Building Demand Response and the Electric Grid: Development and Application of an Operational Cross-Sectoral Model of Building-Side Electrification and Supply-Side Renewable Energy Integration

by

Lauren Stanislaw

Bachelor of Arts in Mathematics, Scripps College, 2018

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF APPLIED SCIENCE

in the Department of Civil Engineering

We acknowledge and respect the lək̓ʷəŋən peoples on whose traditional territory the University of Victoria stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.

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Abstract

Towards the goal of a decarbonized future, electrification of building heating systems provides both a challenge and an opportunity. Meeting additional electricity demand without increasing the associated emissions requires additional renewable capacity, but sources such as wind and solar are weather-reliant and unpredictable, making it difficult to ensure that sufficient generation is available at every instant. However, through *demand response,* during which buildings are subject to utility control through technology such as smart meters, building thermal mass can be used as a form of energy storage, and building demand curves can be influenced to better match the timing of variable renewable generation. In this thesis, the tension between these two aspects of building electrification is explored through the development of a novel linked model framework in which operational building and electricity system models transfer information back and forth during model setup and parameter specification steps, allowing exploration of how building system electrification impacts electricity system variable renewable expansion, and vice versa. Demand response is represented through two iterations of model development, first by changing building temperatures based on the presence of renewable curtailment (excess generation), and then by quantifying the amount of energy able to be stored in the building system during demand response events, ultimately allowing building demand response to be scheduled within the electricity system model at times that are optimal for the electric grid. This methodology is an important contribution to the literature because of its ability to represent both the supply (electric grid) and demand (building stock) sectors in operational detail, in contrast to many existing models which tend to focus only on a single sector. As well, this thesis' case studies into residential demand response are particularly insightful given the lack of residential demand response policies in Canada today. Important results of this work indicate that increased efficiency of envelopes and heating systems can effectively limit electricity demand increases associated with increased penetration of electric heating technology, and that building demand response can effectively help cities reach their decarbonization goals.

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List of Publications

This manuscript is based on the following published and submitted papers. The 2021 paper by Seatle et al. forms a basis for this manuscript's Chapter 2, and the 2023 paper by Stanislaw et al. is reprinted in full as Chapter 4 of this manuscript.

Seatle, M., **Stanislaw, L.,** Xu, R. and McPherson, M., 2021. "Integrated transportation, building, and electricity system models to explore decarbonization pathways in Regina, Saskatchewan." *Frontiers in Sustainable Cities*, p.113.

> M.S., R.X., and L.S. all contributed equally to model development and writing the manuscript; in particular, L.S. conducted the building modelling. M.S. performed the primary analysis. M.M. supervised and edited the manuscript.

McPherson, M., Seatle, M., Xu, R., **Stanislaw, L.**, and Knittel, T. 2022. "Enabling broader decarbonization through Energy Systems Integration." *Canadian Institute for Climate Choices*.

> M.M. wrote the document. All other authors contributed charts reviewing specific policies; specifically, L.S. collaborated with M.S. to provide the charts regarding heat pumps, distributed generation, and demand response.

McPherson, M., Rhodes, E., **Stanislaw, L**., Arjmand, R., Saffari, M., Xu, R., Hoicka, C. and Esfahlani, M., 2023. "Modeling the transition to a zero emission energy system: A cross-sectoral review of building, transportation, and electricity system models in Canada." *Energy Reports*, 9, pp.4380-4400.

> M.M. and K.R. conducted the initial survey, with M.M. writing the initial draft. L.S. compiled the charts and wrote each model-specific section with contributions from R.A., M.S., and R.X. The introduction, methods, discussion, and conclusion were written by M.M. and E.R. Valuable feedback was provided by C.H. and M.E.

Stanislaw, L., Seatle, M. and Mcpherson, M., 2023. "Building-to-Grid Model Linkage to Investigate Demand Response Strategies in Residential Buildings." *Applied Energy*. Manuscript submitted for publication.

> L.S. conceptualized the project, performed the analysis and validation, wrote the manuscript, and implemented all aspects of the building model. M.S. implemented and ran the electricity system model. M.M. supervised and edited the manuscript.

Acknowledgements

Completing this thesis has been a massive undertaking, and I am very grateful for all the people who have helped me along the way.

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I am also indebted to my family, especially my grandparents, my parents, and my other parents the Dhamis, for their constant support of my goals and for helping me to value hard work and the pursuit of knowledge. Thank you also to Jonathon's parents for giving me a place to live during the pandemic, and of course thank you to Jonathon for providing me with the best study breaks (and the best food) that anyone could ever ask for. I am very grateful to have all these wonderful people in my life.

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Chapter 1: Introduction

Building heating systems are responsible for a significant amount of energy use. Globally, half of all energy use goes towards heating of all types (including industrial and agricultural uses) [1], and almost half of all building energy use is for heating [2]. In Canada specifically, relatively large building sizes and the cold climate mean that heating is both crucial, and energy-intensive. Almost 1000 PJ of energy were used for residential home heating in Canada in 2019 [3], and over half of this was natural gas and oil [4], representing a large target for carbon reduction efforts.

Thanks to extensive hydropower, the Canadian energy grid is relatively low carbon [5]. However, building system decarbonization would represent a large increase in electric demand and require an expansion of variable renewable energy (VRE) capacity in the form of wind and solar. Because these resources are weather-dependent, increased reliance on VRE is a challenge for modern electric grids, which usually have limited storage resources and rely on energy being generated at the same moment that it is needed.

Fortunately, electrified building loads also provide an opportunity to electric grids in the form of flexibility. For example, smart control of building loads can schedule system operation to occur at times when demand is low or renewable generation is high, allowing buildings to maximize their use of clean energy [6]. Buildings' thermal mass could also be used for energy storage, for instance by preheating buildings when renewable generation is high, allowing less energy to be used later, when renewable generation may be lower [7,8]. For strategies such as this to be successful, both the building load and the electric generation schedule must be considered. This makes it important to coordinate building system decarbonization with electric grid decarbonization.

In Canada today, the transition towards decarbonized buildings is guided by two distinct policy goals: energy efficiency, which focuses on improving building envelopes and appliances, and demand response, in which various schemes are used to increase or decrease energy use at crucial times. Policies that encourage energy efficiency most often feature financial incentives for residential property owners to voluntarily upgrade their appliances and increase the heat retention properties of their walls, windows, and roofs. In contrast, demand response policies are often targeted at industrial and commercial consumers, who sign contracts which allocate a certain amount of their energy use to be available for utility control. A review of these policies can be seen in Tables A1-A5 in the Appendix.

To maximize the impact of these policies, potential next steps should focus on increasing participation levels and expanding demand response programs to include residential buildings. Past Canadian attempts to decrease carbon emissions via voluntary policies often failed, in part because policies were not adopted at a high enough rate to cause widespread change [9]. However, many studies highlight the importance of building electrification, efficiency increases, and flexibility through demand response as important foci for decarbonization efforts [10–16].

To help motivate and plan for such a policy expansion, models can be used to represent the building system in operational detail. Engineering models calculate detailed estimates of thermodynamic energy use based on building properties [17,18]. These calculations are often based on simulation engines developed specifically for this purpose, such as TRNSYS, EnergyPlus, or HOT2000. To model large numbers of buildings, these models typically rely on archetypal characterization, in which a group of buildings is sorted into representative categories, and each is modelled [19,20].

