Modelling and analysis of energy flexibility strategies for a residential building cluster

Megi Busho[1,2]✉, Michaël Kummert[2]
[1]Natural Resources Canada, CanmetENERGY Varennes
[2]Polytechnique Montréal, Montréal, Canada
✉megi.busho@nrcan-rncan.gc.ca

Abstract

As energy flexibility becomes more important for utility grids globally, energy modelling and simulation tools provide a means to develop and test strategies to cope with the increased strain on grids predicted in the future. In this paper, the results of a simulation study are presented, which focused on a cluster of residential buildings undergoing flexibility strategies during the month of January in the climate of Montreal, Quebec**.** TRNSYS was used to model the building portfolio, which is built up of varying insulation levels, electricity usage, water-draw profiles, and temperature setpoint profiles. Results show the cluster of homes was able to successfully reduce peak electric power an average of 15-25% with the strategies taken, however, larger than expected rebound peaks were observed. These new peaks are discussed in the context of the grid overall and attempts to reduce them are investigated. Discussion also compares the pros and cons of the four flexibility strategies tested.

Introduction

In order to achieve greenhouse gas emission reduction targets, utility grids are increasingly interested in reducing their emissions from electricity production. Even in areas such as Quebec, where electricity is largely produced by renewable, low- or non-emitting sources, the utility grid still requires a few supplementary fossil fuel plants to meet winter peak power demands [1]. During these winter peak periods, the electric grid is strained due to a higher demand from customers, in the Quebec case attributed to cold temperatures and the abundance of electric heating. Other electric grids globally may face peak periods in summer due to high cooling loads, or even face blackouts when demand is too high for the grid to supply. Energy flexibility and resilience thus become increasingly important, especially considering the annual increase in global electricity demand [2]. Some utility pricing structures incorporate time-of-use or critical peak pricing which deter or delay customers from using energy-intensive devices during peak times. The importance of demand-side management has resulted in growing popularity of incentive-based demand response (DR) programs. These programs encourage customers to reduce electric consumption during peak periods, usually with financial incentives. The ability to know in advance a building's potential for flexibility and its success in DR programs is a useful application of energy modelling. Furthering this approach to model clusters of buildings during flexibility events can provide energy aggregators numerous benefits such as quantifying power reductions in advance and avoiding the creation of new power peaks. This paper demonstrates the energy modelling of a diverse cluster of buildings undergoing DR events and discusses benefits and potential improvements of the flexibility strategies used. The rest of the introduction will further detail some relevant information regarding building energy flexibility and the key performance indicators generally used in studies.

Several studies have investigated flexibility in buildings and in more recent years, much emphasis has been placed on building energy flexibility at the cluster level [3]. Among these studies are international collaborations such as the IEA EBC Annex 67, which provides an encompassing definition of energy flexibility in buildings as "the ability for a building to manage its demand and generation according to local climate conditions, user needs, and grid requirements" [4]. One of the follow up studies to the IEA EBC Annex 67 is the IEA EBC Annex 82, which aims to continue the work done previously and expand the energy flexibility context to the multi-building or clustered, aggregated level [5]. The authors of this document are involved in the IEA EBC Annex 82, and the study carried out here was originally developed as a part of the common exercise undergoing for this Annex, with some additions and some changes in the KPIs used to evaluate results.

At the single building level, energy flexibility might not have a significant impact on the electric grid, but it must still be studied to confirm the building's potential to respond to events and to be included in a cluster. As well, single building studies are still generally more common in the literature, especially for real life case studies due to less complex coordination. When considering flexibility in clusters, Zhang et al. [6] state two key benefits: the coordination of buildings within the cluster to compensate for others which may not be able to offer much flexibility at a time, and the benefit of aggregation being able to offer a larger scale of flexibility for the grid. The needs and benefits

of aggregation in multibuilding flexibility has been discussed in various studies and it is regarded as an important means to ensure fluctuations both on the demand and supply side are properly handled [7], [8].

