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Analysis of energy flexibility strategies for residential and commercial building clusters through simulation

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Mémoire présenté en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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Ce mémoire intitulé :

Analysis of energy flexibility strategies for residential and commercial building clusters through simulation

présenté par **Megi BUSHO**

en vue de l'obtention du diplôme de *Maîtrise ès sciences appliquées*

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RÉSUMÉ

Puisque l'électrification dans divers secteurs contribue à l'augmentation de la demande d'électricité, les réseaux peuvent être confrontés à des périodes de pointe plus critiques que jamais. Les conditions météorologiques extrêmes ne font qu'aggraver le problème. Les fortes chaleurs entraînent une augmentation de la demande d'électricité pour le refroidissement et, dans les régions froides où la proportion du chauffage électrique est élevée (comme au Québec), les basses températures entraînent une augmentation de la demande d'électricité pour le chauffage. La gestion de l'énergie parmi les consommateurs est donc devenue de plus en plus pertinente, non seulement pour réduire la consommation annuelle mais aussi pour contrôler quand l'électricité est utilisée, faisant de la flexibilité un objectif important.

Les bâtiments représentent une grande partie de la consommation totale d'électricité. Si leur énergie est bien contrôlée, ils peuvent être des acteurs majeurs de la flexibilité. Cette possibilité permet aux bâtiments de participer à la gestion de la demande, par exemple en réduisant leur consommation pendant des événements de pointe. Lorsque les bâtiments sont regroupés en grappes (*clusters*), les efforts de flexibilité donnent des résultats agrégés et présentent un potentiel élevé pour les réseaux électriques. La flexibilité dans les grappes de bâtiments est le sujet d'analyse de ce mémoire, qui explore différentes stratégies de flexibilité dans des groupes composées de différents types de bâtiments et leurs caractéristiques.

Pour étudier ce sujet, le logiciel de modélisation TRNSYS a d'abord été utilisé pour simuler les besoins en énergie d'une grappe de 2400 maisons unifamiliales avec différents niveaux d'isolation, des points de consigne de chauffage et de profils de charge. Quatre stratégies de flexibilité ont été testées, qui ont ajusté les points de consigne pour le chauffage des locaux et de l'eau dans la grappe. Ces stratégies ont permis de réduire la pointe de 15 à 25 % par logement pendant les heures des événements de pointe. Bien que de fortes réductions de puissance aient été constatées pendant les heures des événements de pointe, des effets de rebond ont été créés, qui ont été atténués par des ajustements des taux de participation.

Pour approfondir l'étude, une plus grande variété a été introduite dans la grappe par l'ajout de bâtiments commerciaux/institutionnels (CI), qui ont des systèmes de chauffage hybrides gaz-électricité. Pour ce faire, un modèle TRNSYS initial a été créé sur la base d'un bâtiment CI réel au Québec, en utilisant des données opérationnelles et des caractéristiques physiques. Ensuite, 30

variantes de bâtiments CI ont été créées sur la base de ce modèle initial. Ainsi, la grappe complète, soit 2430 bâtiments, a fait l'objet d'essais de stratégie de flexibilité, où les bâtiments CI ont utilisé leur système de chauffage hybride en alternant les sources de chauffage pendant les épisodes de pointe. Le cluster dans son ensemble a atteint une réduction des pointes de 36 % pendant les heures des événements, avec seulement une petite augmentation des pointes par rapport à la journée moyenne comportant des évènements de pointe. Les avantages de la flexibilité dans les grappes, en particulier dans celles contenant différents types de bâtiments et différentes sources d'énergie, sont mis en évidence dans cette recherche, contribuant ainsi aux travaux existants dans le domaine.

ABSTRACT

As electrification in various sectors contributes to increasing power demands, grids may face increased strain and more critical peak periods than ever before. Weather extremes add to the problem, as high heat drives up cooling power demands, and in cold regions with high shares of electric heating, such as in Quebec, low temperatures drive up heating power demands. Managing power across electric consumers has thus become increasingly relevant, not only to reduce the annual energy use but also to control when electricity is used, making flexibility an important goal.

Buildings, which represent considerable shares of electric consumption, can be major participants in achieving flexibility, if their loads are well controlled. Having this ability allows buildings to be involved in demand side management, such as through demand response (DR) programs. When buildings are grouped into clusters, flexibility efforts have aggregated results and present an even larger potential for electric grids. Flexibility in building clusters is the subject of analysis throughout this thesis, which explores different flexibility strategies in clusters composed of varying building types and characteristics.

To investigate this topic, TRNSYS has been firstly used to simulate the power requirements of a cluster of 2400 residential homes of varying insulation levels, HVAC schedules, and load profiles. Four flexibility strategies were tested, which adjusted the space and water heating setpoints in the cluster and were able to achieve power reductions of 15-25 % per home during the DR hours. Although large power reductions were found during the DR hours, large rebound peaks were created, which were mitigated through adjustments in the participation rates.

To further the investigation, more variety was introduced in the cluster though the addition of commercial/institutional (CI) buildings, which have hybrid gas-electric heating systems. To make this addition, an initial TRNSYS model was created based on a real CI building in Quebec, using operational data and physical characteristics. Modifications were then made to then create 30 CI buildings variations based on this initial model. Thus the total cluster, 2430 buildings, underwent flexibility strategy testing, where the CI buildings made use of their hybrid heating system by fuel switching during DR events. The total cluster achieved peak reductions up to 36% during DR hours, with only a small increase in peak over the average DR day. The benefits of flexibility in clusters, specifically in clusters containing varying building types and energy sources, are highlighted in this research, thus contributing to the body of work in this field of study.

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LIST OF SYMBOLS AND ABBREVIATIONS

AESO	Alberta Electric System Operator
ASHRAE	American Society of Heating Refrigerating and Air Conditioning Engineers
BMS	Building management system
CI	Commercial/Institutional
CO_2	Carbon dioxide
Cst	Constant (setpoint schedule)
CV-RMSE	Coefficient of the variation of the root mean square error
DHW	Domestic hot water
DOE	Department of Energy
DR	Demand response
DSM	Demand side management
EBC	Energy in Buildings and Communities
FSI	Flexibility savings index
GHG	Greenhouse gas
HVAC	Heating, ventilation, and air conditioning
IBPSA	International Building Performance Simulation Association
.IDF	Intermediate Data Format
IEA	International Energy Agency
IESO	Independent Electric System Operator
KPI	Key performance indicator
LF	Load factor
MPC	Model-predictive control
NMBE	Normalized mean biased error
PV	Photovoltaics
RBC	Rule-based control
RC	Resistance-capacitance

RSI	Thermal resistance (SI unit)
SHGC	Solar heat gain coefficient
SSM	Supply side management
TMY	Typical meteorological year
VM	Virtual meter
WLRS	Wake-leave-return-sleep (setpoint schedule)
WS	Wake-sleep (setpoint schedule)

CHAPTER 1 INTRODUCTION

Energy needs around the world increase as more industries and economies grow. While total energy use is significant, and the subject of various efficiency measures, the timing of electricity use specifically has become an increasingly important consideration. For electric utilities, the balance between supply and demand is an important aspect to ensure continuous and dependable service to users. Sudden, sharp fluctuations on the supply or demand side can result in blackouts, as seen in recent events, which utility grids must be proactive to avoid [1]. Extreme weather episodes and generation from renewable sources, which are often intermittent, also pose challenges for electric grids, as demand also grows with increased electrification in many sectors. During high demand periods for electric grids, some methods of meeting the demand might be to purchase power, or use dedicated peak power plants, which may produce higher greenhouse gas (GHG) emissions [2]. To reduce the need of these measures, grids might incentivize consumers to adjust their power needs where possible. This leads to energy flexibility, defined for buildings by the International Energy Agency (IEA) as "the ability for a building to manage its demand and generation according to local climate conditions, user needs, and grid requirements" [3].

Buildings, which account for over a third of global energy consumption [4], have the potential to provide flexibility if their energy is carefully managed. This potential is increased when buildings are considered at a cluster or district level, which would provide collective amounts of flexibility that would make a significant impact for the utility grid [5]. Individual buildings, unless using an exceptionally high amount of energy they can easily curtail, likely would not have the ability to provide the grid with a meaningful amount of flexibility. Fortunately, the measure of successful flexibility does not have to fall to the responsibility of individual high demand buildings, though they have their share, but the collective efforts of several buildings which can be made up from various sectors and of various power demands. Taking several entities into account for flexibility creates a cluster which have the most promising opportunities, especially when different energy systems are available within the cluster [5].

Clusters have the benefit of increased magnitude of flexibility potential, as well as the ability for some buildings to compensate for others at instances when the latter cannot provide flexibility [6]. This benefit of coordination mentioned by Zhang et al., has not been a topic of much research, outside of a few studies which will be discussed in the literature review. On this topic, Le Dréau et al., have noted that one of the barriers existing in flexibility research is the lack of control strategies on the district level, which they recommend to overcome with the coordination of strategies within clusters [7]. Thus, in order for building clusters to make impactful flexibility actions, their energy use should not only be considered on the aggregated level but must also be carefully managed to avoid creating new challenges and fluctuations for the grid. This gap in the research presents an inspiration for this thesis, which aims to investigate the coordination of flexibility strategies in clusters of buildings, during critical peak periods for the grid.

To investigate this topic, a cluster of buildings undergoing flexibility strategies during simulated demand response (DR) events will be analysed. The strategies have been created and then modified as necessary to best coordinate the power response of the cluster.

1.1 Research Objectives

The work presented in this thesis investigates building clusters undergoing flexibility strategies, to examine the benefits possible based on different cluster formations and how these buildings can be optimally coordinated. To explore this concept, the following sub-objectives of the research were defined:

- Creating a commercial/institutional (CI) building model within TRNSYS, inspired by a real building in the location of study.
- Forming diverse models for the 2430 buildings in the cluster of the study, using a method of input file selection to make numerous modifications to original models feasible.
- Analysing the power, energy, and costs of the residential and CI buildings modelled.
- Coordinating flexibility strategies in the clusters of buildings to investigate best results.

1.2 Organization of Thesis

The thesis begins with the general introduction of the study and research objectives, within Chapter 1. In Chapter 2, a literature review is performed, focused on subtopics related to the project undertaken. The literature review dives into: energy management in buildings, building energy modelling, flexibility in energy markets, building cluster flexibility, and gas-electric hybrid systems. In Chapter 3, an overview of the case study and building models is given, focused on details not presented in Chapters 4 & 5. As this is an article-based thesis, Chapter 4 contains a conference paper presented at the IBPSA-Canada eSim conference, and Chapter 5 contains a journal paper submitted to the Journal of Building Physics. In Chapter 6, a few supplementary results are presented which were investigated after the papers presented in the previous chapters were already written. In Chapter 7 a general discussion will be made about the results and findings throughout the study, and in Chapter 8 general conclusions and recommendations will be made. The overview of this thesis organization is provided in Figure 1.1.

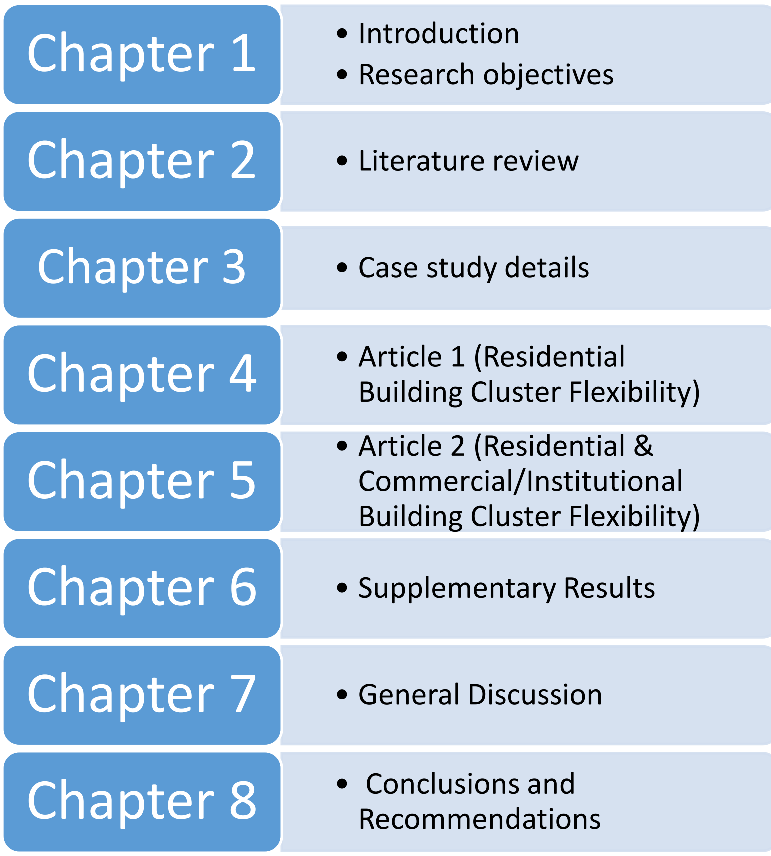

Figure 1.1 Organization of thesis

CHAPTER 2 LITERATURE REVIEW

This chapter will present the concepts and related work into subject areas related to this thesis. The topics that will be explored throughout this literature review are: energy management in buildings, building energy modelling, flexibility in energy markets, building cluster flexibility, and hybrid gas-electric systems.

2.1 Energy Management in Buildings

Efficient energy management is necessary to achieve greenhouse gas emissions reduction goals, made by several countries around the world. Buildings represent a large portion of the world's energy use and must be responsibly managed to help meet these targets. Although efficiency and energy saving measures are gaining traction around the world, energy demand of buildings has seen steady increases since the 2000s, explained simply by more buildings being constructed, and the equipment and services used within them, especially in developing countries [8]. In an extensive review paper which focused on the current and future trends in energy consumption of buildings, many improvements in building technology are discussed, such as the increased efficiency of lighting and glazing, and advancements in cooling technologies [9]. Heating technologies however were considered an area that is behind in comparison. Although advancements in building insulation have been made, these materials are mentioned as not widely used currently. Building codes progress for these aspects but might not have such large impacts in the short term, since new constructions only make up a fraction of the building stock [10]. Space and water heating, especially in cold climates such as throughout Canada, are energy intensive building services that should be well controlled. Fortunately, building digitization is aiding in this regard, and the IEA estimates that it could reduce energy use in buildings by 10% [8].

In another review paper regarding building energy developments, energy monitoring is mentioned as a fast growing, but users and building managers require guidance on efficient strategies and best practices [11]. This point is quite understandable, although energy monitoring gains momentum, questions arise on what needs to be done to optimize systems – the vast amount of data available can be overwhelming to analyse. Building management systems (BMS) can bring together varying information such as occupancy, lighting, plug loads, heating, ventilation, and air conditioning (HVAC) data, among others, to help building operators estimate and manage their building needs. In [12] numerous relevant studies are reviewed, in which building energy use was optimized using

BMS data. Several of the studies mentioned [13], [14], [15] have related occupancy data to estimated electrical consumption of buildings. These important findings can help operators quickly notice potential anomalies in building operation, anytime estimations are far from reality, leading to better energy management. As well, occupancy estimation can be used to improve lighting controls, as presented in a Canadian office case study in [16], where lighting electricity was reduced by 62%. Another study estimated that improved controls can help the U.S. commercial building sector reduce energy consumption up to 16%, even when already generally efficient buildings were taken into account [17]. The controls of HVAC systems specifically is certainly an area that can garner high energy savings when monitoring and optimization are prioritized, since these systems represent a major portion of a building's energy. For example, improved controls in several air conditioning studies [18], [19], [20] resulted in cooling energy savings anywhere from 17 - 27% in the mentioned studies. Yao et al. found a range of 29-34% HVAC energy cost savings possible in summer and 64-82% HVAC energy cost savings possible in winter for their simulation study into optimal scheduling of HVAC systems. In that study, both the supply air temperature and flow rate were optimized to achieve these savings [21]. In [22] heating energy was reduced by 62% in an Ottawa, Canada, laboratory building due to fault corrections in the HVAC system, which were found through virtual meters (VMs), created through calculations of variables available in BMS data, which serve as an alternative to additional purchase and installation of physical metering.

The management and control of a building's power is a key component of flexibility as will be explored throughout this thesis. Control strategies for energy flexibility have been reviewed in [23], and have been categorized as also commonly seen in other literature [24], as rule-based controls (RBC) and optimal control which encompasses direct optimal control, and model predictive control (MPC). RBC methods tend to be more simple to implement as they are triggered by a determined condition which can be specified in the BMS for example. Direct optimal control on the other hand involves an optimization objective function and MPC methods rely on a model which is capable of predicting future aspects such as temperatures [23], [24]. Su et al., remark that energy monitoring will be an integral aspect to reach low carbon goals, to be able to make rapid adjustments to water, electricity and heating for example, and will be a fundamental for future smart cities [11]. Indeed, monitoring of building loads is an essential aspect of flexibility, and energy modelling comes into play to assist with prediction and estimation – this will be explored in the next subtopic of this literature review.

