexibility. A typical Canadian house is used as a case study and a simple setpoint temperature modulation approach is implemented. Simulation results show that the amount of flexible energy is quite significant, especially during colder weather. The energy rebound effect after the DR event is also analyzed and the implemented control strategy saves about 20% of energy for a DR duration of 2 hours without thermal comfort compromise.*

Keywords: *energy flexibility, demand response, thermal mass, control strategy*

CONTEXT

Demand Response (DR) is generally considered a feasible solution to reduce peak electricity demand and flatten the demand curve for the utility. It is less costly and more environmental-friendly than operating reserve power or investing extra plants when the capacity is insufficient for the peak demand (Davito et al. 2010). DR can play an even more significant role for the load balancing when the grid integrates renewable energy sources (RES). The highly variable generation power and dependence on climate conditions of the RES add more challenges to match supply and demand for the grid.

On the consumption side, buildings are a key asset for DR due to their high energy demand, as well as the flexibility of the demand (Li et al. 2017).

Demand Response programs have been successfully implemented in practice to shift the peak power demand of buildings from critical periods to off-peak time (Palensky & Dietrich 2011). For instance, the utility could turn off heat pumps or electric water heating systems in buildings during peak time through a direct load control program. This possibility of demand response of buildings is due to the elasticity of building energy demand in time, or more concretely, energy flexibility of buildings.

Energy flexibility of buildings is defined broadly as "the ability to manage its demand and (energy) generation according to its local climate conditions, user needs and energy network requirements" by the Annex 67 of International Energy Agency (IEA) Energy in Buildings and Communities Programme (EBC) (Jensen, Marszal-Pomianowska, et al. 2017).

The flexibility of buildings is largely contributed by the energy storage systems (thermal mass, hot water tanks, ice storage, phase change materials, battery etc.) or energy generation systems (photovoltaic panels, solar thermal collectors, wind turbines etc.) in or around buildings.

This new terminology is closely related to more established terms like load shifting or load shedding as elaborated in the section Methodology, but it is a more general concept and can be applied to broader circumstances, especially for future smart grid and smart buildings, where two-way communication between the grid and buildings would become a common practice. It can also act as a label for buildings similar to the energy performance certificate in many countries. In fact, the European Energy Performance of Building Directive (EPBD) has already proposed such a "smartness indicator" for buildings (European Commission 2016). The context of energy flexible buildings was more thoroughly explained in the position paper published by the Annex 67 (Jensen, Henrik, et al. 2017).

This paper investigates the energy flexibility of residential buildings associated to the thermal mass. We will present a methodology to quantify the energy flexibility using simulation studies and introduce several Key Performance Indicators (KPIs) to evaluate the flexibility. Special care will be given to important factors that impact the KPIs.

LITERATURE REVIEW

The literature has not included much research about the energy flexibility when this paper was written, while the

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Annex 67 of IEA is still in the process of exploring a standard approach to evaluate the flexibility.

Clauß et al. (2017) reviewed most of the previous studies related to the energy flexibility and listed existing KPIs in a wide range of studies, like for PV or thermal storage systems. De Coninck and Helsen (2016) used a model predictive control (MPC) approach to optimize energy cost based on dynamic imbalance price in Belgium. The energy flexibility was achieved by adjusting the temperature within the thermal comfort band (between 21.8 °C and 23.5 °C) as well as by thermal storage tank associated with the heat pump system.

Le Dréau and Heiselberg (2016) discussed about the energy flexibility for two types of residential buildings in Denmark (a passive house and an old house built in the 80s) as well as for two kinds of heating systems (radiators and underfloor heating). The adopted KPIs were the amount of thermal energy stored $\Delta Q_{heat,charged}$ and the amount of energy discharged $\Delta Q_{heat,discharged}$ (see Table 1). The charged amount was always positive and the discharged always negative. Another indicator was the shifting efficiency, calculated as the absolute ratio of these two terms. Reynders, et al. (2017) and Reynders, et al. (2015) took a similar approach to assess the energy flexibility of detached and terraced dwellings respectively for 4 different ages in Belgium. The proposed KPIs were flexibility capacity C_{ADR} and storage efficiency η_{ADR} (see Table 1). Like the paper by Le Dréau and Heiselberg (2016), the authors focused on the storage performance of the thermal mass and thus C_{ADR} was always positive.

Table 1: KPIs in the literature

KPIs	Equations
Le Dréau 2016	$\Delta Q_{heat,charged}(-) = \int_0^{\infty} \Delta q_{heating}\, dt$ $\Delta Q_{heat,discharged}(+) = \int_0^{\infty} \Delta q_{heating}\, dt$ $\eta_{shifting} = -\frac{\Delta Q_{heat,discharged}}{\Delta Q_{heat,charged}}$
Reynders 2017	$C_{ADR}(+) = \int_0^{l_{ADR}} (Q_{ADR} - Q_{ref})dt$ $\eta_{ADR} = 1 - \frac{\int_0^{\infty_{ADR}} (Q_{ADR} - Q_{ref})dt}{C_{ADR}}$

Note: explanations of terms above are listed in the Nomenclature.

The methodology and KPIs proposed by the last two teams investigated the energy flexibility from the perspective of buildings. They looked at the building thermal mass as a storage medium and characterized how much energy the building could store or discharge in a DR event based on their indicators. And those indicators are not directly associated to the electric load of grid. Therefore, those KPIs are difficult to interpret from the utility perspective. KPIs that quantify the flexibility of electric power and energy demand of buildings are assessed from the grid perspective in the present study.