In Canada, several such models exist and are well-equipped to explore building energy use as a function of the physical characteristics of buildings and the actions of building occupants. For example, the Canadian Hybrid Residential End-Use Model (CHREM) uses detailed home assessment data to represent existing residential buildings and explore a number of retrofit strategies to improve the technology used therein [21–27]. Similarly, the Spatial Community Energy Carbon and Cost Characterization ($SCEC^3$) model is used to explore several future growth and building occupancy scenarios in the city of Prince George, British Columbia [28,29], while a number of works by Hachem et al. assess the effects of different building orientations and shapes on solar generation potential for a community [30–32]. However, the body of work regarding these building models is very sector-specific, focusing only on building-side issues with no tie-ins to how building-level changes and increased electrification might affect electric grid operation [33].

On the supply side, models of the electricity system are similarly well-developed in Canada, yet also fail to represent demand-side concerns (such as demand response or changes in building and appliance characteristics) in sufficient detail [33]. The primary type of operational-level electricity system model is the production cost model, which represents an electric grid's ability to meet demand, typically by employing linear or mixed-integer linear programming to optimize the generation and transmission assets of an electricity grid [34] according to complicated market dynamics that take fluctuating prices, demand, and availability into account [35,36]. Some examples of production cost models in Canada include the Hydro-Electric Resource Management Evaluation System (HERMES), which determines the daily operation of the Manitoba Hydro power system [37–39]; the Strategic Integration of Large-Capacity Variable Energy Resources (SILVER), a provincial-scale academic model focused on the effects of increased variable renewable penetration in an electric grid [40,41]; and several papers which explore the operation of isolated microgrids in the far north and the effects of storage systems and transitional fuels (such as diesel) on these grids [42–45]. Although these electricity system models can answer a variety of questions regarding grid operation, they do not represent demand in great enough detail to explore the impacts of building-level system changes.

To better explore the interactions between building efficiency, variable renewable expansion in electric grids, and building demand response, it is therefore necessary to build an integrated "multi-model," which can be built on existing model frameworks but can also represent both supply and demand in sufficient detail. Constructing and using such a model is the objective of this thesis, and is achieved via two major phases of development. In the first phase, a building model is developed and validated, and a rough version of demand response is performed by adjusting building temperature setpoints based on curtailment, or the availability of excess renewable generation. In the second phase, a higher-resolution version of demand response is enacted by quantifying demand response availability within the building model and then using the quantified values as constraints within an electricity system model. This transfer of information allows building demand response events to be scheduled directly within the electricity system model, as if building demand response was a generator or storage reservoir attached directly to the grid. These two phases of development are comprised of the following milestones:

Phase 1: Model development, validation, and curtailment-based demand response.

a. *Create a city-scale building model.* The city of Regina, Saskatchewan is notable for its high solar and wind potential, and because the city has committed to being fully powered by renewable energy use by 2050 [46]. To facilitate this goal, a detailed model of residential building energy use in Regina is constructed based on census data.

b. *Use building model outputs to inform electricity system model inputs.* To understand the impacts of building envelope upgrades and heating and cooling system electrification on the grid, the demand curve produced by the building model is passed to a city-scale electricity system model, where it is used as part of the city's demand. For this thesis, we use the SILVER electricity system model, a version of which was built for the city of Regina in [46].

c. *Perform a case study incorporating curtailment-based demand response and increased building efficiency.* Possible building-side contributions towards Regina's renewable goals are investigated according to two variables: first, increased building efficiency is modelled by retrofitting building envelopes to the highest tier of the BC Step Code and replacing natural gas-powered heating and cooling systems with highly-efficient ground source heat pumps. Secondly, demand response is enacted by increasing building heating and cooling setpoints when variable renewable energy is being curtailed, and relaxing setpoints at all other times. Results show that energy use is able to be shifted towards times with high variable renewable generation, and that increasing envelope and device efficiency limits the demand increases associated with a higher penetration of electric heating and cooling systems.

d. *Validate the model.* To ensure that our model framework works as intended and is accurately representative of reality, a number of validation checks are performed. These include comparing the model to measured data, performing sensitivity analyses to determine the effects of the independent variables, examining the results to determine that the constraints linking the building and electricity systems are working as intended, and comparing our model to the literature both generally and in specific cases that are similar to the case studies we conducted. Overall, we found our model to match sufficiently to both measured data and the literature, and to be working as expected in all the reviewed cases.

Phase 2: Improved demand response scheduling via direct integration with an electricity system model.

a. *Quantify yearly demand response availability.* Energy availability for demand response events throughout the year is quantified by simulating demand response events under various weather conditions and then mapping the weather conditions to each hour of a typical year. Following this, a validation of our approximation is performed by comparing a high-resolution model of demand response with our approximation-based estimate.

b. *Use yearly demand response availability as a series of constraints within an electricity system model.* To model demand response events which shift realistic amounts of energy based on the building model, we use the demand response availabilities from the previous step as constraints on energy shifting within an electricity system model which is responsible for scheduling DR events. Additional constraints on the the frequency, duration, and amount of energy able to be shifted by demand response events are also incorporated, based on the framework presented in [47]. For our electricity system model,we again use the SILVER electricity system model that was developed in [46].

c. *Perform a case study exploring the effects of different demand response event magnitudes (degree change and event frequency) in two versions (present day and highly efficient) of the city of Regina.* To understand the value of demand response and how this value might change as buildings and appliances increase in efficiency, we simulate a series of demand response events in both present-day Regina (based on census data) and a highly efficient version of the city in which building envelopes are retrofit to the highest tier of the BC Step Code and natural gas-powered furnaces are replaced with ground source heat pumps. We show that demand response events that shift large amounts of energy at once are the most effective in terms of cost and emission savings because these events are more effective at enabling fossil fuel powered generators to turn off. We also show that increased efficiency has mixed effects on building performance because more-efficient buildings can maintain comfortable temperatures for longer, but are less able to be passively warmed or cooled by favorable outdoor conditions.

These milestones are novel and significant in terms of both their methodologies and the scenarios explored. On the methodological side, this work’s focus on cross-sectoral and integrated modeling schemes goes above and beyond many existing models which tend to look only at electricity supply OR electricity demand. Additionally, the model linkage framework developed in this thesis is a novel formulation whose incorporation of operational detail allows precise investigation of supply-demand interactions. Within the scenario space, the case studies explored herein illuminate new pathways towards decarbonization via electrification of city operations, expansion of VRE resources, and an understanding of how building stock characteristics and demand response event definitions can impact costs and emissions. Overall, through its cross-model linkage and its detailed exploration of different building-side scenarios, this work represents an important contribution to the small field of integrated energy models.

The rest of this thesis is organized as follows. In Chapter 2, the model’s early development and the achievement of milestones 1a through 1c is discussed. This chapter is based on a paper by Seatle et al. [46], but is condensed to focus specifically on the building model. Next, Chapter 3 details the model’s validation (milestone 1d). Following this, the three milestones which comprise Phase 2 are discussed in detail within the submitted manuscript which constitutes Chapter 4 of this thesis. Major conclusions are presented in Chapter 5, which focus on this thesis’ limitations, avenues for future research, and the significance of the model and its results.

Chapter 2: Model Development

Overview

In this chapter, the early development of the building model and its linkage to an electricity system model via a curtailment signal is discussed. Following this, a case study is performed regarding the effects of building envelope and appliance retrofits as well as curtailment-based demand response via building setpoint changes. Our results show that increased appliance and envelope efficiency can limit the electric demand increases associated with increased electrification of heating and cooling systems. We also show that the curtailment signal successfully achieves its intended effect of shifting some building energy use towards times with high variable renewable energy availability. However, our curtailment-based demand response scheme restricts heating and cooling setpoints at all times of the year, and therefore may be impractical or unpopular to implement, which motivates further study regarding demand response.