2.2 Building Energy Modelling

Building energy modelling is a key component of the research studies mentioned throughout this literature review. Having accurate energy models unlocks numerous opportunities for buildings to better optimize their energy use, find and correct inefficiencies, and be able to provide flexibility, among other capabilities. Consulting a review by Swan et al., of residential building energy modelling, provided the concepts of the top-down & bottom-up approaches of energy modelling. The top-down approach involves having aggregated data from the building not necessarily distinguished by end uses [25]. Like the name suggests, the model is based off high level data and could be created from general historic data such as total electric power, for example, available from BMS or metering. The bottom-up approach requires more details, such as specific energy end use data, physical characteristics, and schedules, to give a few examples The level of detail required is higher, but this type of model can be better at addressing specific needs or optimizing aspects such as building systems [25]. Similar to these definitions, the black box, white box, and grey box modelling terminologies are also often used to describe model types. White box modelling requires input data from many sources, higher levels of detail and knowledge of physical systems. These models are often created in software such as TRNSYS, EnergyPlus for example [26]. Black box modelling on the other hand, is more mathematical or statistical based, not necessarily having knowledge of physical systems for example. In between these two, grey box models, such as resistance-capacitance (RC) models, take aspects from both techniques, and are made with a mixture of available data and physical systems knowledge [27].

In a recent review of the state of the art of building energy modelling, over 100 studies were analysed and several interesting findings were reported. From the studies analysed in this review, the majority used the bottom-up method, specifically white box models. The next most common were grey box models, which the authors note had optimal calibration results, then followed by black box models [26]. In the review, several key variables were reported as most commonly used for calibration, such as HVAC data, occupant counts, and schedules.

Many studies have focused on the comparison of modelling approaches. In one study, estimating the power used by electrical equipment in an office building was the focus and this was done with both a data model, and with a bottom-up approach. In this study, the authors found that both methods provided good correlations to the metered data, highlighting that both methods are effective depending on what data is available [28].

As mentioned previously, the HVAC systems of buildings tend to use a large amount of a building's power, and it is for this reason they are often a major focus for modelling. In [29] some challenges of building energy modelling are discussed and analysed through the creation of a building model in three different software (eQuest, Trace 700, and EnergyPlus with OpenStudio). In this study, data was available from the campus building being modelled with these tools, and was used for calibration. The authors found that the EnergyPlus model was the most accurate to the real building modelled, though each software resulted in low error values for the variables calibrated, with one variable exception. The study lists a few challenges throughout the modelling process such as: accuracy of data and building information, program usability and user interfaces, efficiency of actual equipment, and modelling human behaviour. Considering the white box modelling approach taken, the need for accuracy in input data is highly important to obtain accurate results. The same is true regarding the efficiency of equipment – if these numbers are known it can greatly help accuracy, but the aging of equipment or broken components can make these aspects difficult to estimate [29].

2.3 Flexibility in Energy Markets

In addition to efficient and responsible energy management, power management must also be considered, especially in energy intensive industries or buildings. When discussing flexibility, potential exists on both the supply side, and the demand side. On the supply side, utilities could have peaking power plants which are specifically used during periods of increased demand [30]. On the demand side, it is the users who take the responsibility of managing their power demand, and this is usually encouraged by the utility in some way, through time of use pricing or real time pricing for example. These methods encourage power consumption outside of peak hours, so grids can avoid supply side flexibility measures, which are often more costly [30]. In a review of control strategies for energy flexibility, four possible flexibility objectives are listed: load shifting, peak shaving, reduction of energy cost, and increased consumption of renewables [23].

An interesting trend has been noted in a number of research papers, about the relation between increased electric peak demands with global temperatures rising. This is highlighted in a review by Santamouris et al., where they summarize that that for every degree of ambient temperature rise, up to 4.6% increase in peak electricity demand can be expected. This is an important consideration for the future needs of power grids, as the authors have cited global warming to intensify these power demand increases [31]. Certainly, in warm climates peak power demands are amplified with high cooling needs, and this is reflected in the several demand response programs available in cooling dominated areas such as throughout the Middle East [32], [33] and Australia [34].

In a review of Northern Europe's demand response potential, the importance of flexibility is highlighted as several countries have made climate goals which will add more strain to the electric grid [35]. The papers cited in this review have found that flexibility can bring down peaks in a range of 15-29%, and in general the industrial sector shows the greatest promise for flexibility. The studies cited in this review have also found high potential for the heating energy in households to be a promising source of flexibility, especially in the countries with high electric heating or heat pumps [35]. Several European grid operators have implemented flexibility programs to date, with the highest number in Italy, and many other notable markets such as those in France, Belgium, Poland, and the United Kingdom [36].

In North America, local utilities have implemented these programs in varying manners. Duke Energy for example, which manages electric utilities in several southeastern U.S. states, offers a smart home thermostat program, giving the utility the ability to make small adjustments to participants' setpoint temperatures during periods of high electric demand [37]. In the northeast, companies like Enel provide demand response programs options to businesses with varying event durations, even as short as 10 minutes, depending how long power reductions are needed [32]. Enel also coordinates demand response program in Canada for business participants in Alberta, with the Alberta Electric System Operator (AESO), and in Ontario, with the Independent Electric System Operator (IESO). Through the IESO program, day ahead alerts are given, with the event notification occurring approximately 2 hours in advance, while in the AESO program, day ahead alerts are also given but event notifications can be as short-term as ten minutes in advance. This short-notice program relies on the commercial participants which can respond within minutes to help stabilize the electric grid during critical periods [38], [39]. At the time of writing, demand response in most of Canada has been mostly limited to business, and other large consumers, as programs similar to the ones mentioned in Ontario and Alberta also exist in British Columbia, Saskatchewan, Quebec, and the Maritimes [40]. Although, time-of-use rates like those used by many Ontario households are a form a of flexibility, to encourage off-peak electricity usage.

Perhaps the most advanced province in Canada for flexibility programs would be Quebec, which has numerous tariff structures and flexibility programs for its users in all sectors, including residential. As this province has the highest rates of residential electric heating in Canada [41], flexibility cannot be underestimated even for small power users. Through the province's electric utility, Hydro-Québec, winter credit and flex rate options exist for commercial, industrial, and residential clients who can reduce their demand during peak hours, and a new time-of-use rate option will also be available residential participants in late 2026 [42]. Additionally, the Hilo program by Hydro-Québec uses smart thermostats to automatically make setpoint changes during a DR event for participating residential users based on their temperature preferences [43]. A few of Hydro-Québec's regular tariff structures & their optional flexibility program counterparts are listed in Table 2.1. In this table, for simplicity, daily or monthly access charges are not listed, as well as some specific conditions. Viewing the energy cost outside of peak demand events in the flex rates highlights quite large incentives for customers to enroll in these demand response programs. By 2035, these programs are estimated to provide as much as 3 GW of flexibility during peak events based on recent projections from Hydro-Québec [44].

Overall, the necessity for energy flexibility around the world is evident through the many existing and emerging demand response programs mentioned. A review of demand response in buildings has also noted this upward trend in the research, with the number of research articles about this topic dramatically increasing since the 2010s [45]. A 2024 review paper evaluated over 240 software tools for energy and flexibility management and found considerable solutions available in open-source tools [46]. This suggests a high level of accessibility for buildings to achieve flexibility, and a market which is following the research in terms of highlighting its importance.

Table 2.1 Summary of Some Hydro-Québec Electric Rates Options, 2025 [42]

Rate	Consumer	Structure of Rate
Rate D	Residential	• 6.905 ¢/kWh up to 40 kWh/day times the number of days in the period • 10.652 ¢/kWh for remaining energy • Maximum power demand of 65 kW for this rate
Rate Flex D	Residential	• 4.774 ¢/kWh up to 40 kWh/day times the number of days in the period, outside of peak demand events • 8.699 ¢/kWh for remaining energy outside of peak demand events • 45.088 ¢/kWh during peak demand events • During the summer period, Rate D is applied
Rate G	Small Power Business	• 11.933 ¢/kWh up to 15,090 kWh for billing period • 9.184 ¢/kWh for remaining energy • $21.261 / kW for power demand > 50 kW • Maximum power demand of 65 kW for this rate
Rate Flex G	Small Power Business	• 9.800 ¢/kWh outside of peak demand events • 54.442 ¢/kWh during peak demand events • During the summer period, Rate G is applied
Rate M	Medium Power Business	• 6.061 ¢/kWh up to 210,000 kWh for billing period • 4.495 ¢/kWh for remaining energy • $17.573 / kW for billing period’s maximum power demand
Rate Flex M	Medium Power Business	• 3.820 ¢/kWh outside of peak demand events • 60.262 ¢/kWh during peak demand events • $17.573 / kW for billing period’s maximum power demand • During the summer period, Rate M is applied

2.4 Building Cluster Flexibility Studies

Although much of the flexibility research to date targets single building applications, there is a growing interest and shift in recent years to multi-building studies [47]. Upon investigation into several of these studies, Vigna et al. provide a definition of a building cluster as follows:

> *"a building cluster identifies a group of buildings interconnected to the same energy infrastructure, such that the change of behaviour/energy performance of each building affects both the energy infrastructure and the other buildings of the whole cluster. This definition does not assign fixed dimension and boundaries to the building cluster scale, but it is based on building interconnection that could be physical and/or market related."[47]*

Jurjevic and Zakula performed a review of demand response in buildings and highlighted some interesting trends found in their search of publications on this topic from 2020-2023. The majority of the papers analysed in their review were for studies where less than 10 buildings were included, and of those more than three quarters were single building studies. The next most common sample size found in [45] was for studies including more than 1000 buildings, which was more often seen than the sample sizes in-between 10 – 1000. This indicates quite a considerable interest into large-scale studies, which bring about greater flexibility potential. Another interesting finding from this review is that the majority of the studies examined were focused on a single building type instead of a variety within their sample size (i.e. only residential, or only commercial, instead of residential and commercial which only had 8% of the share of papers in this review) [45]. The relatively small share of studies in this area points to new opportunities for researchers. It was also noted by Li et al. that new solutions should be implemented in flexibility studies that target diversity in building stock, and multicarrier systems (those with multiple energy resources) offer higher levels of flexibility [5]. In another review, of recent publications of residential building flexibility studies, it was also mentioned that single building studies made up the majority of studies found, then followed by district or community level studies [24]. In this review, the methods of flexibility found most often in the papers consulted were load shifting, followed by load shedding (also sometimes referred to peak shaving, as was earlier in this chapter), generation, and modulation of load.

In a study by Lagner et al., peak shaving is simulated for a building cluster of 10 homes in Germany, using heat pumps with an optimized control algorithm, and achieved 38% peak load reductions for the cluster. This study used RC models for the homes, which were modelled as either renovated or un-renovated, to represent some diversity within the cluster [48]. In another recent study using RC models, Pettruci et al., modelled the energy use of 10 homes in Quebec, and tested scenarios with different energy resources or controls added to increase flexibility. Among their case studies were scenarios with added PV, heat pumps, and MPC. In this study, energy and peak reductions found achieved up to 40% and 32% respectively for the modelled cluster using these technologies. This study also discusses the importance of aggregators, who can manage the energy demand of a portfolio of consumers, and coordinate it for grid stability [49].

In another study of a residential cluster, by Dong et al., 200,000 simulated homes were controlled through an algorithm developed to coordinate the response of the cluster during demand response events. This study resulted in peak shaving for the cluster up to 28% during events, which was a better result than when the individual buildings were not coordinated with the algorithm, and only performed a demand response action without taking into consideration the actions of the other homes [50]. This study shows the importance of the coordination of strategies and control in building clusters to achieve optimal results.

Many cluster flexibility studies conducted are archetype based, using existing general prototype models such as those from the U.S. DOE EnergyPlus building models. Zhang et al., conducted a cluster flexibility study with these models, however, have modified the models used to be reflective of the Canadian building stock in terms of their envelope and building systems. This study tested two rule-based heating setpoint strategies on 54 commercial building models, using the thermal mass of buildings as the flexibility source and achieved peak power reductions of 22-27% [6]. The authors mention a few limitations of their study, such as the lack of validation of building models with real world data, as well as a lack of investigation into the synergy among the buildings [6]. In fact, the investigation of synergies among building clusters is a fairly unexplored research area, with only a few papers surrounding this topic found. One notable paper in this topic is by Kaminski and Odonkar who investigated the diversity of building types within clusters to find optimal combinations for load reductions, among other KPIs. The U.S. DOE building models were used in this study as well, and the location simulated was New York City. Upon their investigations and ranking system, the authors found that small and medium office buildings combined with school buildings in clusters tend to provide high potentials for their energy KPIs considered in their study location [51].

Throughout these studies and the numerous more that explore flexibility in clusters, the importance of the research is vastly recognised and is further growing. Specifically, investigation into flexibility for clusters of mixed buildings, with different combinations of energy resources is an important part of the future of this research, as more energy resources get utilized across various sectors. The careful management and coordination of these resources will be essential for clusters of buildings to effectively provide flexibility to the grid.

2.5 Hybrid Gas-Electric Systems

For buildings around the world, natural gas is most widely used for heating, accounting for 42% of the heating share, followed by oil and electricity, each around 14% of the heating share according to 2022 data from the IEA. In many countries, efforts to reduce GHG emissions have been supported through incentives to replace fossil fuel heating equipment, or in some cases even bans on fossil fuel heating in new construction [52]. The electrification happening for heating will certainly add to the peak demands of electric grid, as investigated by various studies, often testing projected scenarios with varying amounts of electric heating. One study focused on California specifically investigates storage needs with increased electrification, and project that in their net-zero scenario, up to 75 GW of storage capacity might be required [53].

In another study focused on various scenarios of New England transitioning to residential electric heating, total electric demands were estimated to increase up to 59%. In this heating dominated climate, with natural gas currently most prominent, the research team estimated that some sub-regions could increase their peak by as much as 158%. To reduce this grid strain, the researchers cite that natural gas might still be necessary to balance the grid, specifically mentioning the need for flexible resources [54]. Another similar study exploring the transition to increased electric heating in the UK looked into possible electrification scenarios and estimate similar issues for their grid with the increased peak demands. As they estimate a need of approximately 40 GW of additional generation capacity in high electrification scenarios, they note that homes having a secondary heating source can reduce this problem. This research team recommends that the UK's decarbonization goals might be more realistically met with a reduced reliance on fossil fuels, rather than mass electrification, and mention that hybrid gas boiler/heat pump systems could support this [55]. Both these studies highlight the benefits of keeping gas systems even in high electrification scenarios, as it can be a flexibility resource. More generally, it is practical for homes to have a secondary heating system, as that can ensure comfort even during emergency or black out situations, for example.

In Canada, space heating in the residential sector comes from natural gas for 54% of the share, and electricity for 30% of the share, according to 2022 data [56]. For the commercial and institutional sectors, these shares for space heating are 80% for natural gas and 13% for electricity in the same year, 2022 [57]. Electrification has been ongoing in Canadian heating, as these shares for electric heating have generally increased since 2000. For some provinces the share of residential and CI heating from electricity can be much higher, such as in Quebec as previously mentioned, due to considerable generation from hydroelectric dams; this is further discussed in Chapter 5.

In Quebec, the electric utility, Hydro-Québec, and the major gas utility, Énergir, recognize that hybrid systems are beneficial in decarbonizing the grid while still managing electric peak demands. These utilities have partnered to offer a “dual-energy rate” (known as *biénergie* in French) available to customers who can switch to gas for space heating during times when temperatures fall below -12˚C (or -15˚C, depending on the location) [58]. At these temperatures and below, electric heating throughout the province contributes significantly to the high electric demand for the grid. Similar to the flex rates as previously described, the dual-energy rate offers a discounted energy cost outside of these peak periods, and higher costs during, to encourage the switch to gas heating [42].

Overall, hybrid gas-electric heating systems can be a beneficial tool to manage peak events for the grid, as we add more electric demand from heating electrification, or electric vehicles, for example. Considering this fact, the project in the second paper presented in this thesis, in Chapter 5, explores the benefits of having hybrid gas-electric systems available in a cluster of buildings undergoing flexibility strategies.

2.6 Summary

The topics explored throughout this literature review are some of the main themes surrounding the research topic which will be explored in this thesis. For buildings, energy management and modelling are major components to unlock flexibility, which is important throughout many energy markets around the world. Numerous studies have explored flexibility in clusters, but gaps and limitations often include having adequate variability in the building types studied, or their sources of flexibility. As well, cluster flexibility studies have often been focused on future building stock, where researchers have applied technology to buildings studied which do not always reflect the current building stock in the locations studied. The research conducted in this thesis is thus relevant because it will attempt to contribute to filling these gaps, through the two research papers listed in Chapters 4 and 5, and their supplementary details and supplementary results in Chapters 3 and 6, respectively.

CHAPTER 3 CASE STUDY DETAILS

In this thesis a cluster of buildings has been modelled, and flexibility strategies are applied to the buildings and coordinated to best benefit the cluster, while still considering individual building effects such as their costs. In this cluster study, the buildings are not thermally or directly connected electrically but can be considered to be within the same general area which is experiencing the same weather and electric grid conditions. To perform the energy simulation on the cluster, the creation of a portfolio of buildings was one of the first steps. Initially only residential buildings were considered within the cluster, and commercial/institutional (CI) buildings were later added to further investigate how the addition of different building systems within a cluster can provide more flexibility. The majority of the details involving the creation of the models is included in Chapters 3 and 4, however in this subsection some of the details not specified in those chapters will be discussed.