METHODOLOGY

The energy flexibility in buildings investigated in the present study is categorized into two scenarios: downward and upward flexibility.

- The **downward flexibility** (also called negative flexibility) is similar to the conventional peak load shifting. It shows the capability of buildings to use less energy during peak periods when the power supply is in potential shortage. This case is more commonly researched in the literature. A typical electricity pricing scheme would reflect this situation by imposing higher price during peak periods.
- The **upward flexibility** (also called positive flexibility) is to use more energy in buildings when the power generation exceeds the demand. It can be interpreted as "valley load shifting". This situation happens more often when renewable energy resources are integrated in the grid, where the variable renewable power production may overload the grid. When it happens, it is often more economical to use the over-generated electricity than to store it. Therefore, the flexible demand of buildings can be manipulated for such situations too.

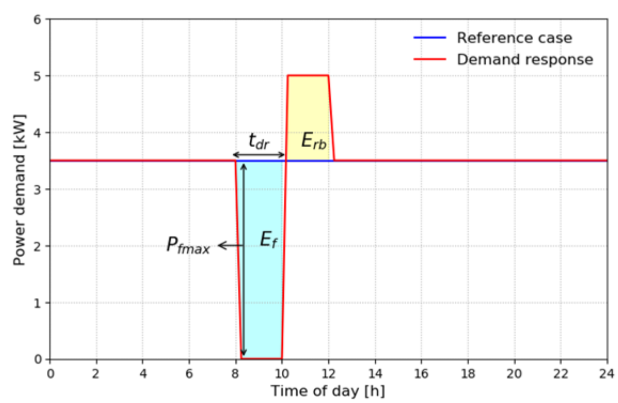

Figure 1: Flexible energy demand of buildings (downward flexibility) with E_f: flexible energy; E_{rb}: rebound energy; P_{fmax}: maximum flexible power; t_{dr}: duration of demand response event

KPIs

To quantify the energy flexibility contributed by the building thermal mass, we introduce the four indices below in the present study. Figure 1 presents a conceptual energy flexibility of buildings with a

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downward flexibility event happening from 8 am to 10 am.

Flexible energy E_f

The flexible energy quantifies the amount of energy that has been shifted compared with the reference scenario, either downward or upward. It indicates the decreased or increased energy usage during the DR event. The cyan shaded area shown in Figure 1 indicates the downward flexible energy amount during a DR event.

$$\boldsymbol{E_f} = \int_0^{t_{dr}} \left(P_{dr} - P_{ref}\right) dt \tag{1}$$

Note that P_{dr} and P_{ref} in the equation are *electric power*, unlike the terms shown in Table 1 are *thermal*. This index also shows the amount of shifted power in average during the DR duration (the average shifted power equals E_f divided by the time of DR duration t_{dr}).

Rebound energy E_{rb}

After the DR event, there is a high possibility in energy rebound, positively or negatively. If we have saved energy during the peak (the case of downward flexibility), we may immediately see power demand go up after the peak. Similarly, if we have increased energy use during the demand valley (upward flexibility), the energy need may ramp down after the event because the thermal mass can store part of the excessive energy. The rebound energy E_{rb} is used to denote this amount of energy rebounded after the DR event (as shown by the yellow shaded area in Figure 1).

$$\boldsymbol{E_{rb}} = \int_{t_{dr}}^{t_\infty} \left(P_{dr} - P_{ref}\right) dt \tag{2}$$

Note that the upper bound for the integration in Equation (2) is infinite, but we take it as 48 hours in the calculation. In all our simulation results, we have confirmed that no rebound effect lasts longer than this horizon; therefore, 48 hours is effectively infinite for our study; it may however be different for other situations.

Flexible energy efficiency η

The DR action does not necessarily save energy consumption for electricity users. The flexible energy efficiency is introduced to quantify the energy consumption change. Similarly, a cost efficiency could also be introduced to take into account the price change, for instance time-of-use or dynamic electricity price; however, this paper intends to be general and not to address the price signals.

$$\boldsymbol{\eta} = \left|\frac{E_f}{E_{rb}}\right| \times 100\% \tag{3}$$

Maximum flexible power P_{fmax}

This indicator is helpful to identify the maximum potential of power change during a DR event against the reference case. Eq. (4) is separated into the downward and upward cases instead of using absolute values to take into consideration that the rebound phenomenon may occur during the DR event.

$$\boldsymbol{P_{fmax}} = \begin{cases} \max_{t_{dr}}\left(P_{ref} - P_{dr}\right) \\ \max_{t_{dr}}\left(P_{dr} - P_{ref}\right) \end{cases} \text{for} \begin{array}{c} \text{downward} \\ \text{upward} \end{array} \tag{4}$$

Case study

The selected residential building for the present study are the twin houses at Canadian Centre for Housing Technology (CCHT), which were built in 1998 according to the Canadian R-2000 building standard. They are three-story houses with basement, the first floor (living zone) and the second floor (sleeping zone). The construction are typically North-American with wood frame structure and brick veneer as exterior finish. The internal thermal mass is relatively low, and the time constant for a response to heating power is in the order of 18 h. A brief summary of the CCHT houses are presented in Table 2 (Zhang et al. 2015). Home automation systems are installed to simulate occupancy by activating appliances, lights, water valves and incandescent bulbs (for internal gains due to humans) based on repetitive daily schedules.