Introduction

The city of Regina, SK represents a unique opportunity for decarbonization efforts. On the one hand, current emissions in Regina are relatively high. Much of Saskatchewan's electricity is generated by burning coal [48], making Saskatchewan's grid one of the highest-emitting in Canada [49]. Additionally, despite its very cold climate, only about 10% of buildings in Saskatchewan use electricity as their primary heating fuel, while the rest rely on natural gas and other fossil fuels [50]. However, Regina is also ideally poised to do something about its emissions: the city has exceptionally high wind and solar generation potential [48], and recently made a commitment to be powered by 100% renewable energy by 2050 [51].

Because of these factors, electrification of building heating and cooling systems in Regina combined with expansion of variable renewable energy (VRE) capacity represents a promising potential avenue for emissions reductions. To explore what this might look like, a model of the residential building stock of Regina is first constructed based on current census data, and then modified to simulate increases in envelope efficiency and the installment of highly efficient and electric-powered heating and cooling systems. Building model outputs are then used as one component of the total demand in an electricity system model. Finally, variable renewable expansion is somewhat at odds with traditional electric grids, which generally do not have storage and instead change electricity generation in real time to align with demand [52]. To help understand whether increasing the demand flexibility of buildings can compensate for the reduced grid flexibility associated with renewable generation, demand response (DR) is simulated within the model linkage by adjusting building temperature setpoints based on the presence or absence of renewable curtailment.

Methods

Building Model

Building energy use is composed of two primary components: thermodynamic demands, which result from heat exchange between a building and its environment; and appliance, lighting, and other plug loads, which are determined by the activities of building occupants [33]. To represent thermodynamic demands, an engineering model can be used to calculate the work required for the cooling and heating systems of an individual building to maintain a reasonable interior temperature [18]. Large numbers of buildings can be represented via archetype-based modeling, in which a number of representative homes are modelled via engineering model, and the result is then scaled up by the number of homes represented by each archetype [20]. Following this, a complete load curve can be calculated by adding data-based appliance, lighting, and plug loads to the thermodynamic load [17].

This approach was used to construct a city-scale building model representing present-day Regina. First, census data [53] regarding the house vintage and type (i.e. freestanding, apartment, etc.) was used to compose a set of six archetypes for the city (Table 2-1). For each archetype, additional details regarding the insulation of roofs, walls, windows, and floors were assumed based on building vintage according to a number of formulas proposed by Tooke et al. [54]. A thermodynamic load curve representing the city's energy use for heating and cooling was produced by modeling the six archetypes in EnergyPlus, a commercial software that calculates building heat exchange [55,56]. Of note, the details for each building's heating and cooling system were taken from a template within the simulation software [57]. Then, the total city-wide building electricity load was calculated by adding the thermodynamic load to an appliance, lighting, and plug load curve taken from a simulated Canadian dataset published by Armstrong et al. [58]. Since only 10% of homes have electric heating and cooling, only 10% of the city-wide thermodynamic load was used in the calculation. Finally, the model was validated by comparison to measured data. Model validation will be discussed in more detail in Chapter 3 of this thesis.

Table 2-1: Defining parameters of the six building archetypes used to represent present-day Regina.

Archetype	Floor Area (m)	Height (m)	Special Wall Features	Heating System	Envelope Properties	Number of Residences of Type
1960 House	9 x 12.2	3	None	Electric forced-air furnace based on EnergyPlus template [57]	Roof, wall, and window U-values, window solar heat gain coefficient, window-to-wall ratio, and infiltration rate calculated based on vintage according to formula from Tooke et al. [54]	18,212
1975 House	10 x 12.5					38,481
1987 House	10 x 13					10,917
2014 House	10.5 x 14					5,991
1960 Apartment	9 x 11.5		2 walls adiabatic			6,845
1975 Apartment	10 x 12					6,938

Linkage with Electricity System Model

SILVER, a provincial-scale and open-source electricity system model, was adapted in this study to represent the city of Regina. SILVER is a unit commitment model, which means that it solves for the least cost dispatch of the grid's generation assets in order to meet a given electric demand curve. More information about SILVER can be found in [40,41], while more details on its modification for this study can be found in [46]. To model variable renewable generation, a rooftop solar capacity of 705 MW, or 50% of available rooftop capacity, was added in addition to the existing resources on Regina's grid. From this capacity, actual solar generation was calculated using a procedure derived from [59,60] and data from a number of sources including weather conditions and rooftop shapes and orientations [61–63].

The electricity system model was linked with the building model through two distinct transfers of information. First, the building electricity demand curve which is output from the building model was used as one component of the total demand served by the electricity system model. Second, a curtailment signal was used to apply a DR scheme of changing the building demand based on solar output. To accomplish the latter, the temperature setpoints of the modelled buildings were changed in response to the presence or absence of excess solar generation. Before the application of DR, all modelled buildings were set to 19°C for heating and 27°C for cooling, which is in line with ASHRAE comfort recommendations [64]. Under DR, a top-down control scheme was used, wherein building setpoints were changed as if by direct control by an electric utility company. Specifically, both setpoints were made more extreme when solar energy was being curtailed, resulting in a heating setpoint of 21°C, a cooling setpoint of 26°C, and more total energy use during those times. However, the heating and cooling setpoints were relaxed to 18°C and 28°C respectively during all other times. All buildings contributing to thermodynamic electricity demand were assumed to participate simultaneously in demand response.

Case Study

After the construction of the present-day building model, two levels of increased efficiency and increased electrification were simulated. In the *100% upgraded* scenario, all buildings received envelope retrofits to the highest tier of the BC Step Code, which was the most stringent progressive building code existing in Canada in 2020 [65]. As well, all buildings also had their existing heating and cooling systems replaced with a highly efficient ground source heat pump based on a template from the EnergyPlus software [57]. In the *50% upgraded* scenario, each building received exactly one upgrade: the older half of all homes received the insulation retrofit, while the younger half of all homes received the ground source heat pump. In this scenario, it is assumed that buildings which already had electric heating and cooling are outfitted with the higher-efficiency ground source heat pump.

Results

Three major conclusions can be drawn from the case study. First, increasing building efficiency limits the electric demand increases associated with a higher penetration of electric heating and cooling systems. Second, demand response results in a slight reduction of total energy use due to the overall setpoint reduction used in our DR scheme. Third, the modeled DR scheme enables almost all curtailed VRE generation to be used towards building heating and cooling. These results are discussed in greater detail in the following paragraphs.

Increasing the penetration of electric heating and cooling systems does increase the total electric demand of the building sector. However, combining heating system electrification with envelope retrofits and the installment of high-efficiency ground source heat pumps results in a load increase that is far smaller than might be expected from the percentage increase of buildings contributing to the electric load (Figure 2-1). Between the current building stock and the 50% upgraded building stock, the penetration of electric heating and cooling systems increases by 400%, but electricity use only increases by 31%. The dramatic difference between these two percentage increases is due to the combined effect of envelope AND heating/cooling system efficiency improvements: in addition to the envelope upgrades, the 50% scenario replaces both fossil-fuel AND older electric heating and cooling systems with higher-efficiency systems, resulting in huge energy savings per building served. Between the 50% and the 100% upgraded building stocks, heating and cooling system upgrades merely represent an increased number of buildings served, since the buildings with electric heating and cooling systems in the 50% scenario are already outfitted with the highly efficient ground source heat pumps. However, the envelope upgrades between the 50% and 100% scenarios still result in a significant amount of energy savings per building: despite a 100% increase in electric heating/cooling system penetration, only a 33% increase in building electricity demand is observed between the 50% and 100% upgraded building stocks (Figure 2-1).