Li et al. conducted a review of residential building flexibility studies, focusing both on the single building level and clusters of buildings [9]. In their review, shifting and shedding of energy loads were the most common strategies observed, and peak power reductions up to 65% were possible, achieved mainly through the methods of rule-based controls, model predictive control, or direct optimal control. It was noted in the review that quantification of flexibility remains a challenge, as there are various metrics used to evaluate the success of a flexibility study, and these metrics, or KPIs, are not always common among studies [9]. This lack of systematic metrics to quantify flexibility remains a general dilemma, also recently noted by the collaborators of the ongoing IEA Annex 82 in their article regarding questions in building energy flexibility [5]. Generally in a flexibility study one or more KPIs are used to evaluate the performance, usually based on power and energy [10], costs [11], or considering both of these aspects [6] [12] [13]. Another review by Li et al. summarizes the flexibility KPIs found in 87 relevant publications, finding 81 KPIs used, which were summed up to 48 distinct KPIs after grouping together common equations and definitions. This review found a number of most common KPIs used throughout the studies, some of which were the Flexibility Savings Index, Peak Power Shedding, and Load factor, which were also used in this study and are shown in equations (1), (2), and (3) [14]. In addition to these KPIs, the percent savings between the cost of the baseline and flexibility cases was also calculated to evaluate the performance of the strategies.

$$FSI = \frac{Cost_{flexible\ operation}}{Cost_{baseline\ operation}} \quad (1)$$

FSI is the flexibility savings index, where $Cost_{flexibile\ operation}$ is the cost of the flexibility case and $Cost_{baseline\ operation}$ is the cost of the baseline case.

$$\Delta P = P_{baseline,peak} - P_{flexible,peak} \quad (2)$$

ΔP is Peak Power Shedding, where $P_{baseline,peak}$ is the peak during the peak hour in the baseline case and $P_{flexible,peak}$ is the peak during the peak hour in the flexibility case.

$$LF = \frac{Load_{avg}}{Load_{max}} \quad (3)$$

LF is load factor, where $Load_{avg}$ is the average power load over a period of time, and $Load_{max}$ is the max power over that period.

Methods

The simulation study presented follows the effects of 4 flexibility strategies applied to a portfolio of 2400 homes in the Montréal, Quebec area. During the energy flexibility events, homes use rule-based controls to load shed in response to a high price signal during this period, from 6-9AM and 4-8PM, commonly referred to as a penalty signal. This period of demand response used in this study corresponds to the winter peak period for Hydro-Québec, the electric grid serving Quebec [15]. The cost structures to evaluate the strategies come from the instructions used in the common exercise for the IEA EBC Annex 82, instead of Hydro-Québec costs, to keep results applicable to various markets. There are 3 levels of cost which were tested, which use the same base rate during times outside of events and penalize the energy used during the DR event at different levels. The low-cost structure has a DR energy price of 1.5x of the base rate, medium has a DR energy price of 2.5x of the base rate, and high has a DR energy price of 5x of the base rate. The building portfolio of this study and the strategies taken are further described.

Portfolio of Buildings

The portfolio of homes was created by combinations of existing data, slightly modified to create as many unique energy profiles as possible. In summary, the portfolio of homes was created by:

- Taking 22 real non-HVAC profiles [16] and week swapping some, creating 40 unique profiles
- Joining a DHW draw profile, taken from 12 real profiles available [17], to these 40 unique profiles
- Applying an HVAC schedule to these 40 unique profiles, either constant (Cst), wake-sleep (WS), or wake-leave-return-sleep (WLRS), resulting in 120 house operation profiles. These setpoint profiles are shown in Figure 1.
- Applying a time shift to these 120 house operation profiles, shifting either -30, -15, 0, +15, +30 minutes away from baseline profiles, resulting in 600 house operation profiles
- Testing these 600 profiles in 4 envelope levels, poor, decent, good (inspired from [18]), and high-performance (matching the Novoclimat standard [19]) resulting in a total portfolio of 2400 homes.