Table 2: Brief summary of CCHT houses

Feature	Details
Liveable area	210 m^2 (2 stories)
Insulation	Attic: R=8.6 m^2K/W; Walls: R=3.5 m^2K/W; Rim joists: R=3.5 m^2K/W
Basement	Poured concrete, full basement Floor: concrete slab, no insulation Walls: R=3.5 m^2K/W in a framed wall
Windows	Low-e coated, argon filled windows Area: 35 m^2 total, 16.2 m^2 south facing
Airtightness	1.5 h^{-1} @ 50 Pa

Simulation setup

The amount of building energy flexibility contributed by the thermal mass is obviously impacted by how the heating, ventilation, and air conditioning (HVAC) system is controlled. An HVAC system controlled by an advanced control strategy such as MPC is more suitable to provide larger energy flexibility than a basic

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thermostatic control, but an advanced control strategy reflects less the common practice. We therefore focus on a simple temperature setpoint modulation on the impact of energy flexibility in this paper. It is not only easy to implement in reality as a potential DR program, but also helpful to interpret the results of KPIs introduced in the paper, which may be extended to more complex contexts for further studies.

The setpoint control scenario during the DR event is

- Decreasing the reference setpoint by 2 °C for the downward flexibility;
- Increasing the reference setpoint by 2 °C for the upward flexibility.

The same control strategy has also been adopted by (Reynders et al. 2017; Le Dréau & Heiselberg 2016). Note that this 2 °C change happens in one time step (15 minutes in our case). The reference setpoint case represents a typical setpoint profile as shown in Table 3.

Table 3: Reference setpoint scenario

Zone	Reference setpoint	DR event
First floor	21 °C	2 °C change
Second floor	21 °C	2 °C change
Basement	17 °C	Not adapted

To investigate the general energy flexibility of buildings, we assume the DR event can occur at any hour of year. In this paper, we focus on the heating season starting from October 15th to April 29th (altogether 196 days); in other words, the DR event happens at 4704 different hours (196 × 24 hr.). To assure each DR event independent, one simulation corresponds to only one event.

A validated building model was built in TRNSYS (Klein et al. 2014) with CWEC weather file for Montreal, Canada. The electric baseboard heating system was modeled using the idealized heating in TRNBuild; therefore, the setpoint control was also idealized in the simulation. Matlab was used to run the simulation in batches for different DR events in different scenarios.

Parameters

The building energy flexibility and the associated KPIs proposed in the paper are performance-based; therefore many parameters could impact the results. The building construction (insulation level, airtightness, thermal mass, retrofit etc.) is a common parameter discussed in the literature as mentioned above. This paper investigates the energy flexibility of one typical housing archetype and the studied parameters include weather, DR duration t_{dr}, setpoint change scale and setpoint profiles representing different occupancy profiles.

RESULTS

A single DR event

The temperature and power change during a 2-h downward flexibility event on a typical day is shown in the following figure. In this case, the setpoint temperatures for the first floor and second floor both drop 2 °C from 7 am to 9 am during the DR event (the black dashed curve in Figure 2 presents the setpoint change for the second floor; the modulation for the first floor is the same).

We can observe that the total power demand decreases drastically when the setpoint suddenly drops by 2 °C. The heating system is shut off during the first hour and then turned on with minimum power to maintain the setpoint. In result, the zone temperature of the second floor drops by 1 °C after 1 hour and remains at the setpoint for the second hour of the event. When the event ends and the setpoints go back to normal, we then observe a power rebound (shown by the magenta curve). Since this is a simple thermostatic control and no strategy is implemented to counteract the rebound effect, this concequence is expected.

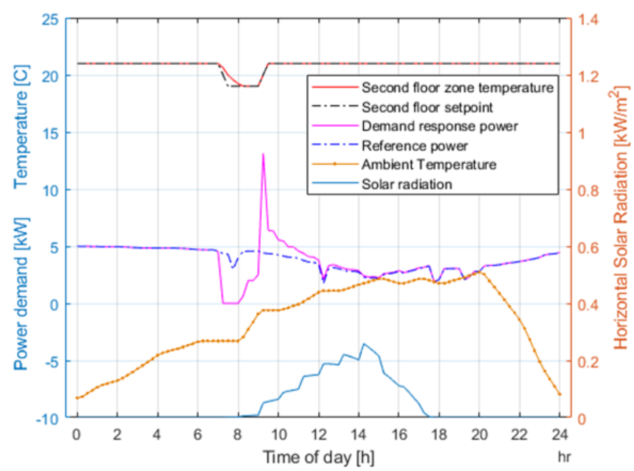

Figure 2: Temperature and power profiles in a DR event (downward flexibility)

The blue curve shows the total power demand in the reference scenario, whose setpoint temperature remains at 21 °C all the time. On this day, the reference power demand stays relatively stable. It decreases slightly when the ambient temperature goes up and the building absorbs the solar radiation during the daytime.

The flexible energy E_f for this DR event is the difference between the sum of the power use for the demand response and the total reference power use from 7 am to 9 am, i.e., the difference between the magenta and blue curves. This is the real power change profile of the

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conceptual line as presented in Figure 1. Similarly, the rebound energy is the difference of the same two terms but the integration period starts after the event (from 9 am on) and lasts for the next 48 hours. From Figure 2, we can see that the rebound effect is strong during the first half an hour and lasts for about 3 hours.