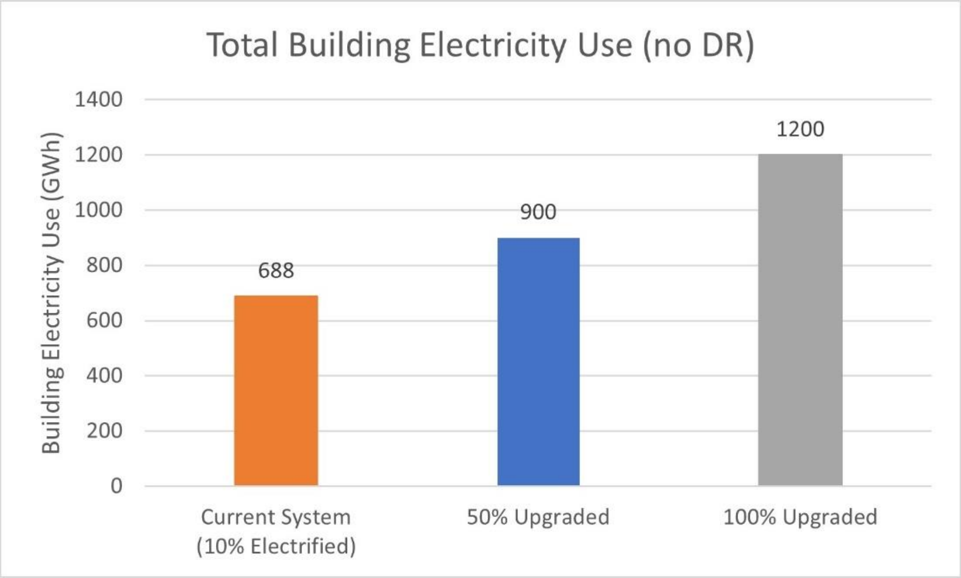


Figure 2-1: Annual building electricity demand in present day (10% electrified) Regina, the 50% upgraded version of Regina, and the 100% upgraded version of Regina.

When demand response is applied, building electricity use decreases slightly (Figure 2-2). Due to DR, annual building electricity use decreases from 900 to 823 GWh in the 50% upgraded building stock and from 1200 to 1091 GWh in the 100% upgraded building stock. These changes are due to the way that DR is formulated in this study. Because setpoints are lowered in the absence of curtailment and because there are more hours without curtailment than with curtailment, our DR scheme results in lower total energy use.

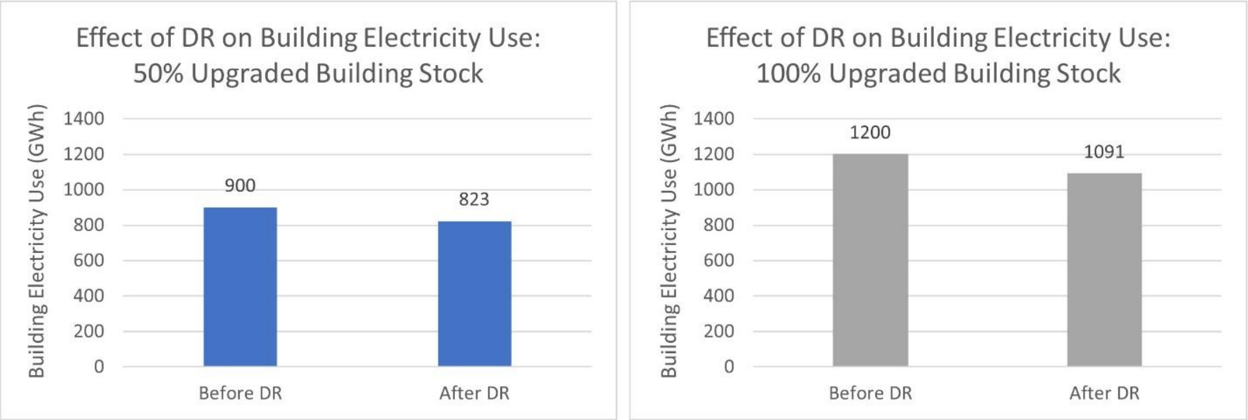


Figure 2-2: Annual building electricity demand before and after demand response in the 50% upgraded (left) and the 100% upgraded (right) building stocks.

Finally, in both the 50% upgraded and the 100% upgraded building stocks, our DR scheme is extremely effective at utilizing curtailed VRE generation. Curtailment is reduced by around 90% in both building stocks (Figure 2-3). This result indicates that our DR scheme is having its intended effect on electricity usage.

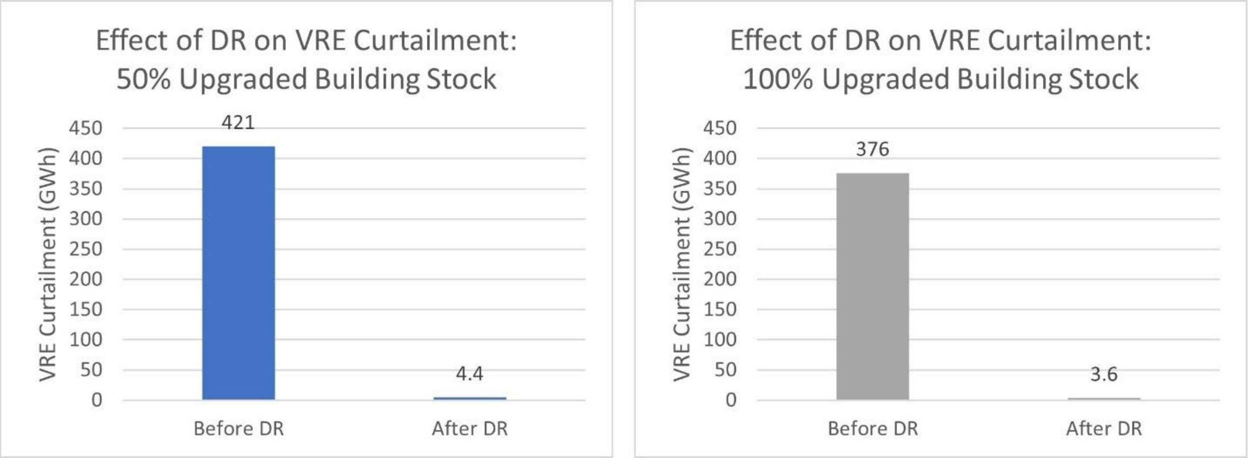


Figure 2-3: Annual VRE curtailment before and after demand response in the 50% upgraded (left) and the 100% upgraded (right) building stocks.

Discussion and Conclusions

Overall, the results of this chapter shed light on strategies for decarbonizing the building sector. To reduce carbon emissions, fossil fuel powered building heating and cooling systems can be replaced with electric systems, but this places a strain on electric grids by requiring extensive renewable capacity to ensure that new electric load is met without relying on fossil fuels. However, the results show that increasing building efficiency through envelope upgrades and increased-efficiency heating and cooling systems can effectively limit the electricity demand increases associated with an increasing number of electrified building functions. This makes it easier for renewable generation to meet that new demand.

The results of this chapter also demonstrate the utility of building demand response towards providing flexibility to the electric grid. The building demand response schemes modelled herein result in an overall reduction of both building electricity use and variable renewable energy curtailment. This translates to reduced emissions associated with building operation.

However, the demand response scheme used in this study is not perfect for two significant reasons. First, although using curtailed energy in the explored scenarios results in lower energy use overall and the utilization of renewable generation that might otherwise have gone unused, this result is not guaranteed in all cases. A more comprehensive goal should seek not merely to reduce curtailment, but rather to reduce the total emissions associated with energy use. Second, our DR framework involves the modification of temperature setpoints during every hour of the year. This represents a very extensive utility control of thermostats, which may not be tolerated by building occupants. It would be better to instead enact demand response only during certain hours.