3.1 Details of Residential Building Modelling

There are 2400 residential buildings modelled in this study, which have been created based on an initial archetype of a 3-story single house, which is shown in Figure 3.1, alongside its Simulation Studio environment within TRNSYS [59]. This building is modelled with 3 thermal zones (one per floor), and has several input files and characteristics changed to create a unique version for each of the 2400 buildings modelled. The homes each were assigned a different combination from: 40 options of domestic hot water (DHW) [60] & non-HVAC data [61], 3 options of baseline HVAC setpoints, 5 options of time-shifts for the mentioned data and setpoints, and 4 options of insulation levels ranging from poor to high performance materials, inspired from [62],[63]. Creating this diversity within the portfolio of buildings was an important aspect, to have results be better reflective of real conditions, and to consider how different buildings would respond to the flexibility measures. Within the model, infiltration was modelled using Type 932, and the 270 L DHW tank was modeled with Type 154.

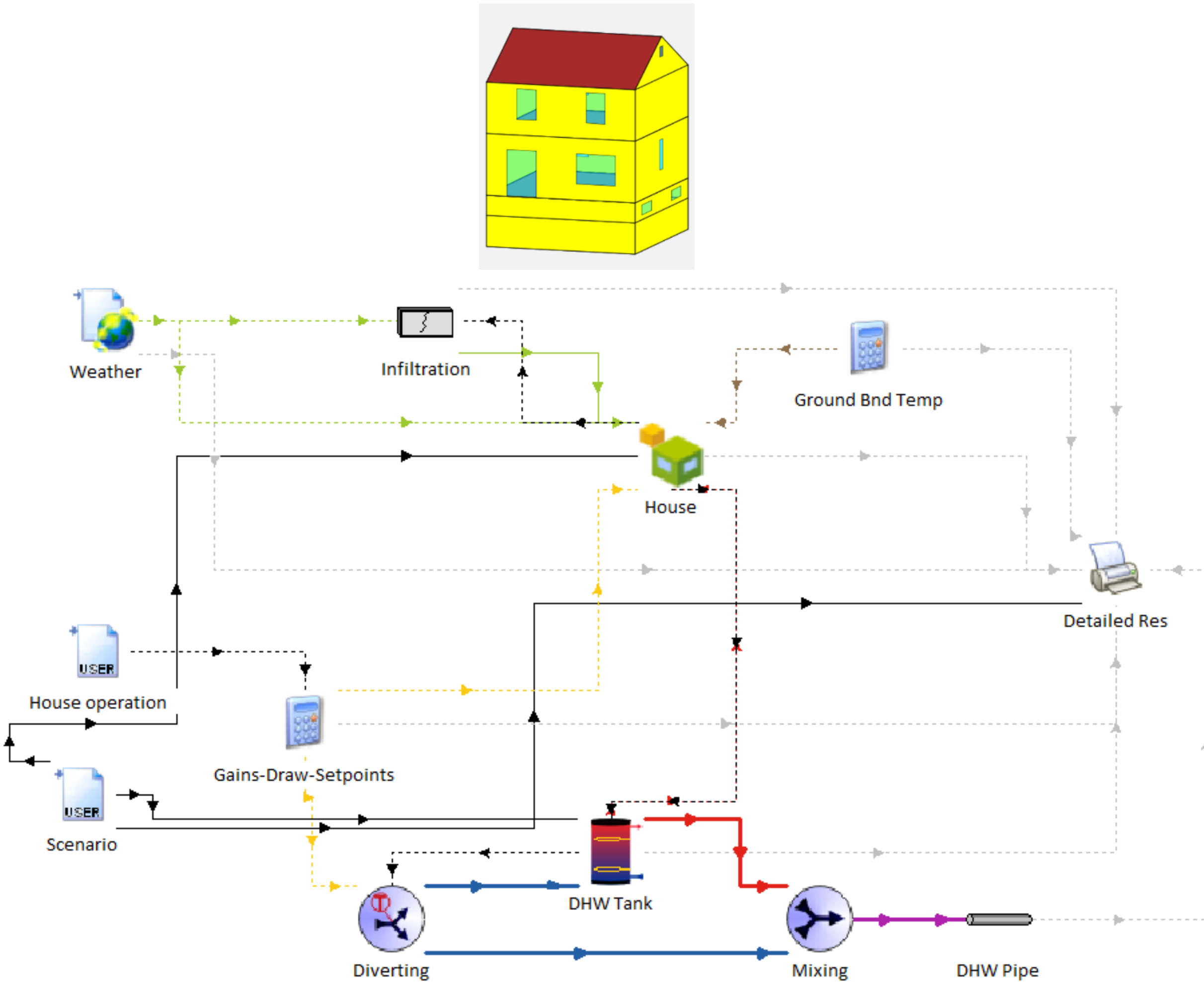

Figure 3.1 Residential building model and its simulation studio environment

The assigned input data files (house setpoints and flexibility strategy, and DHW draw), along with the specified weather file then was used to simulate each building. This was done through MATLAB which grouped the corresponding input files to use within TRNSYS, and results were processed for the individual buildings and then averages and aggregates were calculated for the cluster. Regarding the weather file used, in the study performed in Chapter 4, it was a typical meteorological year (TMY) file for Montreal, Quebec [64], and when the CI buildings were included in Chapter 5, the weather file used was then changed to historic weather files of St-Hubert, Quebec, for 2022 and 2023, since the model creation for the initial CI building required these data files for calibration purposes. The location of the two flexibility studies is shown in Figure 3.2.

Figure 3.2 Southern Quebec, location of the cluster flexibility studies [65]

3.2 Details of CI Building Modelling

Once the flexibility study of the residential buildings was performed, detailed in Chapter 3, a question arose of how other buildings with different systems can interact within a cluster. A limitation of the residential study was that having only one type of building in the cluster could only provide a limited amount of flexibility – due to having only electric systems within the homes and not having major differences in the hours when electricity was most used: early mornings and evenings. To work around this limitation and to study complementarity of different building types within clusters, a CI building was considered as a good addition to diversify the cluster. These types of buildings can have varying hours and magnitudes of peak electric demands based on their individual hours of operation and tend to have various systems within them for their HVAC, which are not usually solely limited to electrically driven. Given these considerations, and the availability of data from an existing building near St-Hubert, Quebec, an initial CI building model was created, and then various characteristics were modified to create 30 CI building models within the cluster.

The ratio of buildings within the cluster, 2400 residential, and 30 CI, was chosen due to the ratio of the floor areas within the cluster representing close to the true ratio of these buildings' floor area in Quebec [66], [67]. The CI building model created in this study is based on an existing building which is composed of mainly office spaces and some laboratory and workshop zones. This was also modelled in TRNSYS with type 56, as shown in Figure 3.3 alongside its Simulation Studio environment.

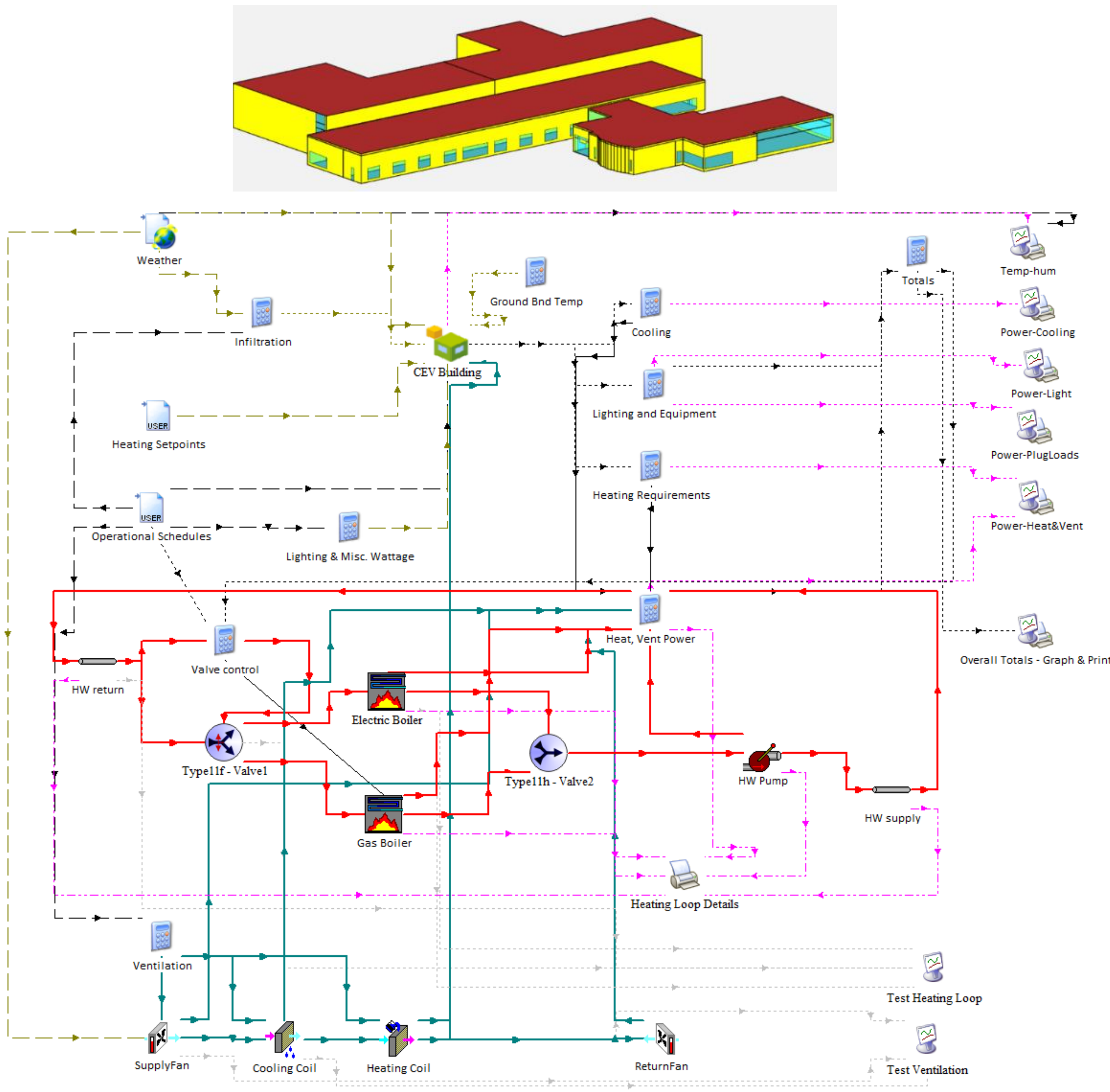

Figure 3.3 CI building model and its simulation studio environment

To create this model, a bottom-up approach was taken, as numerous details and data of the building were well documented. The real building's physical characteristics were found through architectural plans and recommissioning reports, and available operational data from the BMS was used to model and calibrate building systems. Beginning with the geometry of this building, as found in the building plans, these dimensions were drawn in Google SketchUp which then produced an .IDF file. This was then imported into TRNBuild and the envelope properties were then applied, with some assumptions used when information was unclear between different year's architectural plans, as the building had additions built in 1995 and 2017, after its original 1992 construction. The building's envelope is a concrete masonry type and its external material properties are listed in Table 3.1. Comparing this envelope to the 4 options used in the residential building cluster, this type of building falls in general between the good and high-performance constructions. For the creation of the varying CI buildings for the cluster, the focus was on the building systems thus the insulation levels were not as aspect which was changed.

Table 3.1 CI building envelope characteristics

Roof RSI-Value (m^2K/W)	3.68
Walls RSI-Value (m^2K/W)	2.84
Slab RSI-Value (m^2K/W)	2.82
Window U-factor (W/m^2K)	1.69
Window SHGC	0.66

The building plans also indicated the number of desks, and some of the lighting and electrical equipment in each zone, which were inputted into TRNSYS to get the internal gains from these aspects, based on their schedules. The schedules were created from knowledge of the usual business operating hours of the building. Ventilation was also modelled based on the schedule used in the real building, but assumptions had to be made for the fresh air temperature, and flow rate, which was estimated based on ASHRAE Ventilation for Acceptable Indoor Air Quality [68].

For each zone in the building model, the heating capacity available was limited to the capacity installed in the real building. This heating equipment is served by electric and gas boilers in the real building, which are further described in Chapter 5. The building is a medium-power electricity consumer, and is billed with Hydro-Québec Rate M, the tariff described previously in Table 2.1.

With this rate structure, since power is charged in addition to energy, the building operates to stay within a demand limit of 255 kW, which keeps their electricity bills standard across months. To do this, the building uses its electric boiler for heating mainly during time periods when its electric demand is low, its off-peak hours. When electric demand approaches that limit of 255 kW, the gas boiler will take priority. This type of building heating operation is quite common for similar buildings using this rate structure, when they have both electric and other heating available.

3.3 Calibration of CI Building

Having the access to this CI building's operational data allowed that the original model created could be calibrated based on some key variables, although a finely calibrated model was not a main objective of this thesis. For a flexibility study targeting peak electric power reduction, the main focus is on the electric demand of the building, which was calibrated with hourly measurements resulting in accuracy fell within the ASHRAE guideline 14 recommendation for a calibrated model. This guideline recommends hourly NMBE of <10 % and hourly CV-RMSE of <30%, and monthly NMBE of <5% and monthly CV-RMSE of <15% [69] . The results of the hourly calibration for a few key variables are tabulated in Table 3.2.

Table 3.2 Calibration results of CI Building Model

Variable	Hourly NMBE	Hourly CV-RMSE
Electric power	4.9 %	19.7 %
Electric baseload (electricity excluding the electric boiler)	-1.1 %	20.5 %
Zone temperatures (error for all zones averaged)	5.86 %	15.3 %

It is noted that the NMBE and CV-RMSE was also found for the electric and gas boiler power specifically, and while NMBE values did fall within the ASHRAE recommendation or very close, the CV-RMSE values for those specific variables did not. However, as the main objective was to have a model capable of capturing the overall electric use of the building, which was within the ASHRAE guideline, further calibration was not a focus. For two weeks in January, the real and modelled power from the building is graphed in Figure 3.4 using 10-minute interval data. As evident through the plots, not all variation of the real building's demand can be precisely modelled, but the general pattern of peaks and valleys, and their magnitudes was typically captured.

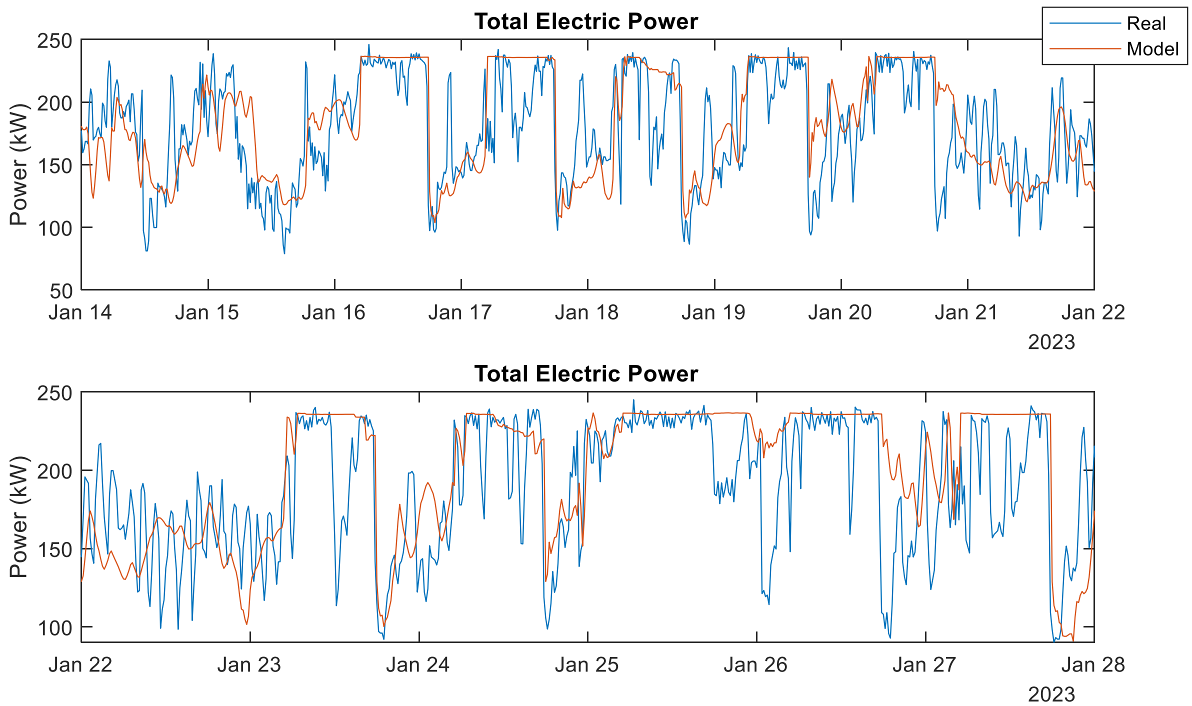

Figure 3.4 Real and modelled power from the CI case study building

Once the initial CI building model created, modifications were made to plug load density, heating equipment sizing, and electric peak demand limit, as well as time shifts as also performed for the residential buildings. Insulation level, although interesting to explore for the residential buildings, was not one of the modifications used in the CI buildings. The modifications, further detailed in Chapter 5, were preformed to create 30 different CI building models. Thus the cluster of buildings studied in this thesis includes a total of 2430 buildings modelled.