Figure 3 shows the upward flexibility event occurring at the same time of the same day as in Figure 2. Contrary to the downward flexibility, the upward flexibility event increases the setpoint temperatures by 2 °C. We can observe an immediate power increase in response to this action. This phenomenon occurs because we allow the setpoint increase by 2 °C in one time step in the simulation and the heating capacity also suffices for this change (note that the setpoint temperatures shown in these two figures are average values over one time step). This sudden peak in power demand could be reduced if it was a concern (as for the power rebound effect in the downward flexibility). For example, the setpoint temperature could be increased linearly over a few time steps.

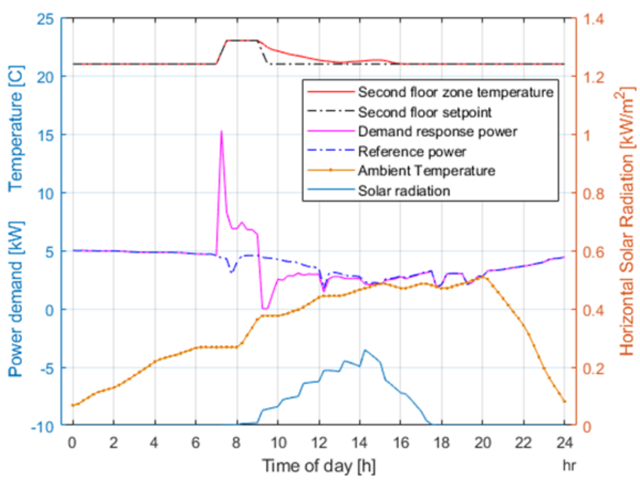

Figure 3: Temperature and power profiles in a DR event (upward flexibility)

When the DR event ends, we see that the zone temperature of the demand response case (the red curve) drops slowly and its power demand remains almost 0 for a while. This is because the thermal mass has stored heat during the event. The power demand then goes back to the same level as the reference case after about 5 hours.

Weather impact

Figure 4 presents the downward flexible energy E_f for 2-h DR events happening every hour for the whole heating season (note the negative values in the y axis). As in Figure 2, each independent DR event lasts for 2 hours with 2 °C modulation of setpoint temperatures for the first floor and second floor (the big blue dot in Figure 4 presents the flexible energy of the single event in Figure 2). Each data point in the figure represents one simulation result, and all the data points were sorted out by the hour of day as well as their correspondent months. The transparent boxes are the same as in boxplots with the top edge indicating the 75th percentiles and the bottom edge indicating the 25th percentiles.

The blue curve in the middle shows the median value of the flexible energy. We can observe the amount of energy that can be shifted is highly correlated to the hour of day. During the night time, the shifted energy is much more significant than that of daytime with maximum value three times of the minimum. This is because the building experiences higher ambient temperature generally during the day and can have solar gains as well. This daily cycle of temperature results in lower energy demand in the reference case and therefore reduced DR potential.

The colors of data points indicate the months. Among the 7 months investigated, it is clear to see that the coldest months (January and December) have higher flexibility than the shoulder months (like March, April and October). The small values of flexible energy that spread out in the top part of the figure mostly fall in the three shoulder months. This seasonal trend is the same as explained for the daily phenomenon in that the reference case has lower energy demand, therefore the DR has also lower potential to shift the energy demand.

Figure 5 shows the upward energy flexibility in a same format as shown in Figure 4, in which the big blue dot indicates the flexible energy of the single event in Figure 3. We find a similar daily and seasonal trend for the upward flexibility due to the same reasons discussed above. The spread of E_f values shows a strong daily variation, but the median upward flexible energy is approximately constant (and close to the available heating capacity). This shows that the thermal mass capacity of the studied building is large enough to store the heating energy provided during the 2-h DR event.

The maximum power shift P_{fmax} shows the same trends as the flexible energy for both cases and figures are not shown in the paper.

Based on our discussion above, we conclude that the potential of buildings to shift heating power demand is higher during colder weather. This is beneficial for the utility, which experiences a higher demand during these periods. The ability to use more power by buildings is also higher in colder weather but the weather impact on the median values is not as significant. The building could still have the potential to use more energy when the grid would experience a significant solar power input during the day.

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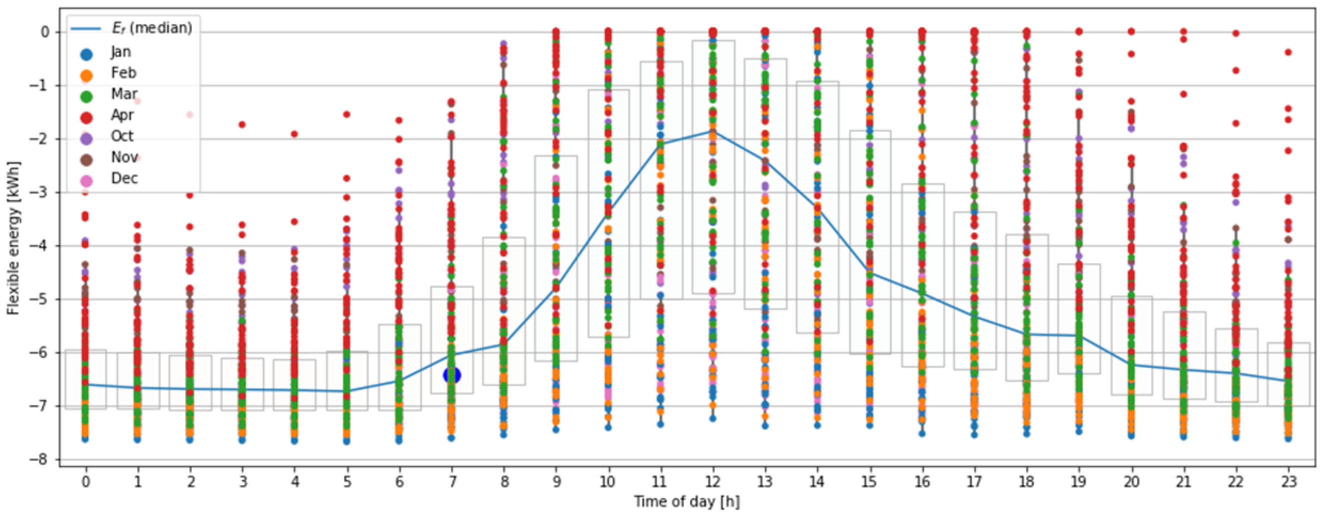