These shortcomings can be addressed by a more comprehensive demand response framework which seeks to optimize the timing of building demand response from the electricity grid’s perspective, rather than just scheduling it to occur when there is curtailment. Under such a strategy, energy use can be shifted away from times when load is very high, thus limiting the use of fossil fueled peaker generation. To limit the negative impact of demand response on building occupants, a better DR framework should also identify the most impactful times to shift load and then only shift at those times. These features will be implemented in the subsequent work that comprises Chapter 4 of this thesis.

Chapter 3: Model Validation

In this chapter, the model is validated via a number of different methods. First, the model is checked for theoretical and physical correctness by confirming the credentials of the modeling software and comparing the modelled results to real measured data. Next, a set of sensitivity analyses are performed by varying key model inputs and investigating whether the model outputs change as expected. Following this, the demand response formulation which is finalized in Chapter 4 of this manuscript is validated by checking the results to ensure that the building-specific constraints which enact demand response within the electricity system model are working as intended. Finally, the model is compared with relevant literature both in general and in regards to some of the specific cases modeled. Overall, these assessments robustly support the validity of the model.

Theoretical and Physical Validation

EnergyPlus, the simulation software used in this thesis, has been extensively validated since its creation. For example, analytical (comparison to known mathematical solutions), comparative (simulation and comparison to equivalent building energy modeling software programs), and empirical (comparison to measured data) test cases are described and used to fix bugs at the software's inception in [66]. Other empirical validations are described in works such as [67–69]. As the software continues to be developed and more features are released, validation tests per existing industry standards are ongoing, as described in [70,71].

Next, the business-as-usual scenario (no envelope modifications, no HVAC system upgrades, and no demand response) from the second chapter of this manuscript was validated against measured data obtained from SaskPower. To assess the level of error between measured data and modelled predictions, two standard metrics were used: the coefficient of variance of the root mean square error [CV(RSME)], which measures the average deviation between modelled and measured data as a percentage of the average measured value; and the normalized mean bias error (NMBE), which characterizes the extent to which the discrepancy between modelled and measured data trends in any one direction as a percentage of the average measured value [72]. Industry standards proposed by ASHRAE indicate that a model predicting hourly building energy use is sufficiently accurate when it exhibits a CV(RSME) of less than 30% and a NMBE between -10% and 10% [64]. Our model's values of CV(RSME) = 17% and NMBE = 0.78% were found to be within this acceptable range, indicating that the model is sufficiently accurate.

As a final validation step, the measured and modelled load curves were compared visually. The modelled and measured curves were found to be similar overall in shape, especially in regards to the timing of demand troughs and demand peaks (Figure 3-1); when combined with the sufficiency of the statistical measures mentioned above, this supports our case that the model is accurately representative of reality. Of note, however, some demand peaks especially in the summer months (Figure 3-1) were seen to be much higher than the measured data. This is likely due to air conditioning systems being undersized and to those days having particularly hot weather during the modelled year. Observed differences in peak size can be very significant to grid operators because they represent a much larger demand that must necessarily be met. Thus, these differences represent a model limitation that should be addressed in future work, for example through more detailed modelling to ensure that these peaks are truly representative of reality, or by changing the sizes of modelled HVAC systems to check whether a larger size system might be less susceptible to high peaks on the more extreme days of the year. Relatedly, it should also be noted that more extreme weather conditions due to global warming could result in excessive building peak loads; this should be taken into account during system sizing calculations, and is another issue that merits future study.

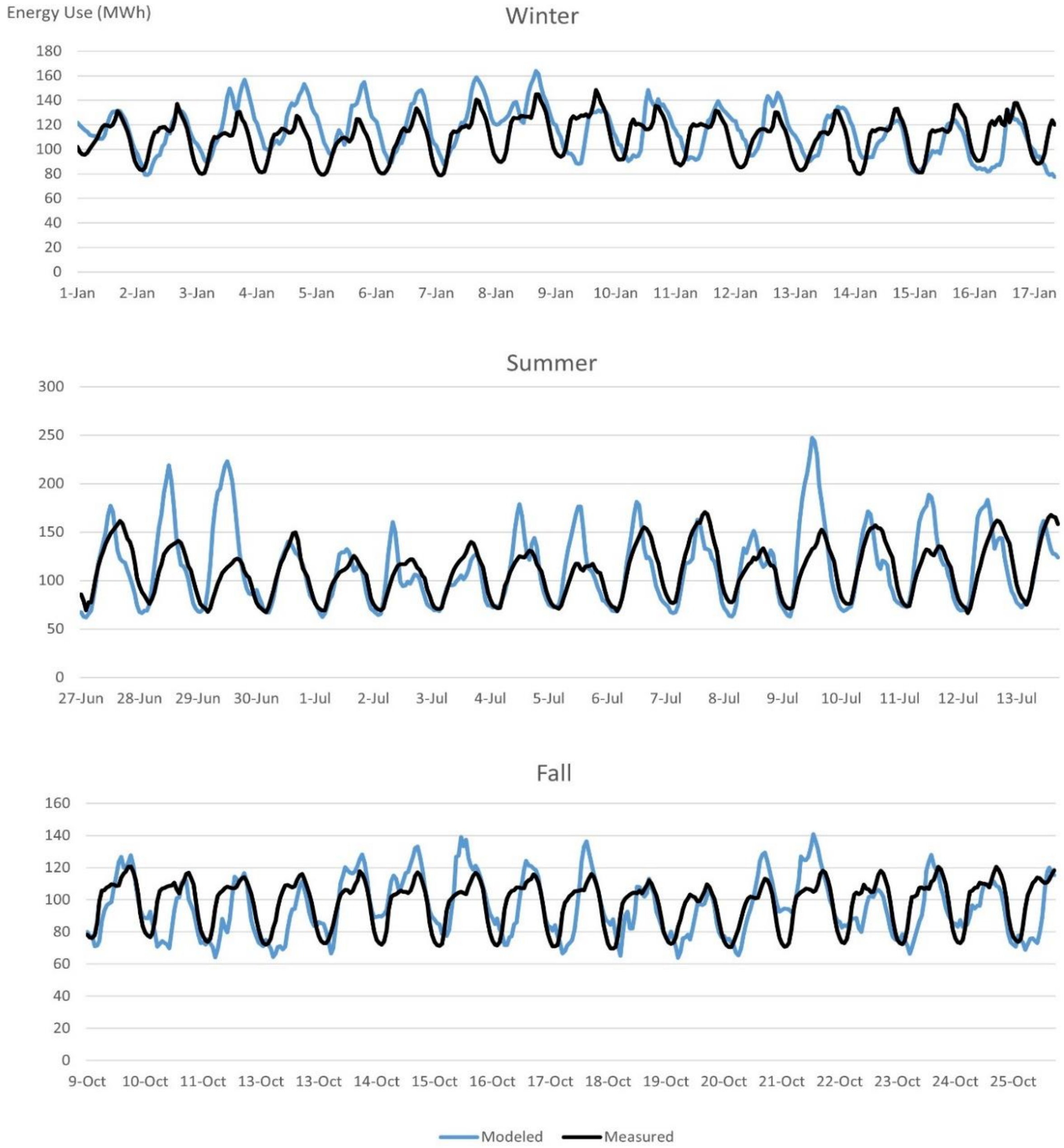


Figure 3-1: Comparison between measured and modeled building energy use from the calibrated model during three seasons of the year. When considered in conjunction with the statistical measures of closeness presented in this section, we found the measured and modelled data to match sufficiently, indicating that our building model is a "good-enough" representation of reality.

Sensitivity Analyses

By varying the values of different model inputs, their effects upon the model results can be isolated. This allows verification of whether known relationships between input and output variables are obeyed, and that uncertain model assumptions do not have too large of an influence on the results [73,74]. In this section, two important inputs are investigated. First, the archetype definitions used to formulate the building model are examined, and it is shown that simplifying our set of defining parameters has a negligible effect on model accuracy when assessed by the same statistical measures used above. Second, the extent to which building efficiency increases reduce building electric load is quantified, and the results are found to be in line with those seen in the literature.