CHAPTER 4 ARTICLE 1: MODELLING AND ANALSYS OF ENERGY FLEXIBILITY STRATEGIES FOR A RESIDENTIAL BUILDING CLUSTER

This article was presented at the IBPSA-Canada eSim conference in June 6, 2024, and has been published in the conference proceedings. This paper was co-authored by Michaël Kummert.

4.1 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 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.

4.2 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 [70]. 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 [71]. 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 [47]. 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" [3]. 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 multi-building 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 [72], [73].

Li et al. conducted a review of residential building flexibility studies, focusing both on the single building level and clusters of buildings [24]. 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 [24]. 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 [74], costs [75], or considering both of these aspects [6], [76], [77]. 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 (3.1), (3.2), and (3.3) [78]. 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.

$$FSI = \frac{Cost_{flexible\ operation}}{Cost_{baseline\ operation}} \tag{3.1}$$

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.

$$\Delta P = P_{baseline,peak} - P_{flexible,peak} \tag{3.2}$$

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.

$$LF = \frac{Load_{avg}}{Load_{max}} \tag{3.3}$$

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.

4.3 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 [79]. 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.

4.3.1 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 [61] and week swapping some, creating 40 unique profiles.
- Joining a DHW draw profile, taken from 12 real profiles available [60], 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 4.1.
- 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 [62]), and high-performance (matching the Novoclimat standard [63]) 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 4.1. 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.

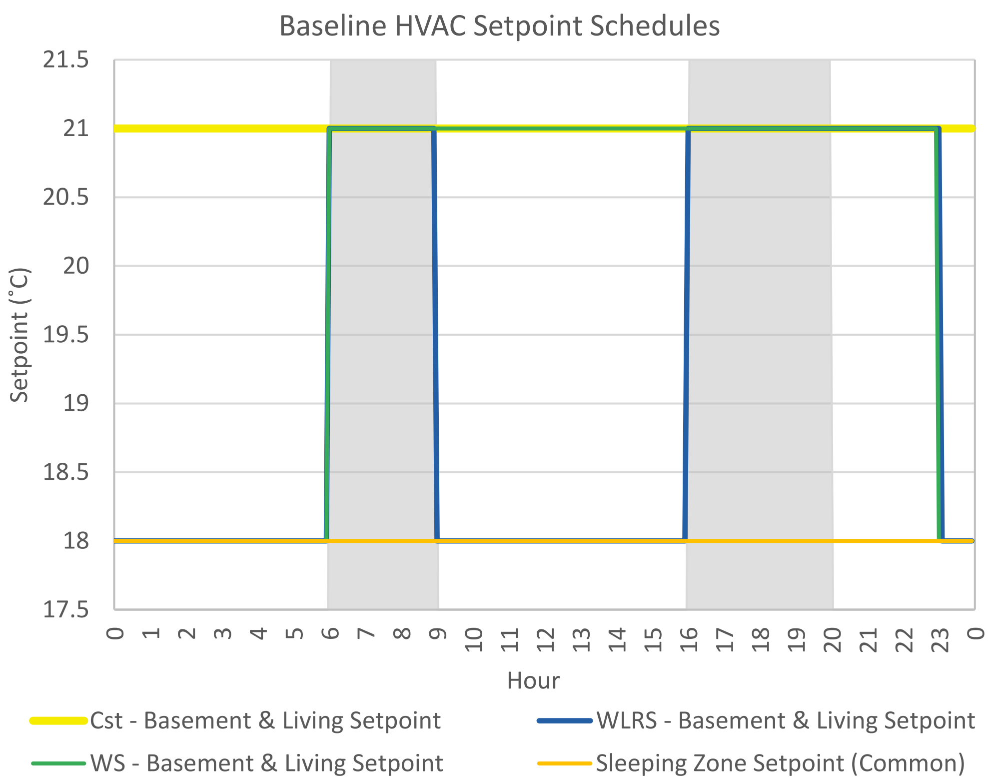

Figure 4.1 Baseline HVAC setpoint schedule

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 4.1 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

4.3.2 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 4.2.

Table 4.2 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.

4.4 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 4.3.

Table 4.3 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 4.2 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.

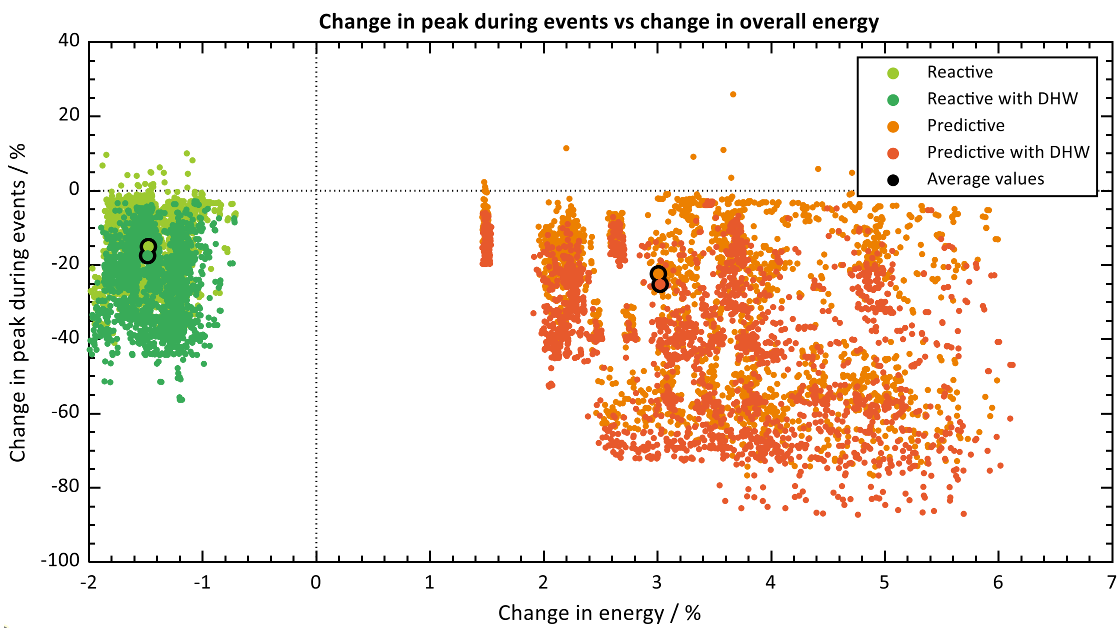

Figure 4.2 Average change in peak during event vs change in overall energy for each home

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 peak column of Table 4.3. These rebound peaks are clear in Figures 4.3 – 4.7 which show the daily profile of the average home for each strategy tested.

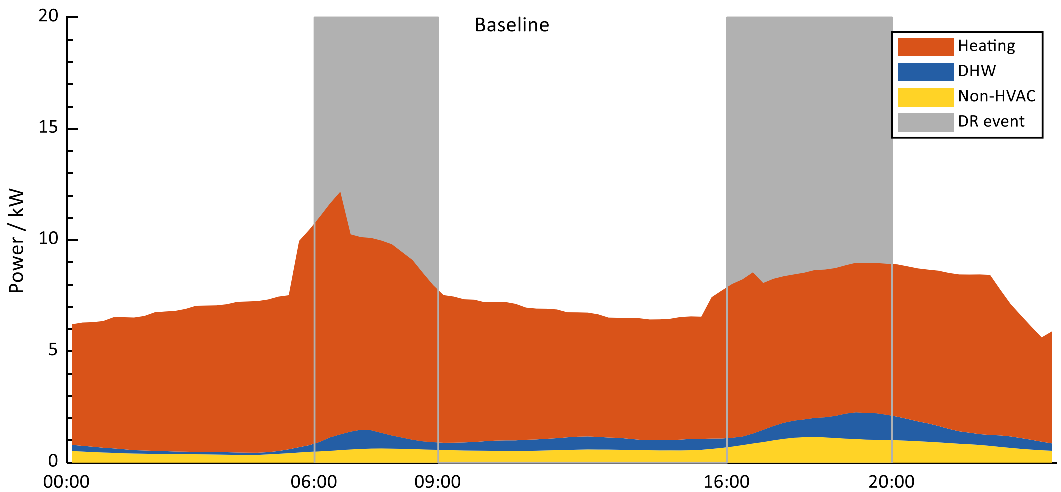

Figure 4.3 Average home daily profile, baseline

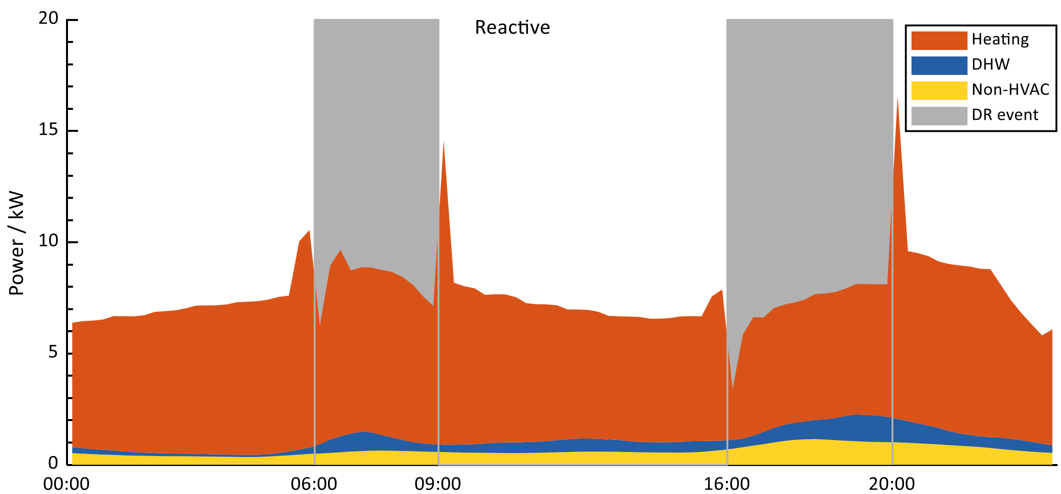

Figure 4.4 Average home daily profile, reactive

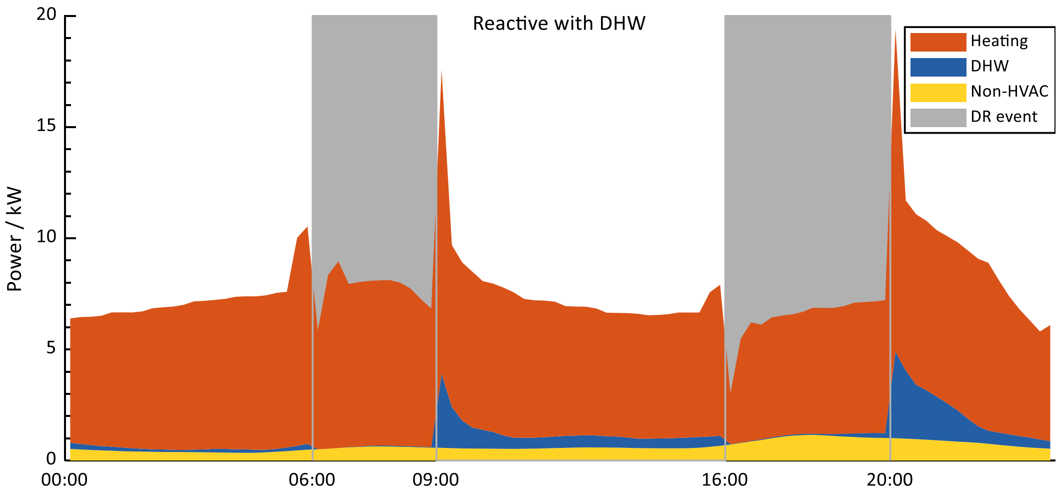

Figure 4.5 Average home daily profile, reactive with DHW

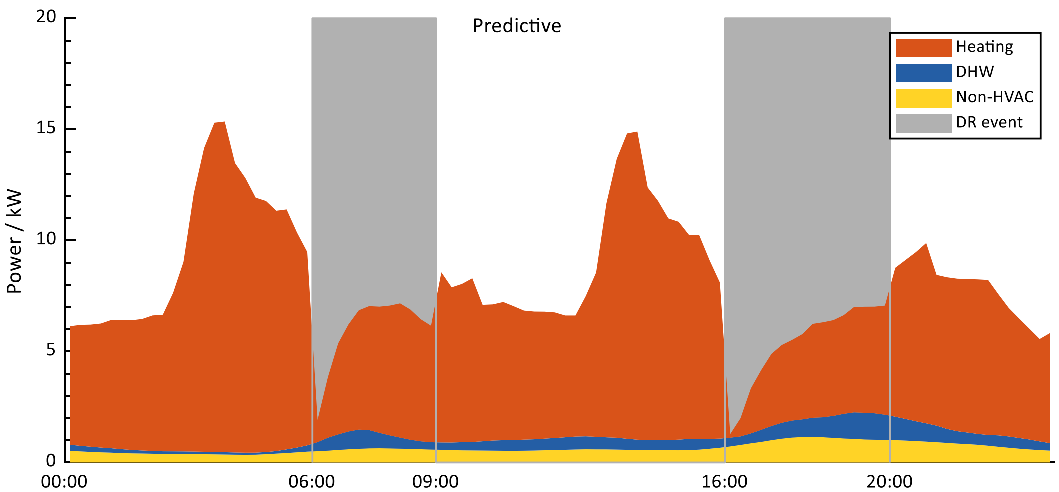

Figure 4.6 Average home daily profile, predictive

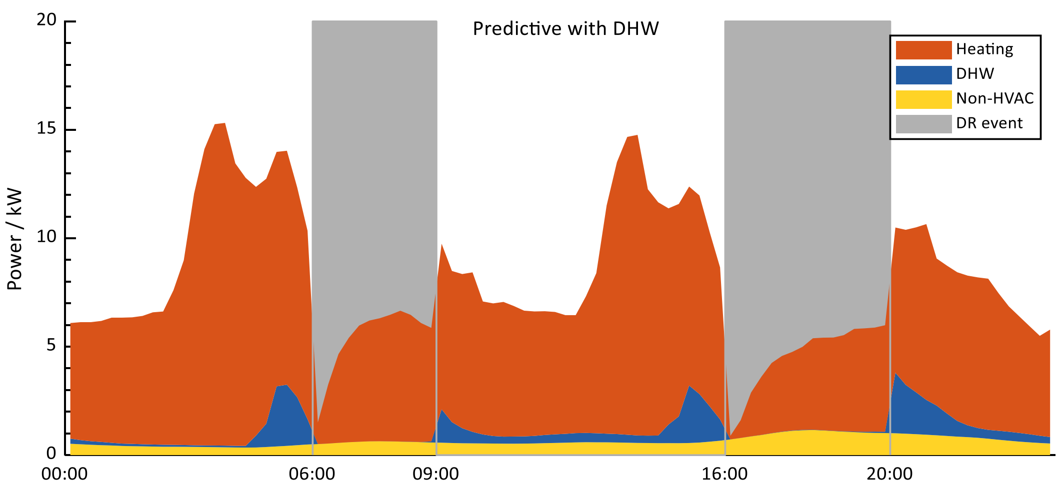

Figure 4.7 Average home daily profile, predictive with DHW

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 4.4. 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 4.4 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 4.5. The high-cost structure was used in the calculation of the FSI.

Table 4.5 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 4.4. 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 4.3. 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.

4.5 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 the 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 4.6, 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 4.6 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 4.8.

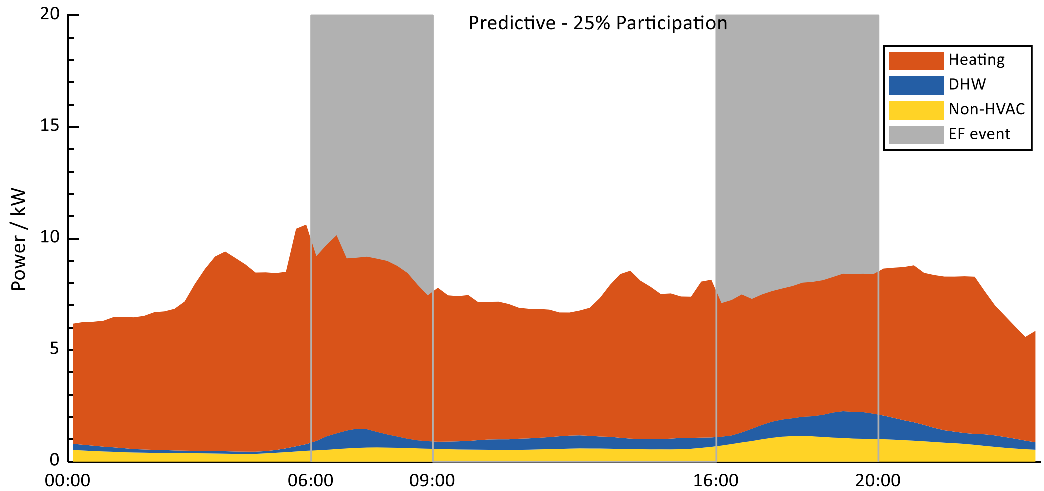

Figure 4.8 Average home daily profile, portfolio coordination of 25% predictive, 75% baseline

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.