The 2400 homes have identical physical layouts, with the expectation of the four options of envelope levels, which are detailed in Table 1. The homes are standalone, 3-storey buildings, with one thermal zone per floor (basement, living, and sleeping zones). Each floor is 60 m^2 and heated by electric baseboard heaters, common in Quebec due to relatively low electricity prices.

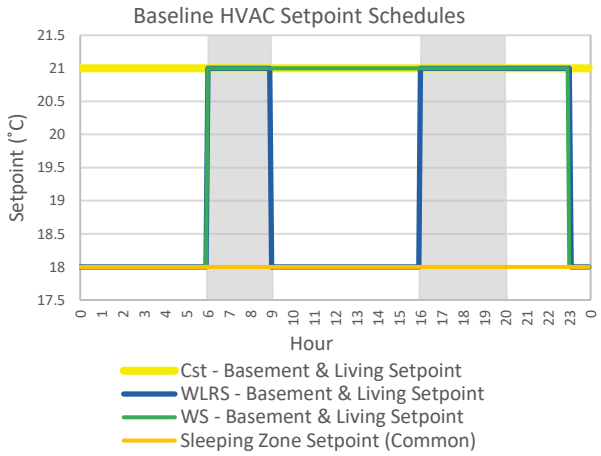

Figure 1: Baseline HVAC Setpoint Schedules

Each home has 9 m^2 of window on the north face, 9.4 m^2 on the south face, 2.7 m^2 on the east face, and 0.3 m^2 on the west face; with the windows distributed mainly on the living and sleeping zones, with little glazing in the basement zone and attic. Each home has a 270 L domestic water heater with upper and lower elements whose setpoints are adjusted in two of the four tested flexibility strategies, while in the baseline case the setpoints of the water heater elements are constant at 56.5˚C.

Table 1: Envelope Characteristics

	Unit	Poor	Decent	Good	High Performance
$ACH_{50\ Pa}$	/h	10	7	4	1.5
$ELA_{4\ Pa}$	cm^2	1023	715.8	409	153.4
Slab RSI-Value	m^2K/W	0.387	0.387	2.04	2.04
Basement Walls RSI-Value		0.352	2.02	2.02	3.69
Walls RSI-Value		0.862	1.86	2.57	4.22
Attic Floor RSI-Value		0.475	4.05	5.72	10.1
Window U-factor	W/m^2K	2.9	1.59	1.22	0.93
Window SHGC	-	0.699	0.431	0.433	0.433

Energy Flexibility Strategies

For each case, baseline and the four strategies, the energy flexibility event was simulated every day for the month of January. Flexibility in this simulation study comes from the thermal mass of the building, through air temperature set point adjustment, in the reactive and predictive cases, and additionally through water heater lower element setpoint adjustment, in the DHW cases. The flexibility strategies are detailed in Table 2.

Table 2: Strategies

Energy Flexibility Strategy	HVAC Setpoint Adjustment relative to Baseline Setpoint	Domestic Water Heater Adjustment relative to Baseline Setpoint
Baseline	None	None
Reactive	-1˚C during event	None
Reactive + DHW	-1˚C during event	Lower heating element off during event
Predictive	+3˚C for 3 hours before event followed by -1˚C during event	None
Predictive + DHW	+3˚C for 3 hours before event followed by -1˚C during event	Both elements +10 ˚C for 1 hour before event followed by lower element off during event