Archetype Definitions

For the fourth chapter of this manuscript, the building model was simplified from six archetypes closely based on census data down to only three archetypes. These archetypes were constructed based on the average parameters (e.g. size, insulation properties, etc.) of the original six archetypes, and the reduction in number of archetypes is beneficial in that it reduces the computational complexity of the model and is in line with the guidelines for an ideal minimum viable city-scale building energy model as suggested by Ang et al. [75].

When validated using the same metrics as the six-archetype model, the three-archetype model performed similarly. The CV(RMSE) increased only slightly, from 17% to 18%, while the NMBE decreased from 0.78% to .070%. In addition to still being in line with the previously-cited industry standards, the differences between the new values and those of the six-archetype model make logical sense: the CV(RMSE) likely increased because our more-simplified set of archetypes exhibits less random variation than the measured data. Similarly, the NMBE for both models is close to zero due to scaling our model so that the total yearly modeled energy use is equal to the total yearly measured energy use. In this context, the decrease in NMBE between the six-archetype and the three-archetype models could either be caused by over- and underpredictions cancelling each other out, or because the differences between the measured data and the less-varied outputs of the three-archetype model happen to be more centered around zero.

To make sure that the three-archetype's low NMBE is not a result of overfitting, we visually compared the measured data to the three-archetype model results and found that they were somewhat matching without being perfectly aligned (Figure 3-2), indicating that the model is well-fit without being overfit.

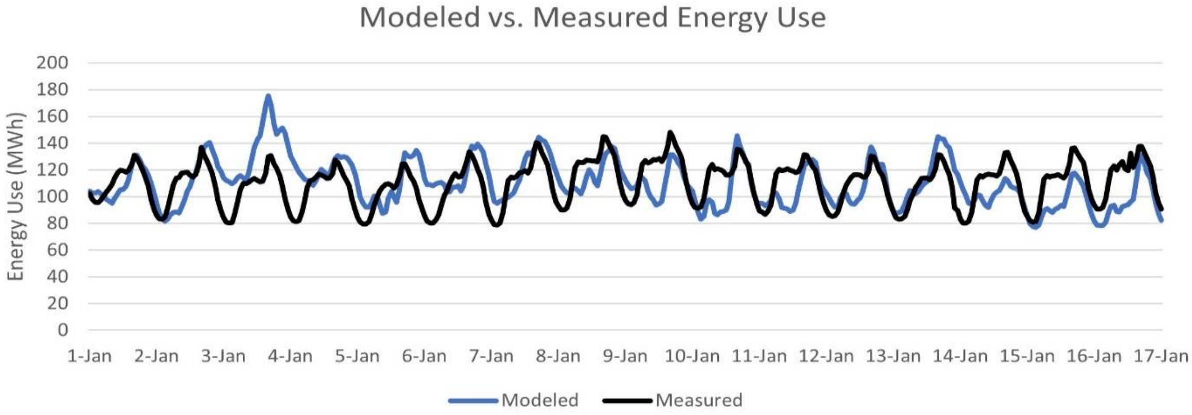


Figure 3-2: Comparison between modeled and measured energy use from the three-archetype model the coldest part of the year.

Effect of Building Efficiency Increases on Building Electricity Use

To explore and verify the effects of envelope and heating/cooling system retrofits, these retrofits were performed individually and together on the three archetypes used in Chapter 4 of this manuscript. The resulting percent changes in total energy use and energy use for heating were then examined. (Note that these archetypes are described in more detail in Chapter 4).

The envelope retrofits had a similar effect in terms of the percent difference on both the old house (1970 vintage) and the apartment (1965 vintage) (Table 3-1), which makes sense given the similar vintage of both archetypes. As well, this percent change is in line with similar works [76,77]. The effect of the envelope retrofits on the new house (2010 vintage) was still substantial, but was smaller than the effect on the other two archetypes (Table 3-1). This makes sense given the higher insulation properties of the new house archetype.

Table 3-1: Heating and total energy use before and after envelope upgrades in the three archetypes used in Chapter 4 of this thesis.

	Annual Electricity for Heating (GJ):		**Change (%)**		*Total Electricity Use (GJ):*		**Change (%)**
	Original Envelope	**Upgraded Envelope**			**Original Envelope**	**Upgraded Envelope**	
Apartment (1965)	93.51	50.93	45.54		140.6	82.73	41.16
Old House (1970)	124.31	66.50	46.50		186.47	108.71	41.70
New House (2010)	108.37	77.87	28.14		168.21	127.58	24.15

Meanwhile, all three archetypes reduced their total and heating energy use by a similar percentage when their electric furnaces were replaced by highly-efficient ground source heat pumps (GSHP) (Table 3-2). This occurs because all three archetypes started and ended with the same type of heating/cooling system. The percent changes associated with the new heating systems are in line with estimates from the U.S. Department of Energy [78,79], and are larger than the percent changes associated with the envelope retrofits.

Table 3-2: Heating and total energy use before and after replacing electric furnaces with ground source heat pumps (GSHP) in the three archetypes used in Chapter 4 of this thesis.

	Annual Electricity for Heating (GJ):		**Change (%)**		*Total Electricity Use (GJ):*		**Change (%)**
	Furnace	**GSHP**			**Furnace**	**GSHP**	
Apartment (1965)	93.51	29.3	68.67		140.6	56.54	59.79
Old House (1970)	124.31	39.45	68.26		186.47	75.26	59.64
New House (2010)	108.37	30.3	72.04		168.21	69.34	58.78

To calculate updated energy use after performing a retrofit, the original energy use can be multiplied by 1 minus the percent change associated with that retrofit [80]:

$$\text{Energy}_{after\ retrofit} = \text{Energy}_{before\ retrofit} \ * \ (1 - \text{Percent Change}_{retrofit}) \qquad (1)$$

Given this formula, the expected effect of successive retrofits can be calculated by successively multiplying 1 minus the percent change associated with each:

$$\text{Energy}_{after\ retrofit} = \text{Energy}_{before\ retrofit} * (1 - \text{Percent Change}_{envelope}) * (1 - \text{Percent Change}_{GSHP}) \qquad (2)$$

Overall, the combined effects of both the envelope upgrades and the heating/cooling system upgrades (Table 3-3) roughly followed formula (2), which indicates that the total effect of both retrofits is true to the individual values of each change.

Table 3-3: Heating and total energy use in each of the three archetypes used in Chapter 4 of this manuscript before and after upgrading envelope insulation properties and replacing electric furnaces with high-efficiency ground source heat pumps.

	Annual Electricity for Heating (GJ):		**Change (%)**		*Total Electricity Use (GJ):*		**Change (%)**
	No Retrofits	**All Retrofits**			**No Retrofits**	**All Retrofits**	
Apartment (1965)	93.51	11.66	87.53		140.6	35.58	74.69
Old House (1970)	124.31	15.67	87.39		186.47	46.92	74.84
New House (2010)	108.37	22.43	79.30		168.21	59.91	64.38

Demand Response Validation

The improved demand response formulation achieved in Chapter 4 of this manuscript consists of a number of constraints which are placed on the electricity system model based on values taken from the building model. To check whether the model's demand response formulation works as intended, a random one of the cases studied in Chapter 4 was selected, and a comparison was conducted between the constraint values within the results data and the constraint values that were specified in the model when running the simulation. The case selected was the Frequent and Highly Efficient case, in which short-lasting but frequent demand response generation events were performed within a 2050 building stock. Overall, the results data matched sufficiently to the values specified during simulation. The examined constraints are discussed in detail below.