4.6 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.

CHAPTER 5 ARTICLE 2 : SIMULATION OF ENERGY FLEXIBILITY STRATEGIES IN A CLUSTER OF DUAL-FUEL COMMERCIAL AND INSTITUTIONAL BUILDINGS AND ALL-ELECTRIC RESIDENTIAL BUILDINGS IN A COLD CLIMATE

This article was submitted to the Journal of Building Physics on April 29th, 2025, for the eSim Special Edition. This paper is co-authored by Michaël Kummert.

5.1 Abstract

In this simulation study, a cluster of residential and commercial/institutional (CI) buildings undergoes flexibility strategies to reduce electric power during winter demand response (DR) events and the effect of these measures is analysed on the cluster level and on the individual building level. The portfolio used to simulate the flexibility strategies is comprised of 2430 buildings, of which 2400 are modelled as residential and 30 as CI buildings; this ratio roughly represents the real ratio of residential to commercial floor area in the location of study. The residential homes are all-electric, while the CI buildings have heating available through both an electric and a gas boiler, providing a dual-fuel heating system to work with for flexibility measures. The flexibility strategies tested are reactive and predictive, in which reactive measures are considered as not having any preplanning required, while predictive measures include preheating outside of peak hours. The study investigates and verifies the complimentary nature of a mixed building cluster in order to provide flexibility during DR events, through peak power reductions of 24-37% during demand response events for the aggregated cluster. Compared to the power reductions obtained for only residential building clusters or only CI building clusters, the joining of all buildings to create the mixed cluster presents a greater benefit and confirms the synergy possible between mixed building types in flexibility studies.

5.2 Introduction

On a global scale, electricity demand has seen steady increases over the past few years and is expected to rise at faster rates over the near future [71]. In response to the growing electricity demand, utility grids must adapt to keep up with the requirements of their consumers, over the various sectors they serve such as residential, commercial & institutional, and industrial, among others. The vastly different needs of these sectors, not only in terms of amount of power but when that power is required, poses challenges in terms of having the capacity available to handle demand fluctuations to meet these peak power demands. Considering this in addition to more renewables being used for electricity production, which come with their own supply variances, energy flexibility and resilience have become increasingly important concepts throughout the world. Energy flexibility in buildings was described by the International Energy Agency through Annex 67 as the “ability for a building to manage its demand and generation according to local climate conditions, user needs, and grid requirements” [3]. In terms of the grid as a whole, increasing flexibility on the supply side can include dedicated power plants that meet the extra required demand, or large-scale storage systems for example, which come with a high financial investment [30]. Importing electricity from other utilities, another method of supply side management (SSM) can also result in high costs and potentially high emissions depending on how the electricity is generated and imported. Considering increasing flexibility on the demand side, demand side management (DSM) can be more feasible and has gained much momentum in recent years, with grids encouraging their consumers to reduce or shift their power use to non-peak periods; demand response (DR) programs being one way to achieve this [30]. Buildings thus have an increasingly important role in energy management and offer various opportunities for flexibility. According to the IEA, the operation of buildings accounts for 30% of global final energy consumption, and this is one area that policy and building code regulations aim for improvements, through better building insulations and increased energy efficiency within [4]. In a similar sense, DR programs aim for buildings to be more flexible to the variations in the grid’s electricity supply; they aim to make buildings more adjustable so that more complex supply side management methods are not as necessary. In a home, energy flexibility can be as simple as adjusting the thermostat for a period of time or using energy intensive appliances outside of the local grid’s peak periods. In commercial or institutional buildings, more potential sources for flexibility may be available as these buildings are generally equipped with more advanced systems that can be controlled and adjusted for flexibility, often multicarrier systems. Multicarrier energy systems are defined as those capable of coordinating multiple energy vectors to enhance energy efficiency and minimize energy waste [46]. These types of systems can be greatly beneficial in flexibility studies as they bring about additional sources of flexibility and could be a potential way to avoid rebound peaks, often a consequence of load shifting or shedding measures.

5.2.1 Aim of Study

Building energy modelling software can help facilitate testing different measures in buildings to verify the potential of flexibility available. This paper builds upon our simulation study presented at the IBPSA-Canada eSim conference of 2024, in which we modelled 2400 residential buildings undergoing flexibility strategies, using building energy modelling software TRNSYS [80]. This study builds upon that work through the addition of commercial/institutional (CI) buildings to the portfolio of buildings, and further investigates the results obtained when the cluster of buildings undergoes flexibility strategies. The motivation is to investigate whether a complimentary nature can exist in terms of flexibility potential, when focusing on a mixed portfolio of buildings which includes residential and CI buildings with dual-fuel heating systems. By this we mean to investigate the benefits, or synergies, of having dual-fuel commercial/institutional buildings included in the portfolio, which can reduce the pressure for numerous individual homes to be equipped with flexibility aiding technology such as PV, battery storage, or so on. The commercial building in this case can take on a responsibility of fuel switching when necessary, for the portfolio to achieve peak reductions while avoiding rebounds and still providing their building services. This will be investigated along with which strategies might be most beneficial in achieving power reductions at the cluster level. This paper contributes to energy flexibility research by:

- Presenting methods of using and diversifying real building data to create varying models to be included in a cluster, in order to assess flexibility potential in cases similar to what can be expected in real world application.
- Investigating flexibility potential in clusters with their existing building systems (specifically, gas and electric heating) without the addition of flexibility aiding technology, whose potential has been continuously verified but can a constraint due to high investment. This supports ready to implement flexibility strategies in the existing building stock, one of the first steps to broad implementation.
- Assessing the results of the energy flexibility strategies on several bases: the whole cluster, the cluster of residential buildings, the cluster of commercial/institutional buildings, and on the individual building level with the average residential and average commercial/institutional building, in order to verify complementarity between the building types.

5.2.2 Related Work

Flexibility in building clusters has been a prominent topic in recent years, as it brings about potential to reduce grid strain due to increased electrification. The larger magnitudes of flexibility offered to the grid is a key benefit of flexibility in building clusters versus the individual building level. Another key benefit, as stated in the work of Zhang et al., is the ability for buildings within the cluster to compensate for others at times when they might not be able to offer much flexibility [6]. It is important to recall that individual and cluster flexibility strategies can involve different measures applied to same building, since goals can shift when optimizing load reduction by the individual building versus the cluster. The best flexibility strategy for a single building could aim to reduce its electricity bill but might not be the best flexibility strategy for that building to undergo when the aim is for a cluster of buildings to reduce their aggregated peaks, due to the potential for rebound peaks. Thus, it is important for cluster flexibility studies to take this into consideration, and having mixed building clusters can be a method to explore as different building types could have varying sources of flexibility and demand profiles.

Kaminski and Odonkor explored diverse building clusters and their potential flexibility benefits by creating cluster combinations of buildings from the U.S Department of Energy (DOE) reference building types and integrating PV and battery storage to reduce peak loads, among other objectives. This study is one of the few exploring complementarity and the importance of diversity within building clusters and one key finding was that building type diversity significantly enhanced cluster performance [51]. A similar study by Hachem-Vermette and Singh explored clusters of different combinations of buildings, also from the DOE reference building types, and explored renewables and energy sharing to reduce the total electric demand of the cluster. This study also found that differences in energy profiles can be beneficial for potential energy resource sharing [81]. Another mixed building study, for a Canadian community including residential, commercial and educational buildings, was simulated to reduce costs and GHG emissions, through different combinations of electric storage and photovoltaic panels, though the focus was not specifically energy flexibility [82]. These studies each include highly valuable insights into the complexities and benefits associated with building cluster modelling, but the addition of PV and/or storage in these studies requires costly investment which might not be possible in certain cases. The approach studied here will focus on building clusters undergoing flexibility strategies to reduce peak power, without modifying the systems already existing in the typical buildings available in the study location, which will be further discussed in the next section. Considering the existing building stock is important as it allows for the flexibility potential to be realized without major building recommissioning. Our study aims to explore the benefits of the mixed cluster of residential and CI buildings, but also the individual benefits of the average residential and average CI building undergoing these strategies, namely in terms of their potential cost savings. Thus, the focus remains on the cluster of buildings, but the effects on the individual building are not overlooked.

Several experimental studies of cluster flexibility were reviewed by Le Dréau et al., and one conclusion mentioned is that a closer cooperation between the grid-side, utilities, and demand-side, users, is important to overcome the complexity of flexibility and to offer successful solutions. This thorough review indicated technical gaps that exists in the research, such as the development of optimized control strategies at the cluster level, and evaluation of scalability and coordination strategies [7]. Most of the studies reviewed had clusters composed of one building type, mainly residential, but a few did include mixed building types within their clusters. One study in their review, conducted in a remote community of British Columbia, Canada, features residential and commercial buildings in their cluster, and attempts to reduce power demand to only allow for higher efficiency electricity generation. They achieved this, but ran into rebound peaks after the load shedding events, and mentioned as one of their conclusions that there exists a a trade-off between the amount of load that is shed and the resulting rebound peak [83]. This was also seen in our previous flexibility work on a residential cluster, and attempts will be made in this study to reduce rebound peaks while still achieving high power reductions, through the addition of the CI buildings, which may offer synergy for the cluster through their dual-fuel system. In [84] it is mentioned that commercial buildings can add complexity to flexibility studies, due to their diverse systems and varied operational characteristics; this can also be seen as a benefit as more potential sources of flexibility can be tapped into.

5.2.3 Energy Context

In Canada, natural gas and electricity are the majority end use energy types, and the residential and commercial/institutional sectors use about a quarter of the country’s energy, while industrial and transportation are the highest energy use sectors, respectively [85]. In commercial and institutional buildings, more than half of the energy used is for space and water heating, and in residential buildings this fraction goes up to more than three quarters [86]. When viewing Canada’s electricity generation, the majority is generated from hydroelectricity, and when focusing on the province of

Quebec, the country's top electricity producer, hydro accounts for over 90% their electricity produced [70]. The abundance of electricity production through hydro allows for a relatively low price and has resulted in electricity being the general public's main source of home heating, usually through electric baseboard heaters [87]. Combining this fact with Quebec's climate, cold and humid during winter months, the electricity grid experiences high power demands and for a few instances during the heating season must resort to purchasing electricity from elsewhere or generation from fossil fuel plants to be able to provide the electricity required to the province's users [2], [70]. Commercial buildings in Quebec, depending on their size and use, are often equipped with fossil fuel powered heating in addition to electric, through a natural gas fired boiler for example. Having both the electric and gas heating available allows building operators in these settings a choice of which heating fuel to use under certain conditions and can be an aid to the grid during periods of high demand. The province's electricity utility, Hydro-Québec, makes available to the public a continuously updating dataset of the electricity demand at a one-hour data frequency, a valuable resource for research. Viewing this data on an average winter day gives a clear example of the morning and afternoon peaks, while the summer months are relatively less variable, making a flatter power demand profile. Around the time of writing this article, winter 2025, the morning and afternoon peaks of a Quebec winter day's electricity demand are evident, as shown in Figure 5.1.

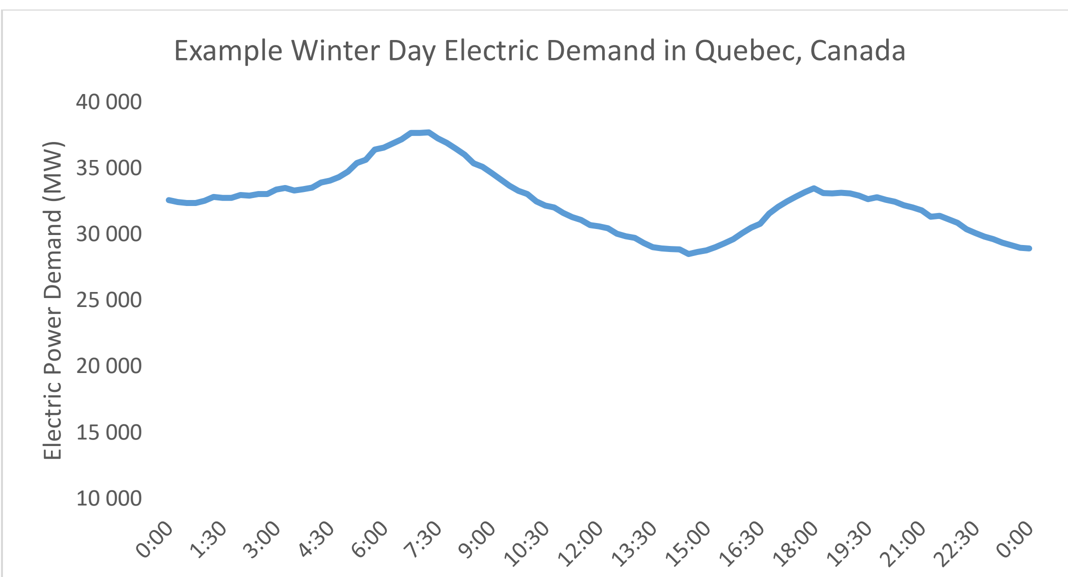

Figure 5.1 Example winter day electric demand in Quebec, Canada [88]

The simulation study detailed in this article is based in Quebec, Canada and will focus on flexibility strategies to target this pattern of peak power demand, however this type of energy market is not unique only to this area. Several markets around the world can be seen as similar, particularly those which experience cold weather and mainly rely on electricity and gas in their energy mix, such as several European countries, U.S. states, and China , among others [89]. Thus, the pertinence of this study is not limited to the study location, and replicability can be considered in several other markets.

5.3 Methodology

As stated in the introduction, the motivation behind this study is to explore the results of a mixed cluster undergoing flexibility strategies, investigating if there is complementary nature that the whole cluster can benefit from to achieve peak power reductions during DR events. To conduct this investigation, we have simulated the power used by 2400 homes and 30 commercial/institutional (CI) buildings during the months of December 2022 – March 2023 in the climate of Montreal, Quebec, Canada. Though a large difference between the number of the buildings, this was selected as the ratio roughly reflects the true ratio of residential floor area to CI floor area in Quebec [66], [67]. All buildings are modelled in TRNSYS [59] and the individual result are aggregated through automated scripts.

5.3.1 Portfolio of Buildings – Commercial/Institutional

The particular heating season used in this simulation study was selected due to the availability of measured operational data from an existing CI building in southern Quebec, which was used to help create and calibrate the initial CI building modelled, before its parameters were adjusted to create diverse similar buildings. Calibration was not a major focus of the study and won't be discussed in this article, since this flexibility study does not necessarily require detailed calibrated models, however, comparing the model of the CI building to the measured hourly data of the inspiration building used achieved NMBE values within or close to those recommended by ASHRAE Guideline 14 [69] for a number of key variables. The existing building, measuring roughly 4110 m^2, was the inspiration for the CI model and is mainly comprised of office space and some laboratory/workshop spaces. It was modelled as a multizone building in TRNSYS (Type 56), with 11 thermal zones, with their heating setpoints as those that were taken from the building's measured operational data. The building has a concrete construction type with a window-to-wall percentage of approximately 30% overall, and this percentage increases to 90% when excluding the laboratory/workshop spaces. Heating in the building is supplied by a dual-fuel heating system which is comprised of one 200 kW electric boiler and two 470 kW natural gas boilers, all connected in parallel. These boilers are modelled in TRNSYS using Type 700 for electric, and Type 751 for gas. For modelling purposes, only one gas boiler was modelled since they are not used concurrently in the real building. As previously mentioned, having both an electric and gas boiler is common for commercial buildings in the study location, and will be the source of flexibility for the CI buildings in this study through fuel switching during DR events. In the real building, selection between natural gas and electric heating is generally automatic, with electric heating taking priority at most instances, except when the building gets close to its electric peak limit (a power value determined by the building operators, which keeps the building electricity bills standard across months, since maximum power is billed in addition to energy). These boilers feed hot water throughout the heating loop, which supply electric heaters around the building operating at all hours, and heating coils in the ventilation system which are operated during occupancy and a few hours before and after. The ventilation system modelled in TRNSYS is a single heating coil (Type 754), cooling coil (Type 752), supply, and return fan (both Type 744) which have been sized to represent the total required for the whole building. Occupancy for this building follows usual business hours with the majority of occupants modelled in the building between 8AM – 5PM, and smaller percentages before and after. Internal gains from electronics and equipment were modelled as a combination of known loads from the building as calculated with [90] as well as the addition of a miscellaneous equipment load which helps close the gap between the modelled and measured data. Occupancy, ventilation, and equipment loads in the building follow schedules as inferred from the building management system (BMS), with higher percentages during the usual business hours.