Figure 4: Downward flexible energy of the heating season

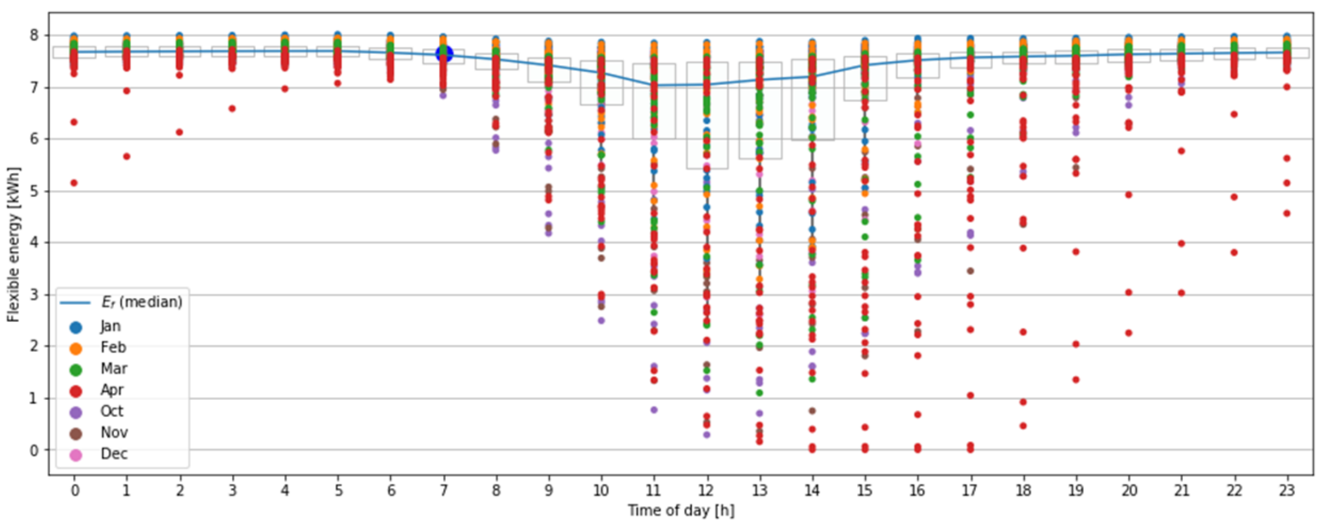

Figure 5: Upward flexible energy of the heating season

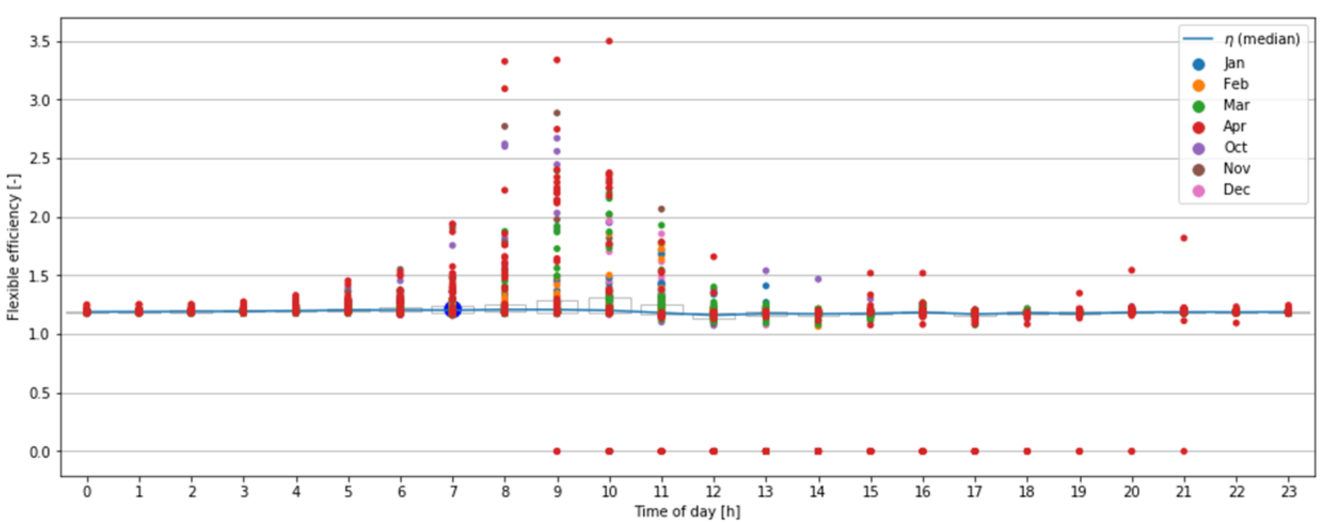

Figure 6: Downward flexible efficiency of the heating season

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Figure 6 presents the downward flexible efficiency. We find a near-constant median efficiency around 1.2. This means that the rebound energy is almost always 20% less than the saved energy (the several zero points represent cases when both the flexible energy and rebound energy are 0). The upward flexible efficiency shows similar results as the downward one; therefore the figure is omitted in the paper. This confirms that the DR strategy in our study is not energy inefficient.