Demand Response Availability and Timely Recovery

The most important constraint placed upon the electricity system model specifies the amount of energy that is available to be "generated" to the grid by enacting demand response upon – or equivalently, temporarily reducing the energy use of – the building stock. To check whether this constraint works as intended, the energy shifted by the electricity model during each hour of demand response was compared to the energy available for shifting within the building model. There were 0 hours during which the model-predicted generation exceeded the amount of generation available, indicating that the most important function of the linked model system works perfectly as intended.

Secondly, all DR generation events are followed by a "storage" or "recovery" period during which buildings use extra energy as a result of their reduced energy usage during the preceding hours; this extra energy use is due to buildings which had previously reduced their heating setpoint now consuming additional energy as they heat back up to their business-as-usual temperature (i.e., in the temperature that these buildings would be set to in the absence of DR). To ensure that a sufficient amount of shifted (generated) energy is recovered (stored) as required, the overall proportion of recovered energy to shifted energy as required by the building model was compared with the actual proportion of recovered to shifted energy as resulted from the model linkage. A minimum of 93.6% of all shifted energy was required to be recovered throughout the year, while the model results showed that 107.0% of shifted energy was actually recovered over the course of the year. This result exceeds the required minimum, implying that the model linkage's energy recovery function is also working as intended.

Approximation of Energy Availability based on Building Simulation

The previous two constraints, which guide demand response generation and recovery, incorporate information from the building model in the form of energy availabilities for generation and recovery during each hour of the year. However, these hourly values are estimated from the building model before running the electricity system model and are not verified after demand response is scheduled. To complete a verification within the building model, the set of yearly demand response events scheduled by the electricity system model were programmed in detail within the building model. The approximate building load curve based on the electricity system model and the detailed building load curve from the updated building model were then compared, and they were found to differ by an average of only 1.45% per hour, indicating that the approximation is highly accurate. More detail on this validation step can be found in the fourth chapter of this manuscript.

Maximum Uptime

The maximum uptime constraint sets a maximum on the number of hours for which a generation event can occur. For the Frequent and Highly Efficient case simulated in Chapter 4 of this manuscript, generation events were specified to last for no longer than 2 hours. The results from this simulation indicated a total number of 363 generation events, of which 6 events lasted for 3 hours, and 0 events lasted for 4 or more hours (Figure 3-3). This represents an error rate of only 1.7% -- in other words, this constraint worked correctly 98.4% of the time.

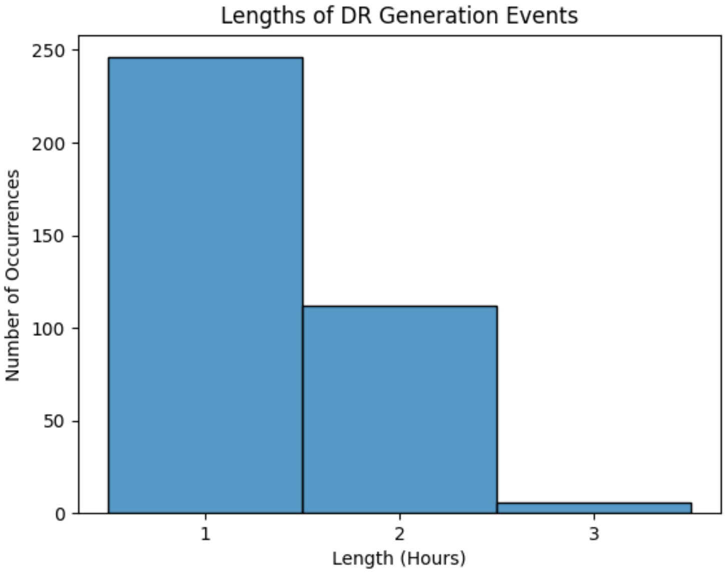


Figure 3-3: Length of all demand response generation events for the Frequent and Highly Efficient case simulated in Chapter 4 of this thesis.

Minimum Downtime

Similar to the maximum uptime, the minimum downtime constraint requires a certain number of hours to pass between subsequent generation events. For the Frequent and Highly Efficient case, a minimum downtime of 3 hours was specified. The simulation results indicated that of 369 total intervals wherein demand response was NOT occurring, the vast majority of these intervals lasted for exactly 3 hours. Some DR events were spaced as far apart as 470 hours, and there were only 3 occurrences of demand response generation events being spaced 2 or less hours apart (Figure 3-4). This is an error rate of only 0.81%, indicating that the model is working correctly 99.9% of the time.

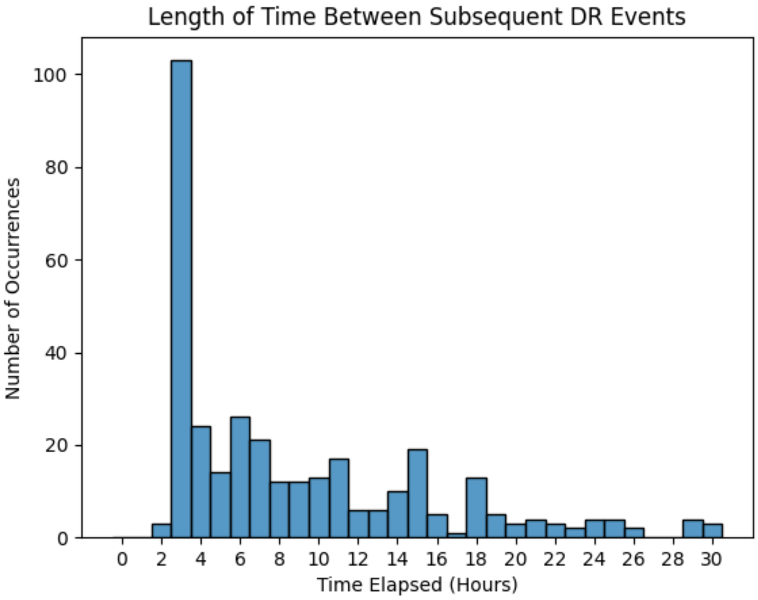


Figure 3-4: Time elapsed during the shortest (30 hours or less) intervals during which no demand response occurred in the Frequent and Highly Efficient case from Chapter 4 of this manuscript.

Maximum Number of Events

Finally, to ensure that demand response only occurs for a small portion of the year, there exists a maximum number of demand response events which are allowed to occur per time interval. In the Frequent and Highly Efficient case, the number of demand response events was constrained to be no more than 4 events per day. The simulation results showed that no day had more than 4 demand response events, indicating an error rate of 0% for that constraint (Figure 3-5).

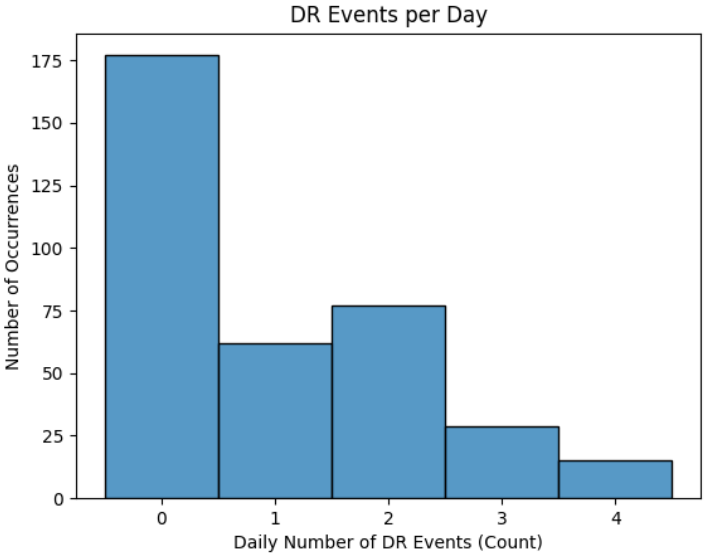


Figure 3-5: Number of demand response events during each simulated day in the Frequent and Highly Efficient scenario simulated in Chapter 4 of this thesis.