To create diverse versions of this building to include in the cluster, the CI building model inspired by the existing building then had various parameters modified to create 30 different versions of CI building models. The process to produce these versions is as follows:

A. The electric boiler capacity was increased (or decreased) while reducing (or increasing) the gas boiler capacity by the same amount, ensuring the heating capacity of the building remained standard (660 kW) across the different CI buildings. This was done to produce 10 buildings varying electric boiler capacities ranging from 150-240 kW, and gas boiler capacities ranging from 430-520 kW.

B. Each building was assigned an electric power limit to stay within, which is common in non-residential buildings in Quebec, as most of the commercial building electricity rate structures charge for both power and energy. These power limits range from 180 to 270 kW with the higher power limits given to the buildings with bigger capacity electric boilers.

C. A miscellaneous load multiplier was applied to the equipment loads of the buildings, ranging from 0.7–1.5. The building's power limit discussed in (B) was also multiplied by this number to better reflect the available electricity the building is likely to use. Thus, the peak power limits now ranged from 126 – 405 kW.

D. Finally, a time shift value was assigned to each building, of –30, -15, 0, +15, +30 minutes, relative to the original building's zone setpoint temperatures and operational schedules, as taken or inferred from BMS data (ventilation, occupancy, equipment). This time shift idea was also done in our previous work [80] and provides the cluster of buildings a more diverse power profile, rather than having sharp load increases at the same time for all buildings, in instances for example when ventilation turns on.

Thus, the characteristics of the 30 buildings were selected, and these buildings were simulated independently for each modelled control strategy.

5.3.2 Portfolio of Buildings – Residential

The residential building portfolio consists of 2400 single-family dwellings. It is described in our previous work [80], but the main characteristics of modelled buildings are summarized below for completeness.

The physical layout of the houses used is identical: standalone, 3-story buildings with one thermal zone modelled for each floor (basement, living, and sleeping zones) and an attic which is an unoccupied, unheated space. Each floor measures 60 m^2 resulting in 180m^2 of heated space per house. The window-to-wall percentage of this building is 11% with majority of the glazing on the north and south faces. The residential building is modelled in TRNSYS with Type 56, and its domestic hot water (DHW) tank of 270 L is modelled with Type 156. 2400 versions of the residential buildings model were created by merging available data from other studies and references and making slight changes to create variability between the models. This was done as follows:

A. Non-HVAC power demand of 22 houses in 5-minute timesteps was taken from [61]. Weeks were swapped for some of these profiles, to create 40 unique non-HVAC power profiles.

B. Domestic hot water (DHW) draw in 5-minute timesteps were taken from 12 available from [60] and assigned to each of the 40 non-HVAC power profiles from (A), creating 40 “house operation” files.

C. HVAC schedules were created based on 3 common household setpoint schedule types: constant (Cst), wake-sleep (WS), and wake-leave-return-sleep (WLRS) setpoints. These 3 HVAC schedules were each applied to the 40 power profiles merged in (B).

D. One of four insulation levels were assigned to each house, inspired from [62] meant to represent varying building stock of houses with poor, decent, good, and high-performance insulation.

E. Finally, a time shift was applied to the houses of –30, -15, 0, +15, +30 minutes relative to the baseline power profiles, as was done for the CI buildings.

Thus, the characteristics of the 2400 residential buildings were determined, and they were simulated independently in TRNSYS for each modelled energy flexibility strategy.

5.3.3 Flexibility Strategies

In our previous flexibility work on residential buildings, power reductions of 15-25 % were obtained during grid peak times, though higher than expected rebound peaks were created. Mitigation to reduce rebound peaks was performed through adjusting participation rates, which resulted in more modest peak reductions [80]. In this study, participation rates were not adjusted, as we can assume that the cluster of buildings in the study are representative already of only a portion of the grid’s users. Though rebound and prebound peaks are still expected in some capacity, the addition of the CI buildings which are dual-fuel / multicarrier systems, able to switch between electric or gas heating, are presented as a possibility to reduce the need for mitigation of these consequential peaks. The idea is that a building which can switch fuels, in this case from electric to gas heating during a DR event, will both reduce its electric power peak during the event, and will not create a new peak before or after the event. Thus the flexibility strategies in this study make use of the dual-fuel / multicarrier system simulated in the CI portion of the cluster. The benefit of this system in the CI buildings also has no effect on the thermal comfort of occupants, since the temperature setpoints are not adjusted. The flexibility strategies tested in this study are categorized by reactive or predictive measures. Reactive measures do not require knowledge of the event in advance, while predictive measures require knowledge of the event at least a few hours in advance. The flexibility strategies are detailed in Table 5.1.

Table 5.1 Flexibility Strategies

Flexibility Strategy	Residential Buildings Flexibility Action	CI Buildings Flexibility Action
Baseline	- N/A, baseline case	- N/A, baseline case
Reactive	- During DR event, reduce zone setpoints by 1 °C from baseline	- During DR event, use gas boiler only instead of electric
Reactive B	- During DR event, reduce zone setpoints by 1 °C from baseline	- During DR event, use gas boiler only instead of electric - After DR event, continue gas boiler priority for 1 hour
Predictive	- Before DR event, preheat zones by setting setpoints to +3 °C from baseline (exception: sleeping zones) using a ramp starting 3 hours before DR event	- Before DR event, use gas boiler only instead of electric for 3 hours - During DR event, use gas boiler only instead of electric - After DR event, continue gas boiler priority for 1 hour

For the winter season simulated, the real dates of DR events were taken from the electric utility, and on these dates in the simulation the flexibility strategies were performed for the building models. This resulted in 15 days with DR events, which each take place between 6-9AM and 4-8PM, between the simulation period of December 1, 2022 – March 31, 2023. Most of the results will focus on the DR days, but a few such as costs will be presented for the whole period studied.

5.4 Results

Various KPIs were computed from the 2430 individual simulation results of the building cluster. The electric power reduction during the DR event was one of the KPIs of most interest, as this is a key element of flexibility. In Table 5.2 the peak power on the average DR day during DR hours is listed for each scenario, for the whole cluster, cluster of only CI buildings, and cluster of only residential buildings. In each column n is the number of buildings aggregated.

Table 5.2 Peak During DR Events on the Average DR Day for Aggregated Clusters

Average DR Day's Peak During DR Hours (MW)			
Scenario	Whole Cluster n = 2430	CI Cluster n = 30	Residential Cluster n = 2400
Baseline	30.1 (-)	6.69 (-)	23.9 (-)
Reactive	22.7 (-24 %)	5.14 (-23 %)	19.2 (-19 %)
Reactive B	22.7 (-24 %)	5.14 (-23 %)	19.2 (-19 %)
Predictive	18.9 (-36 %)	5.14 (-23 %)	15.6 (-34 %)

From Table 5.2 we find that the reduction in peak for the whole cluster during events ranges from 24 % for the reactive and reactive B scenarios, to 36 % for the predictive scenario. It must be remembered that the whole cluster column does not necessarily equal the sum of the CI cluster and residential cluster columns, because the peak for each cluster on their own can be occurring at different times, i.e., the residential building cluster might peak at 6AM, while the CI cluster might peak at 8AM. We note that for the cluster of CI buildings simulated in this study, their aggregated electric peak during event hours does not show further improvements past the reactive scenario – this was somewhat expected as the strategy during DR hours does not change for these buildings, though benefit to the reactive B and predictive scenarios still exist which will be further discussed in the next section. Related to this KPI, we can also view the electric peaks outside of event hours, to view the creation any rebound or prebound peaks; this is shown in Table 5.3.

Table 5.3 Absolute Peak on the Average DR Day for Aggregated Clusters

Average DR Day's Absolute Peak (MW)			
Scenario	Whole Cluster n = 2430	CI Cluster n = 30	Residential Cluster n = 2400
Baseline	30.1 (-)	6.69 (-)	23.9 (-)
Reactive	38.3 (+ 28 %)	6.68 (- 0.3 %)	33.9 (+ 43 %)
Reactive B	36.7 (+ 22 %)	6.65 (- 0.7 %)	33.9 (+ 43 %)
Predictive	31.0 (+ 3.4 %)	6.64 (- 0.8 %)	27.9 (+ 17 %)

Again it is noted that in Table 5.3 the whole cluster column does not always equal the CI cluster and residential cluster columns, since the absolute peak for either cluster of buildings can be occurring at different times. In the baseline case, the peak during events was the absolute peak of the day, though for the other scenarios the absolute peak does not occur during the DR hours, and it has increased from the baseline case. Upon further inspection, the increase in the absolute peak for all scenarios is due to either the rebound energy required to heat the buildings after the event, or the prebound energy required in the preheating of residential buildings before the events. These pre-/re-bounds are evident in the series of graphs displayed in Figure 5.2 – Figure 5.5 , which shows the aggregated cluster's power profiles for each scenario on an average day with DR events. In the legend, R- refers to residential buildings aggregated, CI- refers to commercial/institutional buildings aggregated, and Dhw refers to power from domestic hot water. For the CI buildings, baseload refers to all building power excluding the electric boiler.

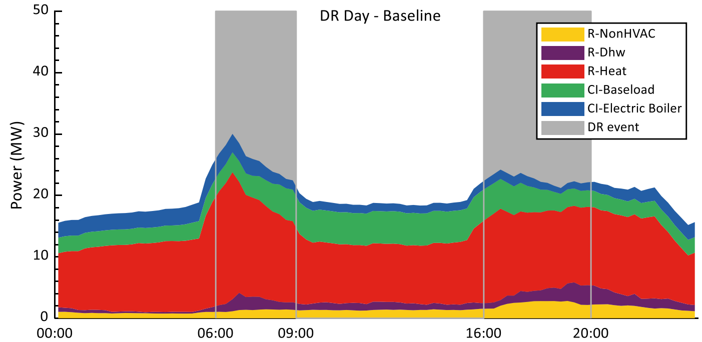

Figure 5.2 Baseline

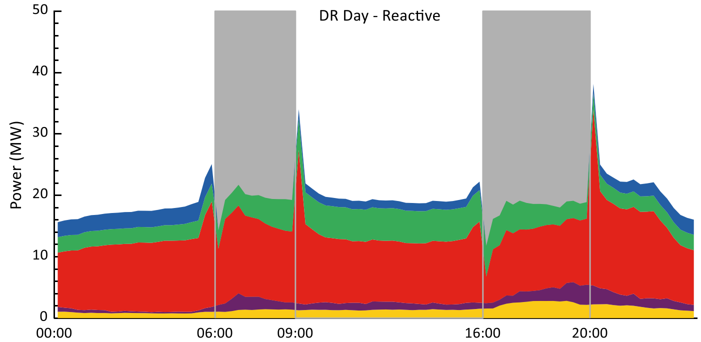

Figure 5.3 Reactive

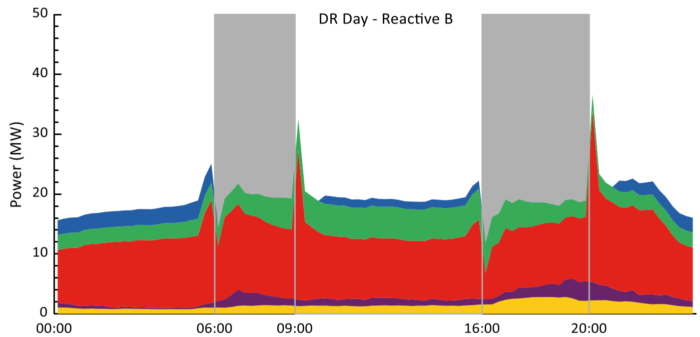

Figure 5.4 Reactive B

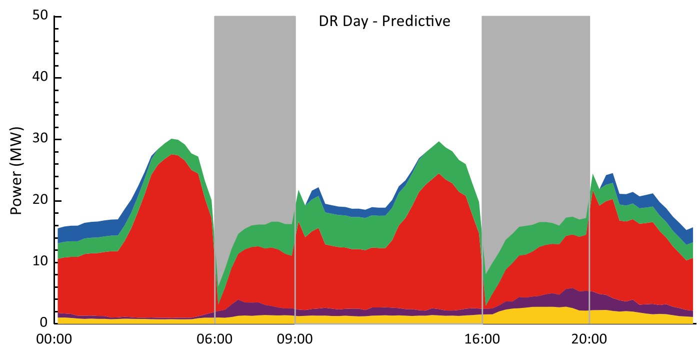

Figure 5.5 Predictive

Figures 4.2 – 4.5: average DR day's power profile for (Figure 5.2) baseline, (Figure 5.3) reactive, (Figure 5.4) reactive B, and (Figure 5.5) predictive scenarios

These consequential re-/pre-bound peaks are generally expected in flexibility studies, though the coordination of strategies between CI and residential buildings was expected to mitigate these instances of increased power. This was somewhat successful, though moderately, and will be further examined in the discussion section. Energy use was also one of the KPIs investigated, both for electric energy and in the case of the CI buildings, gas energy. For the average DR day, these results are shown in Table 5.4.

Table 5.4 Average DR day's energy use for aggregated clusters

Scenario	Electric Energy (MWh)			Gas Energy (MWh)
	Whole Cluster n = 2430	CI Cluster n = 30	Residential Cluster n = 2400	CI Cluster n = 30
Baseline	486	135	350	14.9
Reactive	465	123	341	30.2
Reactive B	461	120	341	34.2
Predictive	472	110	362	46.1

As expected, the CI buildings are able to reduce their electric energy in all scenarios, due to the switch to gas heating during DR events, which increases their gas usage on those days; the lower efficiency of the gas boiler versus the electric boiler, explains the total energy use of the CI buildings increasing for each scenario. It is important to note that although a large difference is seen in the gas usage of the CI building, from Table 5.4, those numbers are only referring to demand response days. We must remember that the CI buildings are modelled as inspired by the case study building, which uses gas for heating when electric power approaches its building peak limit in order to lower their electricity peak demand charges. This means that even in the baseline case, when no flexibility strategies were performed, gas energy is used on particularly cold days, or when other electric loads in the building are high, such as mornings when the ventilation system turns on. The gas energy used by the CI building models during the whole season modelled (December through March), is reported in Table 5.5, along with the emissions estimated for this usage, which are computed using the province's emission factor for natural gas [91]. Emissions from electricity use which would apply to both the commercial and residential buildings are not a focus here since they are very low in the location of study.

Table 5.5 Average CI building's natural gas energy and its emissions

	Baseline	Reactive	Reactive B	Predictive
Total natural gas energy for the period modelled (MWh)	42.5	50.0	51.9	57.7
Resulting total emissions from natural gas (metric ton CO_2 equivalent)	7.76	9.16	9.53	10.59

Since we have relied on gas heating during the DR events, we must consider the emissions associated, and it is understandable that more emissions will be seen versus the baseline case. However, the flexibility offered through these strategies might be worth the extra emissions and this is a topic that could be further examined. Focusing on the residential cluster in Table 5.4 shows that relative to the baseline scenario, the reactive scenarios result in a decrease of their total day's energy consumption, while the predictive scenario increases it. This was expected as it was also the case in our previous residential flexibility study, though the difference seen here is that the addition of CI buildings equipped with gas heating is able to contribute to bringing the whole cluster's electricity usage down from the baseline scenario, even in predictive cases. To compare the change of energy usage required for each scenario to the peak power reductions obtained, Figure 5.6 and Figure 5.7 are presented. The scatter plots present each building of the cluster categorized by their flexibility strategy. Having all buildings available on these graphs is helpful to identify any outlier buildings, or to potentially filter by other characteristics such as the insulation level for the residential buildings; not done here but can be done as part of a future work.