DR duration

The DR duration t_{dr} discussed in above scenarios is 2 hours. This parameter depends on the utility requirements and is related to the impact of DR strategies on thermal comfort (a drop of 2 °C may be acceptable for one hour but not for 6 hours). Different DR durations were compared to assess the impact of this parameter and to investigate whether an optimal value exists.

Figure 7 shows the upward and downward flexible energy amount E_f as a function of the DR duration t_{dr}. For the two scenarios at each duration, each box in the figure presents the results from 4704 simulations. We can see an increasing trend from the median values (the red lines inside the boxes) that the longer the duration, the larger the flexible energy. The top edge of the box indicates the 75th percentiles of the results excluding the outliers accounting for around 0.7% of the results (not displayed in the plot), while the bottom edge indicates the 25th percentiles. We can see that more data points are concentrated to the median values for the upward flexibility than the downward flexibility, which means the upward flexible energy reports steadier values and is less likely to be impacted by other factors than the downward flexibility. This result is consistent with the results from Figure 4 and Figure 5.

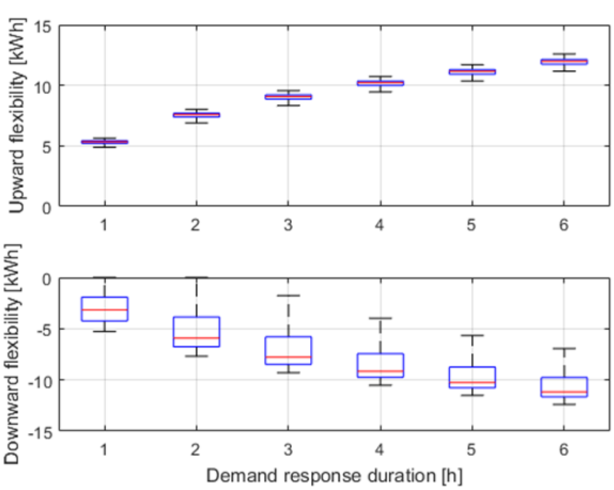

Figure 7: Flexible energy as a function of DR duration

Figure 8 presents boxplots for the rebound energy E_{rb} in a similar style to Figure 7. The upper plot shows the rebound energy for the upward flexibility, therefore it is negative value. The lower plot shows the opposite. We can also observe an increasing trend for the rebound energy as the DR duration increases. However, its increase slows down when the duration becomes longer. This observation is clearer in Figure 9, which shows the median flexible efficiency η as a function of DR duration.

We can see from Figure 9 that the median efficiency is always larger than 1 for both scenarios, which means that the amount of flexible energy E_f is always larger than the rebound energy E_{rb}. For instance, when the DR duration is 2 hours, the downward efficiency is close to 1.2, which signifies that this DR event saves around 20% of energy use. This result is consistent as what we discussed in the last section (Weather impact).

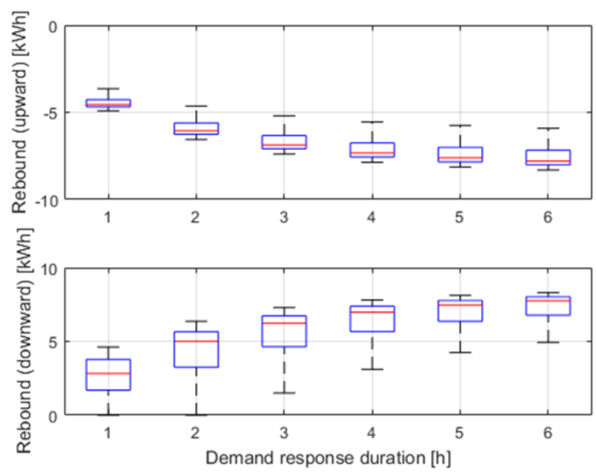

Figure 8: Rebound energy as a function of DR duration

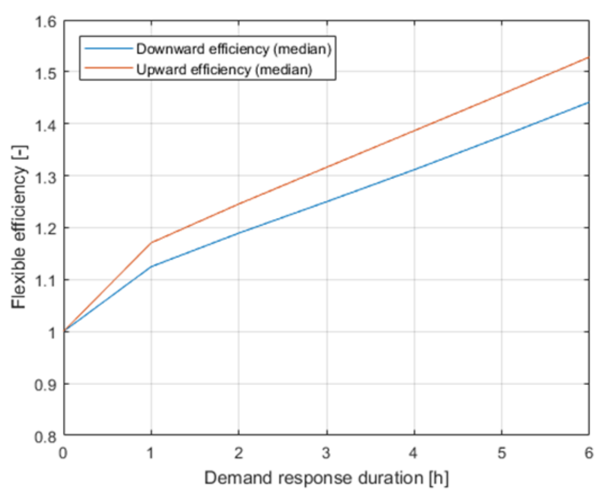

Figure 9: Median flexible efficiency as a function of DR duration

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Although the DR duration does impact the flexible energy E_f and rebound energy E_{rb}, it has negligible impact on the maximum flexible power P_{fmax} as shown in Figure 10. In our case, the heating system has no time delay to respond to the demand no matter when the event begins. Thus the power shift ability can almost always reach its maximum at the beginning of the event.