It is noted that for the sleeping zone, preheating was not done due to the assumption that comfort would be compromised if sleeping zones are 3 °C higher than normal while occupied. It is also noted that for houses with a +15 minute or +30 minute time shift in their normal operation, preheating in the predictive cases is slightly reduced from 3 hours to 2.75 or 2.5 hours, respectively. Similarly, for the homes with a -15-minute or -30-minute time shift, the setpoint is not adjusted back to normal until the end of the morning energy flexibility event, 9AM, though it would normally have been adjusted at 8:30AM or 8:45AM. These small adjustments to the setpoints of the shifted homes are done to ensure heating does not occur during the energy flexibility event, which would unfairly penalize those homes due to the high cost of electricity during events. The assumption is that the occupants are aware of the energy flexibility event ahead of time and have access to programmable thermostats in their home to set up the demand response setpoints in advance. It is noted that this may be a barrier or challenge if this simulation study were expanded to a real-world case study, due to the requirement of programmable thermostats.

Results

The focus of this study is the household peaks and energy use during and outside of events, and their monthly electricity cost. To test the flexibility strategies, the energy flexibility event was simulated to have occurred for each day of January. Input files for each home's TRNSYS simulation contain 5-minute data files of: the setpoints for each zone, with respect to the flexibility case studied, non-HVAC electric demand, domestic hot water draw and heating elements setpoints, and the physical characteristics of the building as previously described. Output files for each simulation contain 15-minute data of: resulting zone temperatures, power per operation (heating per zone, domestic hot water, non-HVAC), resulting total building power, water main supply temperature, domestic water supply temperature and flow. The power and energy related results of this study are listed in Table 3.

Table 3: Power and energy average results

	Average of peaks during DR events (kW)	Average of absolute peaks (kW)	Average energy during DR events (kWh)
Baseline	16.1 (-)	16.1 (-)	2.68 (-)
Reactive	13.7 (-15%)	21.3 (+32%)	2.24 (-16%)
Reactive + DHW	13.3 (-17%)	23.9 (+48%)	2.04 (-23%)
Predictive	12.5 (-22%)	20.0 (+24%)	1.64 (-38%)
Predictive + DHW	12.0 (-25%)	19.9 (+24%)	1.43 (-46%)

The average peak power reduction during the DR events ranged from 15 to 25 % with predictive strategies achieving the largest reductions. Energy reduction during the event period was also successful for all the strategies, with predictive strategies also achieving the highest reductions in this category. However, when considering the daily energy use, the predictive strategies used more energy than the baseline and reactive strategies, which is attributed to the preheating period. This is clearly shown in Figure 2 which presents the percent change in peaks during the event vs the percent change in overall energy, for each of the homes' average daily energy use.

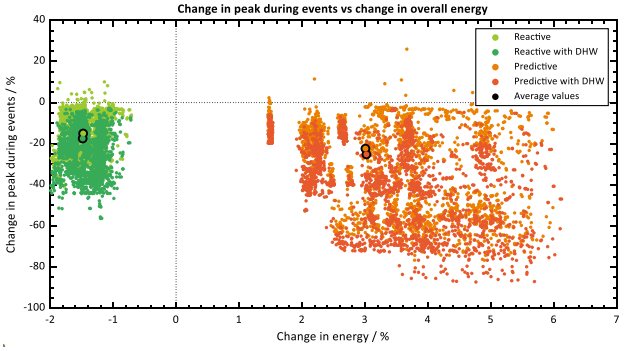

Figure 2: Average change in peak during events vs change in overall energy for each home

In terms of power peaks outside of the event, all strategies produced power demand peaks higher than the original peaks which were being reduced in this study, as can be seen in the absolute maximum peak column of Table 3. These rebound peaks are clear in Figure 3-7 which show the daily profile of the average home for each strategy tested.