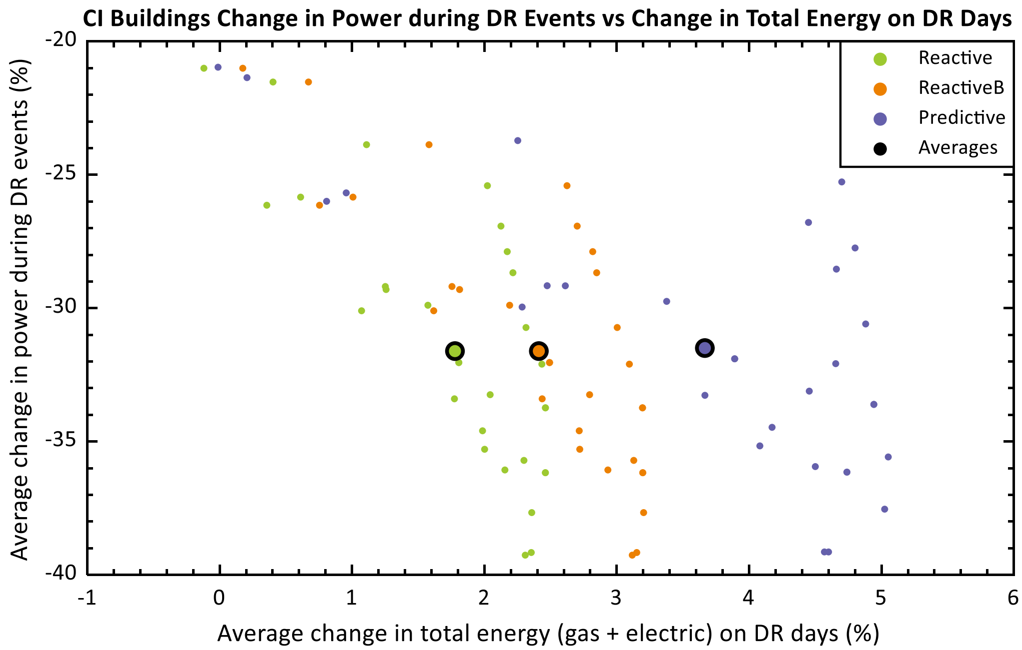

Figure 5.6 CI buildings change in power during DR events vs change in total energy on DR days

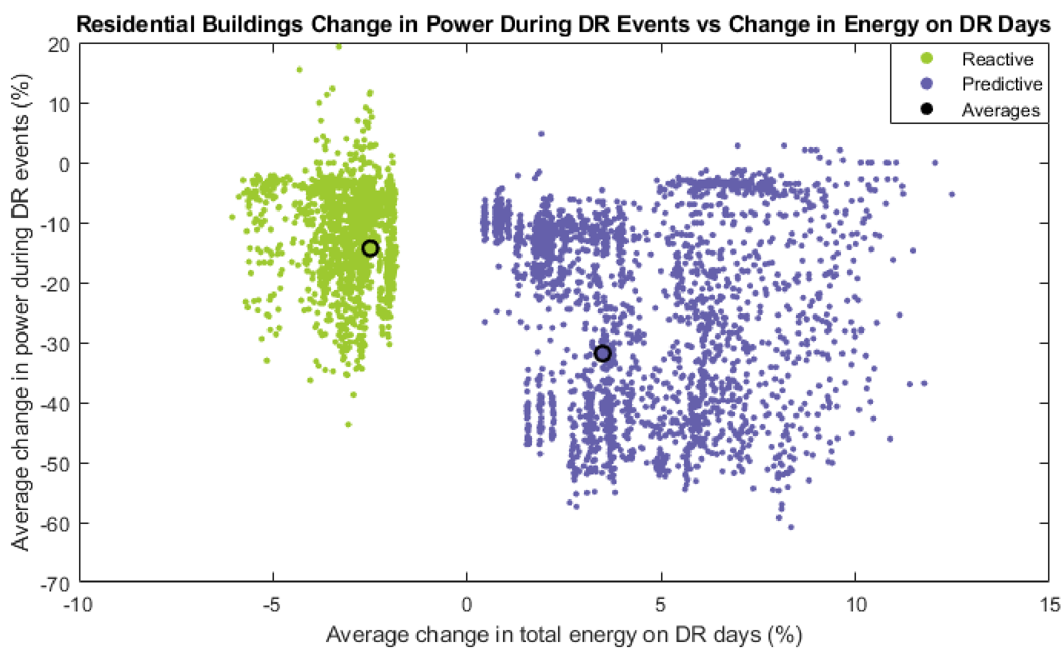

Figure 5.7 Residential buildings change in power during DR events vs change in total energy on DR days

Finally having power and energy results, we were able to calculate costs for each building in the cluster, using the local utility's rate structures Buildings which participate in the electric utility's

DR program have specific electricity rates offered to them, referred to as “flex” rates [42]. These flex rate structures charge energy higher during DR hours (45¢/kWh for residential, and 60¢/kWh for commercial), while discounting energy used outside of DR hours (4.7¢ /kWh up to 40kWh per day, 8.6¢/kWh above it, for residential; and for CI buildings 6.9¢/kWh). These prices apply for the winter season (defined as December through March). Buildings not participating in the DR program remain in their regular pricing structure (6.9¢/kWh up to 40kWh per day, 10.6¢/kWh above it, for residential; and for CI buildings 6.0¢/kWh and a demand change of $17.5/kW for the billing period’s maximum power).The gas price used for the CI buildings in this study is 5.8¢/kWh, an average taken from [92], and no penalty or incentives are made for gas usage since its time of use does not matter for billing. These costs are tabulated in Table 5.6 for the average building, over the whole period of study, and will be discussed further in the next section.

Table 5.6 Average building’s energy cost for the period of study, in Canadian dollars (CAD)

Average Building's Total Winter Electricity Cost				
	Baseline – Regular Rate	Reactive – Flex Rate	Reactive B – Flex Rate	Predictive – Flex Rate
Res - Electric	1,604	1,585	1,585	1,497
CI - Electric	44,631	22,992	22,977	22,927
Average CI Building’s Total Winter Natural Gas Cost				
	Baseline – Regular Rate	Reactive – Regular Rate	Reactive B – Regular Rate	Predictive – Regular Rate
CI - Gas	2,465	2,908	3,025	3,361

We recall that the reactive B and predictive scenarios were designed for the CI buildings to help the cluster avoid rebound and prebound peaks. These scenarios don’t necessarily have a benefit for them individually, as they would spend slightly more in their combined electric and gas energy costs.

5.5 Discussion

Through the energy flexibility strategies tested for the residential and CI buildings, we view several aspects which support the idea that having the different building types in a cluster, specifically different fuel buildings, can provide added flexibility benefits to the grid. Compared to our previous flexibility study, presented at the IBPSA-Canada eSim conference, which explored only residential building and obtained 15-25% power reductions for the average home during DR hours, we have now achieved 24-36% power reductions during DR hours for the aggregated portfolio of 2430 buildings. The greater power reductions were aided through the addition of the CI buildings, which have a different heating option compared to just the residential cluster. The addition of diverse buildings in energy flexibility studies, particularly those with different energy sources, allows for greater flexibility to the cluster and helps move towards strategies where rebound peaks can be avoided, which are evident especially with load shifting. The reactive B and predictive scenarios feature actions for the CI buildings which would not produce any specific benefit for them individually, but provide benefit to the grid. Specifically, the reactive B scenario was created as a way to decrease the peak power after events, since CI buildings had the gas heating source available which can continue being used after events, so as not to contribute to the rebound. This was successful, as the absolute peak did decrease between the reactive and reactive B scenarios, but by a relatively modest amount of roughly 2 MW. Similarly in the predictive case, CI buildings use their gas heating before the event as this was expected to somewhat "absorb" the prebound peak created by the residential buildings which are performing preheating at that same time. This idea was more successful in this case, predictive, as the absolute peak of the whole cluster decreased more than 8 MW from the reactive case and was only 500 kW more than the peak seen in the baseline case, an increase of 3%. The additional time before and after DR hours that CI buildings can continue using gas heating instead of electric were neither considered to have a reward or penalty from the grid, but these strategies were created because they would allow for the whole cluster to reduce rebound or prebound peaks. In real application, utilities or aggregators can coordinate this type of response through incentives for the buildings to avoid contributing to re-/pre-bound peaks if they can, which could help balance out the participating buildings who cannot avoid it. However, utilizing the local natural gas boilers in our modelled CI buildings, does not help with emissions – this is a limitation in this study, as we wanted to investigate existing building stock, but could be avoided with the addition of BESS or renewables where possible. The use of the gas boilers in CI buildings during flexibility scenarios is what we can expect from existing buildings with this type of heating system installed. Their increased emissions during the DR event would be one of the easiest ways to unlock flexibility for their buildings, but the use of the natural gas boilers before and after events must be examined and determined if they are necessary to help avoid the creation of new peaks which we see in the residential portion of our cluster. As well, a balance could be investigated, where we can optimize for limited emissions and still provide flexibility. Instantaneous or marginal emissions related to electricity could also be taken into account to better assess the impact of different strategies.

In the predictive case modelled in this study, residential houses achieved their highest DR event power reductions, and their highest cost savings, in comparison with the reactive strategy. Although beneficial for the individual building, the prebound peaks created from the residential buildings can pose an issue, as it is larger than the baseline peak which was the goal to reduce, as discussed in our previous work. Together the full cluster of residential and CI buildings were able to almost eliminate the prebound peak, though the resulting absolute peak of the average DR day is still 500 kW (+ 3%) above baseline. Further improvement would be seen if a larger proportion of CI buildings were included in the cluster, or a smaller proportion of residential buildings were; participation rates of the buildings were studied in our previous work as presented at the eSim conference, and they did achieve flatter power profiles, though smaller peak power reductions.

With the cost structures used in this study, CI buildings had a very clear incentive to participate in the local utility's DR program if they were able to. The pricing structure offered to them significantly reduced their seasonal electricity cost, and the additional gas usage required for their flexibility strategies is not a major economic deterrent, although it could be an environmental one if building operators are trying to reduce natural gas dependence already. On the other hand, residential buildings did not achieve such high cost savings, mainly due to their limited amount of flexibility offered, as their electric heating was still required during DR hours. This is attributed to the heat loss occurring fairly quickly during reactive strategies and homes must still apply heating at some point during the DR event, to stay within their 20˚C setpoint – especially in the buildings with inferior insulation. In predictive cases, the thermal mass of the building allows that heating would at least take a longer time to kick in, depending on the home's construction level. In the predictive strategy on the residential homes, fewer of the DR hours are spent heating, which adds to the energy that gets the penalized price during those hours. Although the highest cost savings for homes come with the predictive strategy, it requires the preplanning and potentially uncomfortable conditions while preheating.

5.6 Conclusions and future work

This study demonstrates that coordination between residential and commercial/institutional buildings in a cluster can provide complementarity between the building types and allow for better results compared to the individual clusters with just one type of building included. The cluster achieved power reductions of 24-36% during the DR hours, compared to our past results of 15-25% for a residential-only cluster. This provides promising potential, as the buildings use their existing systems without investment into flexibility aiding technology such as storage systems - though these would be beneficial to reduce or eliminate the CI buildings dependency on natural gas, or to improve comfort in residential buildings during DR hours. Future work could assess the relative benefits of peak demand mitigation (including rebounds) and emission reduction, taking into account the natural gas used for heating but also dynamic emission factors for electricity.

The idea that the CI buildings can provide a synergy when combined with residential buildings in a cluster is verified through the limiting of rebounds, but the magnitude of improvement is related to the number of each building type, as well as the load of each building. Outside of DR hours the absolute peaks of the average DR day increase, but not as much as they do in a residential-only cluster, which could produce peaks up to 46% higher than the baseline peak, in this study. The best result of this study in terms of peak reduction during DR events and absolute peak reduction was the predictive case in the whole cluster. Although a prebound peak was still created, it was relatively unchanged from the baseline peak, just 500 kW (3 %) more for the aggregated cluster. Though it could not be fully avoided, it is relatively small, in comparison to our previous flexibility simulation study in a residential only cluster.

Improvements can be made in this simulation study, which can further improve and prepare it for potential field studies. One area for improvement as mentioned is that the study takes only into consideration building types that are representative of existing building stock, though more and more complex building systems are being used today. Incorporating heat pumps, PV, or storage for example, is one potential future work that could better prepare for the newly developing building stock.

CHAPTER 6 SUPPLEMENTARY RESULTS

In this chapter, a few extra results are presented which were investigated after the writing of the papers which were presented in the previous two chapters, Chapter 4 and Chapter 5.

6.1 Further Analysis on Residential Buildings

The diversity of the residential cluster coming from the 3 options for space heating setpoints schedules and the 4 insulation levels modelled are interesting aspects for comparisons. Having this type of diversity in the cluster allows to investigate which strategies would be best suited for certain homes and can be used to make recommendations accordingly. Previously seen in Figure 4.2 and in Figure 5.7 were the residential buildings resulting power and energy, categorized by the flexibility strategy used. In this section, the energy results of the residential buildings used in Chapter 3 are plotted on the basis of their setpoints schedules in Figure 6.1 and their insulation levels in Figure 6.2.

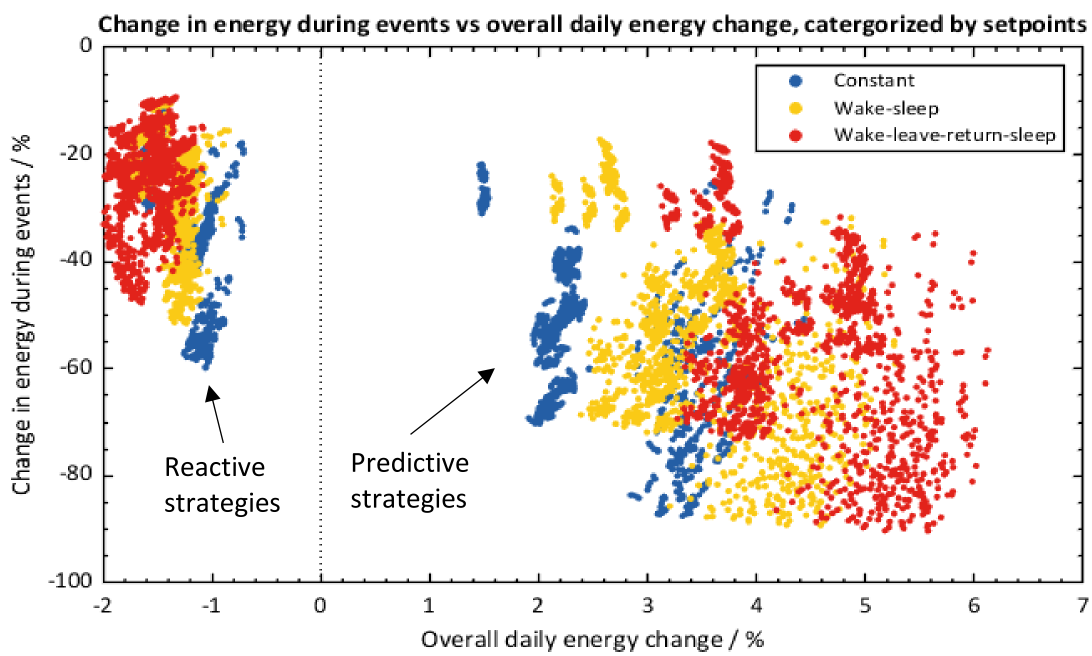

Figure 6.1 Change in energy during events vs overall daily energy change, by setpoints

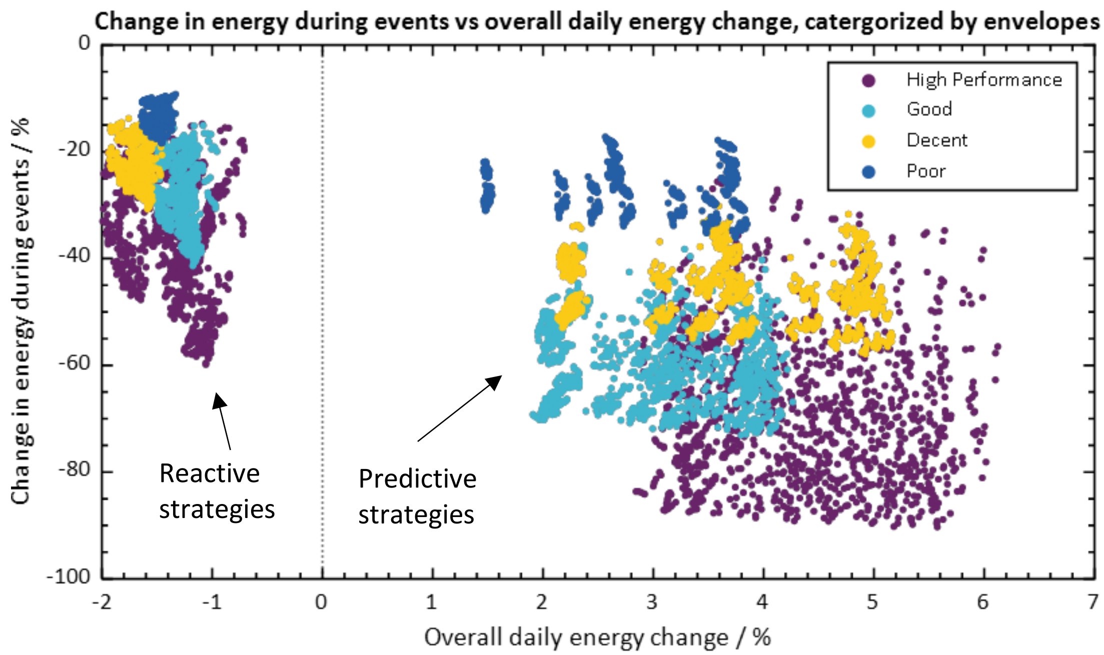

Figure 6.2 Change in energy during events vs overall daily energy change, by insulation level

Recall that for the residential buildings, reactive strategies did not increase daily energy, so the homes using these strategies are on the left side of these graphs, while the predictive strategies, which did increase daily energy, are on the right side of these graphs. In these two graphs, energy was the focus for both axes, because the residential buildings are billed based only on energy, and these figures can help find which strategies could result in lower costs for the individual homes.