Based on the above analysis for the four indicators, we conclude that the flexible energy increases as the DR duration increases, so does the rebound energy and flexible efficiency. However, the increase of the flexible energy slows down when the duration is longer. And long duration of DR events could lead to thermal comfort compromise; therefore, 2 to 3 hours could be an optimal DR duration.

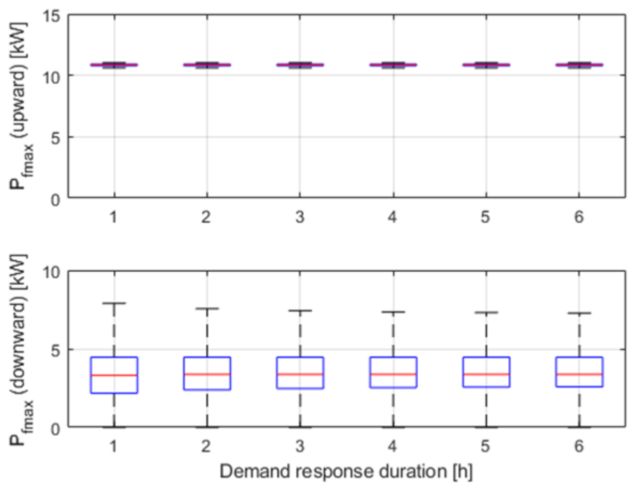

Figure 10: Maximum flexible power vs. DR duration

Setpoint temperature change

In the previous simulations, the setpoint temperature change is always 2 °C, upward or downward. This section investigates the impact of that parameter for a DR event duration of 2 hours.

The top two plots in Figure 11 shows respectively the downward and upward flexible energy as a function of setpoint temperature change. We can see that when the setpoint drops by 2 °C, the median downward flexible energy amount is about 1.5 times that obtained with a 1 °C decrease. When the setpoint increases by 2 °C, the median upward flexible energy is about twice as large as with an increase by 1 °C. The flexible efficiency however remains almost the same for both cases, as can be seen from the middle two plots. This shows that the rebound effect remains nearly relatively the same no matter how the setpoint temperature is modulated during the DR event.

The lower two figures show that the maximum power reduction capability does not change much for the two setpoint changes, while the maximum power increase capability for the 2 °C change is twice than for 1 °C.

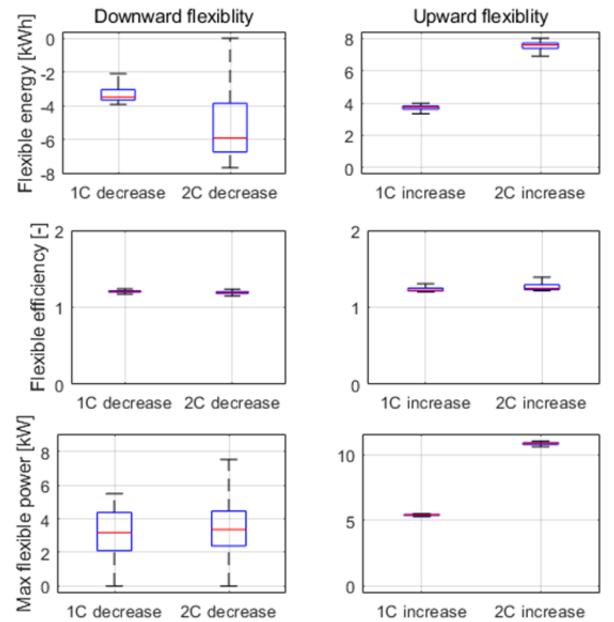

Figure 11: Setpoint temperature change

In summary, we find that 2 °C increase of setpoint is more effective than 1 °C increase for the upward flexibility. For downward flexibility, 2 °C drop of setpoint gives a higher flexible energy but the improvement over a 1 °C increase is not as large as for the upward flexibility. This conclusion is interesting if a 2 °C drop is deemed unacceptable for thermal comfort, although it should be noted that the temperature will not reach the lower setpoint very quickly for shorter DR durations.

Occupancy (constant setpoint vs. setback)

For all the simulations above, we used a constant setpoint profile for the reference case. This scenario is not uncommon in reality if the installed thermostat is not programmable. If the reference setpoint profile includes a setback, we would expect different results. The studied setback scenario is summarized in Table 4, which represents a typical setback profile in Canadian households.

For the downward DR event, we impose a 2 °C decrease during the event. For the upward DR event, we assume a upper limit of 23 °C, the same as the constant setpoint case. This means 6 °C increase for both zones when they are unoccupied, 2°C increase when the first floor is occupied and 4 °C increase when the second floor is occupied. In the same way, the basement is not adapted

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for DR events. Note that the DR duration always remains 2 hours for this case.