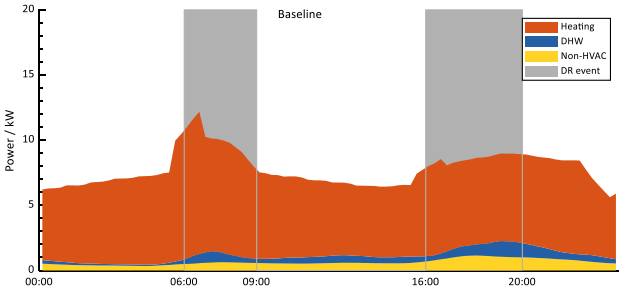

Figure 3: Average home daily profile, baseline

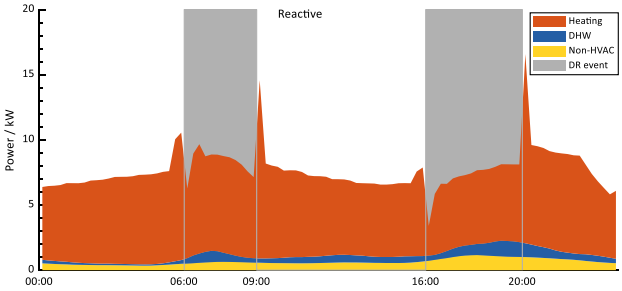

Figure 4: Average home daily profile, reactive

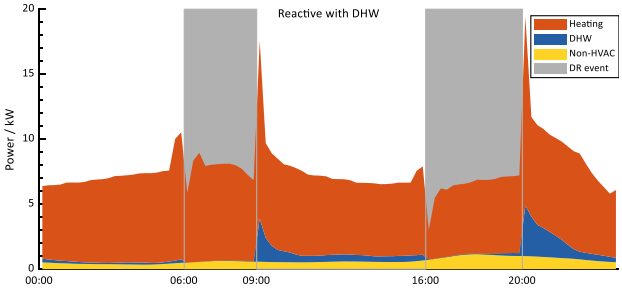

Figure 5: Average home daily profile, reactive with DHW

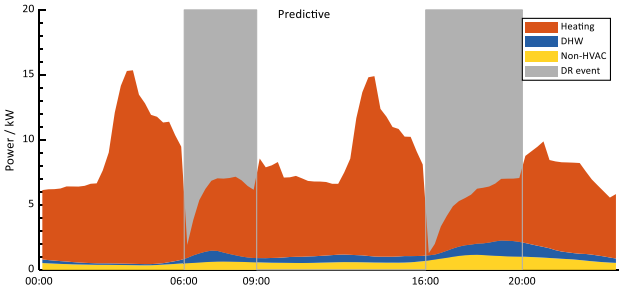

Figure 6: Average home daily profile, predictive

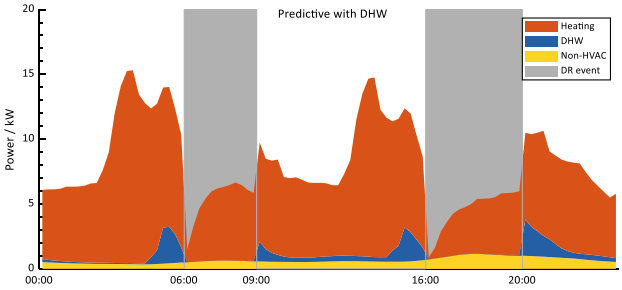

Figure 7: Average home daily profile, predictive with DHW

Despite the high rebound peaks in the flexibility cases, cost savings were still achieved in each case with the 3 options of pricing structure used. The resulting energy costs for the month of January for this simulation study are presented in Table 4. It is important to note that though the pricing structures used here resulted in cost savings, it is possible that when using other DR pricing structures, the high rebounds peaks seen in this study could have been more detrimental to costs.

Table 4: Costs per average home, using 3 pricing structures

	Cost, low ($)	Cost, medium ($)	Cost, high ($)
Baseline	67.8 (-)	87.8 (-)	137.7 (-)
Reactive	65.4 (-3.6 %)	82.0 (-6.5 %)	123.7 (-10 %)
Reactive + DHW	64.6 (-4.7 %)	79.9 (-9.0 %)	117.9 (-14 %)
Predictive	65.7 (-3.1 %)	78.0 (-11%)	108.6 (-21 %)
Predictive + DHW	65.0 (-4.2 %)	75.6 (-13 %)	102.2 (-25 %)

Finally, the KPIs for each of the flexibility cases, as previously introduced, are tabulated in Table 5. The high-cost structure was used in the calculation of the FSI.