In Figure 6.1 we notice the distinct groupings that occur from the setpoint schedules of the homes. For the homes which use a WLRS schedule on a regular basis, it is evident that predictive strategies (red dots on the right side Figure 6.1) of can result in some of the highest daily energy increases on DR days, ranging from around 3-6%. Comparatively, when these homes employ a reactive strategy on DR days (red dots on the left side of Figure 6.1), the energy reductions during events range from around 10-50%, and daily energy reduces between 1-2%. The WS schedule homes show a fairly similar pattern, while the constant schedule homes plateau their daily energy increase around 4% for predictive strategies, and can achieve the greatest reductions in reactive strategies (blue dots on the left side of Figure 6.1) out of the 3 setpoint schedules, up to 60%. When we focus on the highest energy reductions possible during events, the bottom of Figure 6.1 shows that all 3 setpoints strategies can indeed achieve reductions up to 80%, and it is the insulation level graph which should be consulted to give more details regarding this aspect.

From Figure 6.2 it is evident that the homes with high performance insulation resulted in the highest achieved reductions in energy during events, as they are the only insulation category reaching more than 40% in this aspect for reactive strategies, and more than 75% reduction in this aspect for predictive strategies. This graph also shows that the poorly insulated homes only offer a limited amount of flexibility, not quite reaching 20% energy reductions during events for reactive strategies, or 40% energy reductions during events for predictive strategies.

When these two graphs are viewed together, some suggestions can be made regarding best strategies for homes based on their insulation level and regular setpoints. For example, a home with poor insulation and constant setpoints (the collection of blue dots in both graphs found at x = 1.5, and y between 20-30), predictive strategies might be the best option for them individually. This would only cause about a 1.5% energy increase for a DR day, likely not noticeable in billing, but 20-30% energy reduction during events. Throughout most of the result reporting, percentages have been used to show energy and cost savings, among other KPIs. It is important to recall that for poorly insulated homes, these percentage savings values would result in quite high absolute amounts, since these buildings are already using more energy for heating, in comparison to the other insulation levels. For a home with high performance insulation, high levels of flexibility are achieved with either reactive or predictive strategies, so the choice could be up to preference for occupants. However, a WLRS setpoint home of this insulation level might not achieve such high cost savings with predictive strategies, because their usual operation is already quite cost effective in comparison to pre-heating their home. Having this type of information could be helpful for aggregators to know in advance how certain homes might respond during demand response events, which helps with ideal cluster formations. This will be further discussed in Chapter 7.

6.2 Further Analysis on CI Buildings

For the CI buildings modelled the diversity between them came from the building systems, through the modifications to the boiler sizes, plug load densities, peak power limits. These aspects were targeted as opposed to setpoint schedules and insulation as was already explored in the residential cluster. Having these modifications, one aspect to investigate was the CI buildings' change in total energy on DR days versus their ratio of gas to electric boiler size, which is shown in Figure 6.3.

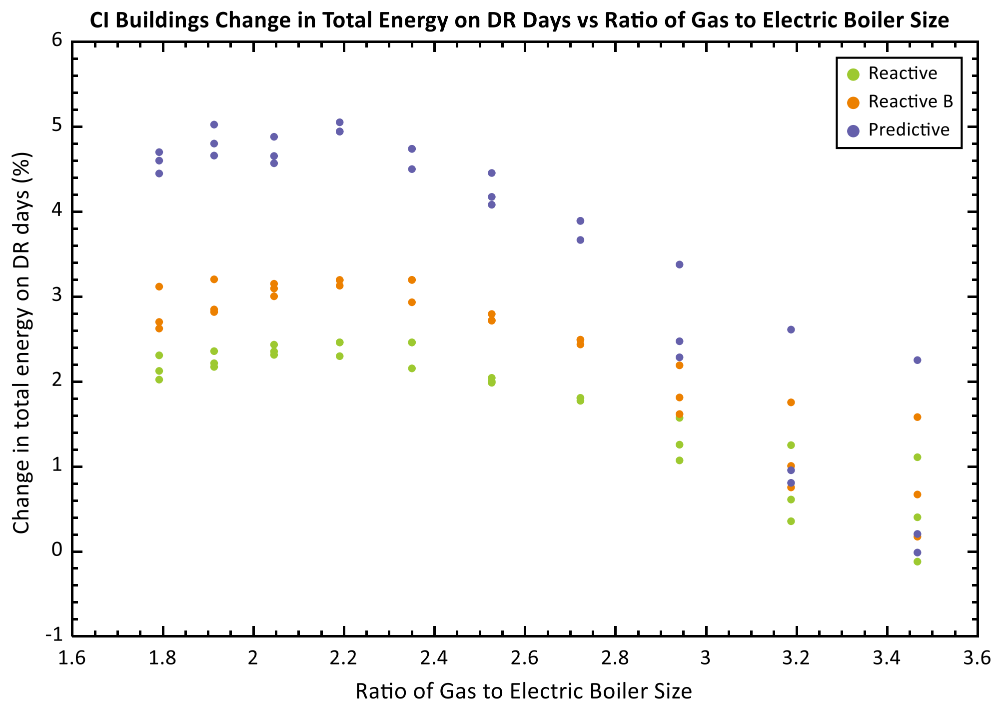

Figure 6.3 CI buildings change in total energy on DR days vs ratio of to electric boiler size

It is recalled that all CI buildings had the same total heating capacity but distributed between gas and electric boilers differently as described in Chapter 5. In Figure 6.3, a general downward curve is seen, indicating the CI buildings with larger gas capacities had a smaller change in their used energy on DR days through the strategies tested. This is explained through the fact that the buildings with larger gas boiler capacities were likely already using this equipment more often to meet the necessary heating demand of the building.

A comparable relationship can be deducted from graphing the CI buildings' change in total energy on DR days vs their building peak limit, shown in Figure 6.4. It is recalled that the building peak limit is a power demand value which the building is modelled to not exceed, as it allows for the same demand charge for each billing period through the electricity tariff used, Hydro-Québec rate M. In Figure 6.4, the increasing curve shape is indicating that buildings with a higher peak demand limit have increased their energy consumption on DR days more than those with lower peak limits implemented. Considering that the peak limit is indirectly acting as a secondary limit to the electric boiler, aside from its physical capacity, we can deduce that the buildings with low peak limits were already using their gas boiler more often than the buildings with higher peak limits. The buildings with low peak limits, seen to the bottom left of Figure 6.4, could be close to reaching their peak limits even at low electric boiler charge, due to the other electrical demands in the building. Through this deduction, it is also estimated that the buildings with lower peak limits might not be able to provide flexibility as much as those with higher peak limits through the fuel-switching strategy tested in this project. Having the knowledge of the building systems and their usual operation allows these types of estimations in advance of DR events, which can help aggregators coordinate the best strategy to achieve the required demand reduction.

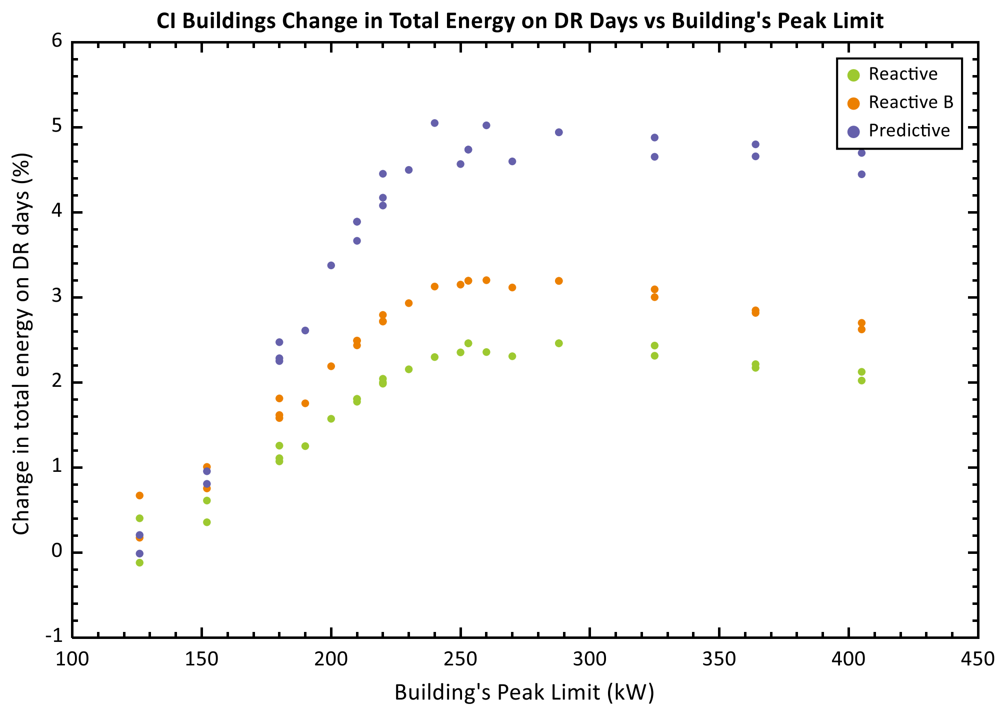

Figure 6.4 CI buildings change in total energy on DR days vs building's peak limit

CHAPTER 7 GENERAL DISCUSSION

Throughout this thesis, flexibility strategies for clusters of residential and CI buildings were created and analysed on the cluster level as well as the individual building level. The portfolio of buildings used was created with the existing building stock in mind: the CI buildings modelled were based on an existing building, and the residential buildings were modelled with varying insulation levels representative of different vintages. Keeping in line with the existing building stock, the flexibility strategies tested in this study were also created to reflect what can be done in common Quebec buildings during demand response events. The residential buildings adjusted electrically driven space and water heating, while CI buildings used fuel-switching in their commonly seen hybrid gas-electric heating systems. In several of the flexibility studies consulted throughout the literature review, buildings were modelled with added flexibility aiding technology such as PV, storage, or used advanced controls to achieve high peak reductions. Throughout this thesis, simple, rule-based control for buildings representing the existing building stock was simulated to achieve peak reductions as high as 36% during DR events. These results demonstrate that existing buildings can play a significant role in flexibility events, through fairly simple energy management.

While the strategies used in this study achieved power reductions during DR hours, rebound and prebound peaks were seen outside of the DR hours. In Chapter 4, where flexibility strategies were tested in an all-electric residential building cluster, the optimal method found to reduce the rebound and prebound peaks was to adjust the participation of the cluster. Certainly in real applications, participation into a DR event already represents only a percentage of users on a grid, and thus the rebound peaks seen in this simulation study would likely not be problematic to the electric utility. Nonetheless, adjusting the participation within the Chapter 4 article did result in a more constant load profile, while still obtaining power reductions during DR hours, though in more modest amounts than when participation was at 100%.

It should be noted that the flexibility strategies involving domestic hot water tanks can result in favorable conditions for legionella, which can be associated with respiratory diseases. In Quebec, the *Institut National de Santé Publique* has recommended against interrupting power supply to domestic hot water tanks until the risk of legionella can be addressed by the industry, and to the author’s knowledge, Hydro-Québec does not recommend or offer technical solutions to implement that DR measure [93]. The strategies involving DHW in this thesis must therefore be considered as a theoretical assessment of a potential that will only be achievable once the associated health risks will have been fully addressed.

In Chapter 5, the addition of CI buildings, which used hybrid gas-electric heating systems, brought about a new possibility to mitigate the rebound and prebound peaks seen from the residential cluster. In this case, the CI buildings were controlled to switch to gas heating during DR events, as well as before and after the event in the reactive B and predictive strategies. In the predictive strategy, the CI buildings' use of gas heating during the residential buildings' preheating allowed for the most successful peak shifting away from the DR hours, with only a moderate increase in the absolute peak of the day, +3%. When we consider a peak shifting strategy like this occurring in real world application, we recall again that the participation level in the DR program would already account for only a percentage of buildings served by a grid, and thus the moderate increase in absolute peak, 0.9 MW within the cluster tested, could be considered as acceptable.

Although varying participation levels were considered in the first article presented in this thesis, it would have been interesting to explore participation levels in the CI sector as well. This was decided against since the number of CI buildings used in this study was already quite limited, to stay within the desired ratio of residential to CI floor space. Although the study could theoretically have been proportionally scaled up to investigate participation on the CI side, the extra computational time was a limitation. Another limitation in this study surrounding the CI buildings is that only one type of envelope and one type of activity were considered for all the 30 buildings modelled. Since the envelope data for this building model came from the information of the real building, it was not as straightforward to categorize and apply different levels, as was done for the residential buildings. Additional types of CI buildings within the cluster, such as retail space or schools, for example, would have further increased variability.

The reactive B and predictive scenarios used in Chapter 5 for the CI buildings were created specifically to help mitigate the rebound and prebound peaks seen to occur from the residential buildings – the CI buildings do not incur any additional benefits from these approaches. For energy aggregators, this could be an interesting aspect to explore, if rebound or prebound peaks get to problematic levels before or after DR events. Specifically, how building operators can be further encouraged or incentivized to perform actions that do not necessarily benefit their building, but benefit the grid, is an interesting topic for future exploration. This will likely grow in importance as more flexibility programs emerge and gain more participants.

Overall, the studies undertaken in this thesis have further investigated aspects of flexibility in clusters which contribute to the growing research in the field. The gaps previously noticed in other literature were explored throughout this research, such as by having variability in the building stock, and reflecting currently used common building systems. The results presented points towards a high potential for the existing building stock in Quebec, in the residential, commercial or institutional sectors, to provide flexibility to the grid.

CHAPTER 8 CONCLUSION AND RECOMMENDATIONS

Throughout the analysis completed in this thesis, it has been demonstrated that clusters of buildings, representing some of the existing building stock in Quebec, can provide high amounts of flexibility to the grid without complex measures. The strategies used throughout this thesis to unlock building flexibility took advantage of available thermal mass, or fuel switching in the buildings where it was possible.

In the first portion of the study, a cluster of 2400 residential buildings of varying characteristics were able to achieve average power reductions during demand response (DR) events of 15 % with reactive strategies, and 22 % with predictive strategies. These strategies employed simple adjustments to the usual heating setpoints of the homes during DR events, and in the case of predictive strategies, before DR events in addition to during. For this cluster of residential buildings, additional flexibility was achieved when the setpoints of the water heater were also adjusted. As indicated in the previous chapter, this is currently not recommended in Quebec due to legionella concerns, but this option was considered in our simulations to provide a more complete assessment of the flexibility potential. During this study, large rebound or prebound peaks were created outside of the DR hours. Depending on the grid's demand outside of DR hours, these consequential peaks created might not be problematic, but methods to reduce them were investigated, nonetheless. Given the characteristics of this first study, the method used to reduce rebound and prebound peaks was to adjust the cluster's participation rates into the DR events. In real application, this could be a valid recommendation for aggregators who manage DR programs, if peak shifting causes new critical peak events outside of the initial DR hours. Through adjusting participation rates, average reductions during DR hours were more modest, but load factor improved, a benefit for the grid. Additional recommendations for the residential buildings were investigated in Chapter 6. Among these recommendations, it is suggested that for poorly insulated homes with constant setpoints, predictive strategies could be best suited, while for well insulated homes with constant setpoints, reactive strategies could be better suited.

To further advance the flexibility study, adding more variety to the cluster was a goal, through different building types and the HVAC systems available in them. To investigate this, a model was created based on a real commercial-institutional (CI) building in Quebec, which has heating provided by gas and electric boilers. This model then had modifications applied to create 30 CI building variants, and this cluster of CI buildings had energy flexibility strategies applied to it. Having the two energy sources for heating allowed for fuel switching to be the main source of flexibility in these CI buildings. The cluster of CI buildings was able to achieve an aggregated peak reduction of 23 % by fuel switching during DR events. Through this result, fuel switching is shown to be a good recommendation for buildings which have a secondary heating fuel available, to reduce power demands during critical periods such as the DR events tested in this thesis. Although greenhouse gas (GHG) emissions would increase during those hours, it might still be a low-carbon option compared to the grid's emissions during DR hours if fossil fuel generation plants are needed. This is recommended for future investigation in flexibility research involving fuel switching as one of its strategies.

Given that fuel-switching did not create rebound peaks, the intention was to combine the CI cluster with the residential cluster, creating a mixed cluster of 2430 buildings, making it possible to investigate possible synergy between the buildings. For this final cluster, aggregated peaks were reduced by up to 36 % with the new predictive strategy, in which the CI buildings would use gas heating before DR hours, in addition to during the DR hours and slightly after. The use of gas heating directly before and after the DR event was done to help balance out the rebounds created by the residential buildings. It was successful, as this strategy had the lowest absolute peak increase on the DR days, just 3%, reflecting a new total electric peak of 31 MW, occurring outside of the DR hours, while the original peak of 30.1 MW occurred during the grid's DR hours.

In summary, this type of flexibility analysis which uses varying buildings and fuel sources, presents many findings that could be important to electric utilities or aggregators, who can best coordinate the cluster of buildings. Having this knowledge of how the different building types would respond during DR events is highly useful for coordination, as it can help in aspects such as: creating clusters, improving comfort for participants by recommending appropriate strategies, avoiding the creation of new peaks, and even reduction in GHG emissions for buildings who employ fuel switching. Throughout this thesis, the analysis of flexibility in clusters of buildings has demonstrated that high potential for flexibility exists across much of the existing building stock in Quebec, and it can be unlocked without major complexities.

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