Table 4: Reference setback profile

Zone	Temperature	Time
	Occupied / unoccupied	Occupied
First floor	21 / 17 °C	06:00~08:00 16:00~22:00
Second floor	19 / 17 °C	22:00~06:00
Basement	17 °C	/

Figure 12 summarizes the simulation results for the setback profile as a reference case. Compared with the constant setpoint reference case, we can see that the median downward flexible energy of the setback case is around 33% smaller (4 kWh vs. 6 kWh). Both reference cases have very similar maximum and minimum values for the flexible energy, but the values are more widely spread out for the setback case (therefore lower median value). Contrarily, the upward flexible energy of the setback case is much larger, almost twice of the constant case. The difference of the maximum flexible energy is even more pronounced with the setback case reaching 21 kWh and the constant case around 8 kWh.

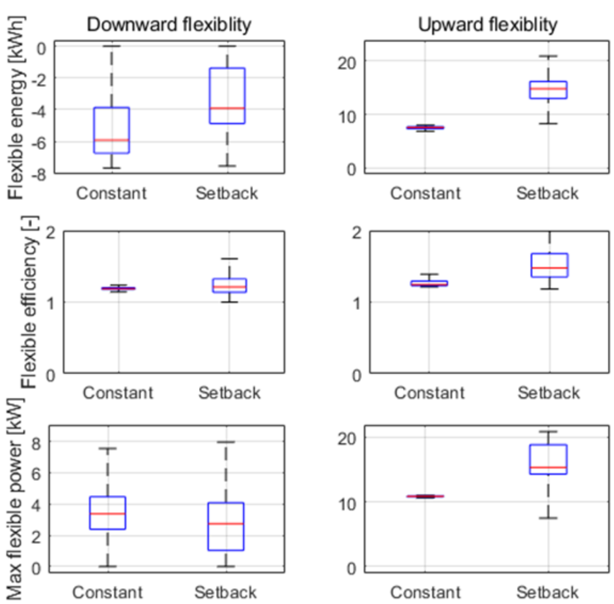

Figure 12: Setback setpoint scenario

The maximum flexible power shows a similar situation as the flexible energy; but the differences between the two cases are smaller. This was expected since the setpoint increases are much larger for the setback case when the zones are not occupied, while for the downward flexibility, the setpoint decrease won't produce much flexibility during the setback periods.

The flexible efficiency does not show much difference for both upward and downward flexibility for the two reference cases.

CONCLUSION

This paper assessed the energy flexibility of an electrically heated Canadian house during the heating season. Energy flexibility is defined as the ability of a building to modify their energy demand compared to "normal" operation.

The energy flexibility was categorized into two scenarios: downward and upward flexibility. The former scenario is similar to load shifting, which shows the ability of buildings to reduce power demand during peak periods. The upward flexibility denotes the ability to use more energy when the power demand is low for the grid. Energy flexibility at the individual building level results from the use of energy storage and on-site generation. This paper focused on the use of thermal mass, through modifications in the building heating setpoint to respond to Demand Response (DR) events.

To quantify the amount of energy flexibility, the paper investigated four key performance indicators, which are flexible energy, rebound energy, flexible efficiency and maximum flexible power. Each indicator applies for both flexibility scenarios (upward and downward). Numerous simulations were carried out based on a validated TRNSYS model of a typical Canadian house modified to use electric baseboard heating, and the indicators were then computed.

Results show that the energy flexibility potential of using thermal mass is significant. The studied house shows a median decrease the energy use by 6 kWh and a median increase by 7.5 kWh for 2-h DR events. The flexibility depends on the time of the DR event, as it is affected by weather and building operation. The flexible energy amount is higher during colder weather because the normal operation of the house has a higher energy demand during these periods. In addition, the maximum flexible power is also very promising, especially for the upward flexibility.

An analysis of the rebound effect after the demand response event shows that the rebound energy is never higher than the shifted energy. The median energy savings associated with the DR event are about 20%.

A sensitivity analysis of the indicators was conducted. Results show that an optimal duration of the event is around 2 or 3 hours considering both the amount of energy flexibility and the thermal comfort in the building. A setpoint modulation of 2 °C as a control strategy during a downward DR event is probably acceptable most of the

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time, because the thermal mass will prevent the building from actually reaching the lower setpoint.. The impact of the reference scenario (constant setpoint or setback) is relatively mild on downward flexibility but strong on upward flexibility, the setback scenario providing a higher upward energy flexibility than the constant setpoint case.

Further work will aim at refining the DR control strategy to account for thermal comfort and to add anticipation of the DR event, through rule-based and model-based predictive strategies. It would also be interesting to expand the study to include other forms of storage and on-site generation and to assess the flexibility during the cooling season.

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NOMENCLATURE

$\Delta Q_{heat,charged}$	Charged amount of heat in a DR event [kWh]
$\Delta Q_{heat,discharged}$	Discharged amount of heat in a DR event [kWh]
$\Delta q_{heating}$	Heat demand difference [kW]
$\eta_{shifting}$	Shifting efficiency [-]
C_{ADR}	Amount of heat stored in a DR event [kWh]
Q_{ADR}	Heat demand in a DR event [kW]
Q_{ref}	Heat demand in a reference case [kW]
η_{ADR}	Storage efficiency [-]
E_f	Flexible energy in a DR event [kWh]
P_{dr}	Power demand in a DR event [kW]
P_{ref}	Power demand in a reference case [kW]
E_{rb}	Rebound energy after the DR event [kWh]
η	Flexible energy efficiency [-]
P_{fmax}	Maximum flexible power [kW]

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