Table 5: KPIs per average home

	Flexibility Savings Index	Peak Power Shedding (kW)	Load Factor
Baseline	(-)	(-)	0.48
Reactive	0.89	-5.22	0.36
Reactive + DHW	0.85	-7.80	0.32
Predictive	0.78	-3.89	0.40
Predictive + DHW	0.74	-3.85	0.40

Evidently, the flexibility savings index shows the higher cost savings for the predictive cases, as also seen previously in Table 4. In terms of peak power shedding, since this KPI formula uses the maximum peaks, occurring at potentially different hours, the high rebound peaks have resulted in a negative value. This means that the highest rebound peak in the reactive and predictive cases are higher than the baseline peak by 5.22 kW and 3.89 kW, respectively. In simple terms, the new absolute peaks created when performing the flexibility strategies are higher than the original peak targeted to reduce, though this original peak has been reduced significantly as previously reported in Table 3. Regarding the load factor, calculated over the average day, the low values in each case indicate a large fluctuation between the average and maximum loads, usually not favoured by the utility. However, recall that different utility grids will have different goals based on their resources, and the high rebound peaks outside of the usual demand peak period could be either negligible or significant. If the grid wishes to reduce the rebound peaks that occurred in these cases studied, this is further discussed in the next section.

Though the average home reduces its peak from 15 to 25 % during DR events, representing around 3-4 kW/home, the results when considering all homes in the portfolio are even more significant and would be impactful to an electric grid.

Discussion

Considering the diverse portfolio of residential buildings was beneficial to obtain an averaged view of results, and it also gives insight to which types of homes might support the grid best through involvement in a DR program. The energy and cost results of the portfolio, as previously shown in Tables 3 and 4 were also evaluated on the basis of the homes' original setpoint strategy and insulation levels. Through this grouping a few more conclusions can be drawn about the results. It was found that the homes with the high performance envelope had the largest peak and energy reductions through the strategies and thus also had the highest cost savings in this study, ranging from 17-46% savings while the poor insulation homes had cost savings ranging from 6-15% on average.

Although the flexibility strategies were able to reduce peak power demand during the DR events, a drawback of the strategies are the high rebound peaks. Depending on the electricity grid, a modest rebound peak is likely negligible, but when they approach the peaks originally being reduced, a new problem is created. To reduce the magnitude of these rebound peaks, coordination of the portfolio strategies was considered and is discussed.

The coordination of the portfolio strategies aims to reduce the magnitude of rebound peaks, and this is done by reducing the participation of the portfolio. With this measure, instead of all 2400 homes responding to the DR event, a selected percentage would participate with a flexibility strategy, while the rest would continue their baseline operation. The homes which would be selected to participate in the event were selected as those which obtained the highest cost savings during the event, information available after having performed all the simulations. This type of coordination would require an aggregator with this prior knowledge to direct which houses would participate, a potential barrier to real-world application, or alternatively a potential opportunity for companies who can offer this service. The percentages tested for these cases were 25 %, 50 %, and 75 % of all the homes to undergo reactive or predictive cases. The KPIs for these cases are listed in Table 6, which refers to the average home within this portfolio. Although some homes did not respond to the DR event with a flexibility strategy, the energy prices used to evaluate the portfolio are the same as previously mentioned, which is why the values for flexibility savings index are not as favourable as the previous cases. In reality, the homes which have opted into the DR event would have the cost structure as previously mentioned, while homes not opting into the event would likely have their normal cost structure, not penalizing the power peaks as much as the participants who would stand to

save more on their energy bill by opting into the event. Compared to the previous cases the values seen for peak power shedding and load factor are generally better in these coordinated cases.

Table 6: KPIs per average home, coordinated cases with reduced portfolio participation

	Flexibility Savings Index	Peak Power Shedding (kW)	Load Factor
Reactive 25 %	0.98	0.59	0.50
Reactive 50 %	0.95	-1.30	0.44
Reactive 75 %	0.92	-3.27	0.39
Predictive 25 %	0.94	1.48	0.53
Predictive 50 %	0.89	0.27	0.49
Predictive 75 %	0.84	-1.67	0.44

The case with 25 % predictive participation tells the best result, with the highest peak power shedding and the highest load factor from all cases studied. The daily profile for the average home in this case is shown in Figure 8.

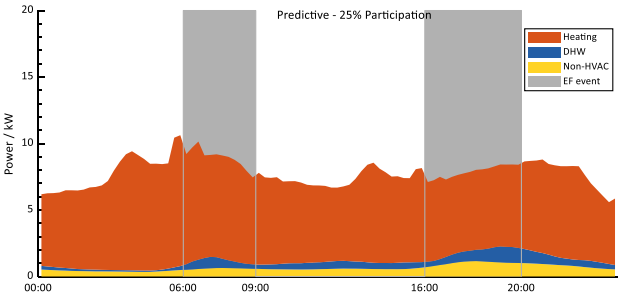

Figure 8: Average home daily profile, portfolio coordination of 25% predictive, 75% baseline.

Evidently, the profile is more flat than the ones seen in the previous cases and all the peaks in this profile are below the original baseline peaks, though not by as much as previously seen. This strategy is beneficial for the grid due to the higher load factor and reduced rebound peaks, however as mentioned previously, the cost structures or incentives offered to customers must be such that this result is possible. An aggregator must have this knowledge prior, from previous testing, and must coordinate which homes should be offered the DR program and which to encourage baseline conditions.

Conclusion

This simulation study demonstrated 4 flexibility strategies taken by a portfolio of 2400 residential buildings during demand response events and evaluated their benefits. Peak power reductions of 15 to 25 % were evident for the strategies, however large rebound peaks were created due to preheating to prepare for the event, in the predictive cases, or adjusting back to baseline setpoints after the event in reactive cases. To reduce the magnitude of rebound peaks, coordination of the portfolio was attempted, which reduced the number of homes following the flexibility strategy to only those which would incur the highest cost savings from participation. These cases had benefits such as less fluctuations in the average profile, however more coordination from an aggregator is involved to achieve them. Energy costs were also evaluated for all the strategies tested and cost savings were evident with the 3 levels of pricing structure used.

Acknowledgement

The authors would like to thank the colleagues in IEA-EBC Annex 82, who provided valuable feedback and suggestions during working meetings.

References

[1] “Provincial and Territorial Energy Profiles – Quebec.” Canada Energy Regulator, Feb. 22, 2024. Accessed: Mar. 12, 2024. [Online]. Available: https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-quebec.html

[2] “Electricity 2024.” International Energy Agency, 2024. [Online]. Available: https://www.iea.org/reports/electricity-2024/executive-summary

[3] I. Vigna, R. Pernetti, W. Pasut, and R. Lollini, “New domain for promoting energy efficiency: Energy Flexible Building Cluster,” *Sustain. Cities Soc.*, vol. 38, pp. 526–533, Apr. 2018, doi: https://doi.org/10.1016/j.scs.2018.01.038.

[4] S. Ø. Jensen *et al.*, “IEA EBC Annex 67 Energy Flexible Buildings,” *Energy Build.*, vol. 155, pp. 25–34, Nov. 2017, doi: 10.1016/j.enbuild.2017.08.044.

[5] R. Li *et al.*, “Ten questions concerning energy flexibility in buildings,” *Build. Environ.*, vol. 223, p. 109461, Sep. 2022, doi: 10.1016/j.buildenv.2022.109461.

[6] K. Zhang, E. Saloux, and J. A. Candanedo, “Enhancing energy flexibility of building clusters via supervisory room temperature control: Quantification and evaluation of benefits,” *Energy Build.*, vol. 302, p. 113750, Jan. 2024, doi: 10.1016/j.enbuild.2023.113750.

[7] V. Maask, A. Rosin, T. Korõtko, M. Thalfeldt, S. Syri, and R. Ahmadiahangar, “Aggregation ready flexibility management methods for mechanical ventilation systems in buildings,” *Energy Build.*, vol. 296, p. 113369, Oct. 2023, doi: 10.1016/j.enbuild.2023.113369.

[8] M. B. Awan, Y. Sun, W. Lin, and Z. Ma, “A framework to formulate and aggregate performance indicators to quantify building energy flexibility,” *Appl. Energy*, vol. 349, p. 121590, Nov. 2023, doi: 10.1016/j.apenergy.2023.121590.

[9] H. Li, Z. Wang, T. Hong, and M. A. Piette, “Energy flexibility of residential buildings: A systematic review of characterization and quantification methods and applications,” *Adv. Appl. Energy*, vol. 3, p. 100054, Aug. 2021, doi: 10.1016/j.adapen.2021.100054.

[10] K. Zhang and M. Kummert, "Evaluating the impact of thermostat control strategies on the energy flexibility of residential buildings for space heating," *Build. Simul.*, vol. 14, no. 5, pp. 1439–1452, Oct. 2021, doi: 10.1007/s12273-020-0751-x.

[11] R. G. Junker *et al.*, "Characterizing the energy flexibility of buildings and districts," *Appl. Energy*, vol. 225, pp. 175–182, Sep. 2018, doi: 10.1016/j.apenergy.2018.05.037.

[12] P. Strauch, W. Wang, and F. Langner, "Model predictive control for demand flexibility of a residential building with multiple distributed energy resources," *Energy Build.*, vol. 305, p. 113884, Feb. 2024, doi: 10.1016/j.enbuild.2023.113884.

[13] K. Zhang *et al.*, "Model predictive control for demand flexibility: Real-world operation of a commercial building with photovoltaic and battery systems," *Adv. Appl. Energy*, vol. 7, p. 100099, Sep. 2022, doi: 10.1016/j.adapen.2022.100099.

[14] H. Li *et al.*, "Data-driven key performance indicators and datasets for building energy flexibility: A review and perspectives," *Appl. Energy*, vol. 343, p. 121217, Aug. 2023, doi: 10.1016/j.apenergy.2023.121217.

[15] Hydro-Québec, *Tarifs d'électricité en vigueur le 1er avril 2023*. Montréal, QC: Hydro-Québec, 2023.

[16] G. Johnson and I. Beausoleil-Morrison, "Electrical-end-use data from 23 houses sampled each minute for simulating micro-generation systems," *Appl. Therm. Eng.*, vol. 114, pp. 1449–1456, 2017, doi: 10.1016/j.applthermaleng.2016.07.133.

[17] S. Edwards, I. Beausoleil-Morrison, and A. Laperrière, "Representative hot water draw profiles at high temporal resolution for simulating the performance of solar thermal systems," *Sol. Energy*, vol. 111, pp. 43–52, Jan. 2015, doi: 10.1016/j.solener.2014.10.026.

[18] D. Boyer, "Le potentiel technico-économique de réduction des émissions de GES du secteur résidentiel au Québec," Écohabitation, Montréal, QC, 2016. [Online]. Available: https://www.ecohabitation.com/media/archives/sites/www.ecohabitation.com/files/page/etude_sur_le_potentiel_de_reduction_des_ges_du_secteur_residentiel_au_quebec.pdf

[19] MELCCFP, *Novoclimat - Exigences techniques - Maison et petit bâtiment multilogement*. Québec, QC: Ministère de l'Environnement, de la Lutte aux changements climatiques, de la Faune et des Parcs, 2023.