Similarly, during each month in the Frequent and Highly Efficient simulation, the monthly number of demand response generation hours was constrained to be no more than 60 hours. Investigation of the simulation results showed that none of the months where DR occurred had more than 60 hours of demand response generation, again resulting in an error rate of 0% (Figure 3-6).

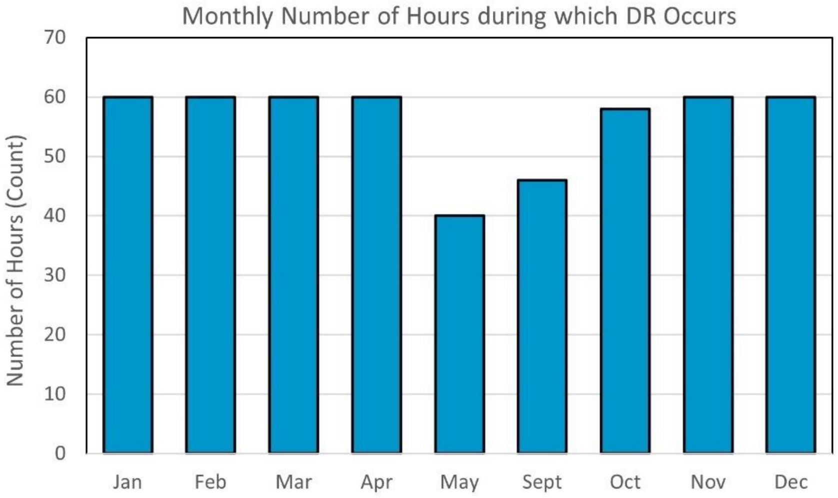


Figure 3-6: Number of demand response hours occurring during each month in the Frequent and Highly Efficient scenario simulated in Chapter 4 of this manuscript. June, July, and August are not included because heating demand is negligible during those months; as a result, no demand response occurs in June, July, or August.

Literature Comparison

Comparable results regarding both the effects of demand response and the effects of envelope and heating/cooling system retrofits have been demonstrated in the literature. Regarding the effects of envelope and heating/cooling system upgrades, Wu et al. [81] performed similar envelope retrofits to the ones seen in this thesis and noted that energy use was halved in older buildings, which is in line with the findings of this thesis. Wu et al. also noted substantial emission reductions of up to 80% when natural gas-powered heating systems were replaced with ground-source heat pumps (GSHP). This is in line with the results seen in Chapter 4, which indicate that cost and emissions savings are doubled (a 100% increase in savings) when forced-air electric furnaces are replaced with GSHP. Similarly, Wills et al. [82] reported a 70% decrease in energy use when retrofitting late 90's homes with upgraded insulation and ground source heat pumps. This figure is well-aligned with the energy use decreases seen as a result of the GSHP and insulation retrofits performed in the sensitivity analysis in this chapter. Finally, Pitt et al. [83] estimated a 36% energy use reduction when extensively retrofitting the envelopes of homes slightly younger than the homes modeled in this thesis; this figure agrees with the energy use reduction seen after improving building envelopes in the sensitivity analysis performed above.

Relating to the effects of demand response via temperature setpoint adjustment, Zehir et al. [84] noted a 3-5% decrease in non-renewable electricity consumption when the setpoints of refrigerators were adjusted based on the presence or absence of solar generation. This demand response strategy is very similar to the curtailment-based demand response used in Chapter 2 of this manuscript, and their consumption decrease is similar to but less than the 8-9% decrease in energy use observed herein; this makes sense given that their fridges were inside climate-controlled buildings and thus are not as sensitive to outdoor temperature changes. Similarly, de Chalendar et al. [85] tested a demand response strategy similar to the one performed in Chapter 4 by reducing office building cooling setpoints by 2°F (about 1°C). Their result of a 13-28% reduction in daily cooling load is similar to this thesis' result of 8-20% of building heating load being affected by a demand response shift of 1°C.

Additionally, the important results and conclusions derived from this thesis are also supported by the literature. As explained further in Chapter 4, one of the main takeaways from Chapter 4 case study was that the characteristics of fossil fueled generation – particularly ramp rate constraints which lead to an inability to frequently change on/off status – are important underlying factors which determine the ability of demand response strategies to reduce the costs and emissions associated with energy use. This result is supported abundantly in the literature. Both Kuo [86] and Zhang et al. [87] report that traditional fossil fuel generation decreases in efficiency when operated at less than full capacity, leading to increased emissions when small amounts of VRE are available. Relatedly, Ding et al. [88] notes that large coal plants tend to be more efficient and lower-emitting per unit than small ones, but have more difficulty adjusting their power output to match fluctuations in VRE availability. More specifically, Liu et al. [89] describes coal power as particularly inflexible due to specific operation requirements such as minimum power and ramp rate, and Li et al. [90] shows that conventional generators struggle to provide adequate flexibility when VRE penetration is high. Because traditional fossil fuel powered generators cannot easily alter their energy production, demand response strategies which allow these generators to turn off and stay off – such as by shifting large amounts of energy at once – are able to be more effective at reducing emissions.

It was also shown in Chapter 4 that the amount of energy available for demand response varied based on the month and the time of day in both the pre-retrofit and the highly efficient building stocks. Generally, decreased thermodynamic energy demand means that a decreased amount of load can be shifted via setpoint change, but the building and envelope retrofits modelled in this work don't necessarily produce uniform decreases in energy use. Rather, the shape of the building demand curve over time is changed with the application of retrofits, and the available flexibility of buildings at different times of the day and year is also changed as a result. The literature strongly supports the mixed effects of increased building efficiency on demand response availability. Satchwell et al. [91] explains why envelope efficiency has an inconsistent effect on the availability of demand response: increased efficiency generally means less flexibility due to reduced total load, but because high-efficiency buildings are less able to be passively heated or cooled by the environment, increased flexibility is available when environmental temperatures are close to desirable indoor temperatures. Baroiant et al. [92] supports this with examples of energy efficiency measures having mixed effects on the shape of the building load curve, usually decreasing it but sometimes causing increases based on the details of appliance operation. This phenomenon is summed up by Gerke et al. [93], who highlight the lack of a clear pattern relating building efficiency and demand response availability, and observe that demand flexibility and energy efficiency are sometimes at odds and sometimes complementary.

Chapter 4: Building-to-Grid Model Linkage to Investigate Demand Response Strategies in Residential Buildings

Abstract

Co-optimization of demand-side electrification and supply-side variable renewable energy integration in electricity systems can lead to dramatically reduced emissions due to synergies between the two sectors. However, few models exist that represent both sectors in sufficient operational detail. To bridge this gap, this paper proposes a novel framework for transferring information between an electricity system model and a building stock model. First, hourly electricity use predictions from the building stock are incorporated into the total demand met by the electricity system. Then, demand response events are simulated in the building stock, and the energy characteristics of these events are used to inform a series of constraints within the electricity system model. This allows the electricity system to determine the grid-optimal times for the building stock to enact demand response. To demonstrate the utility of this framework, a case study into the effects of building efficiency increases, demand response, and variable renewable capacity expansion in the city of Regina, Saskatchewan is performed, and various ways to reduce the costs and emissions associated with electricity use in Regina are compared. Results show that demand response is most effective when large amounts of energy are shifted at once, and that as building envelopes and heating systems become more efficient, the effects on demand response availability are varied. These results simultaneously demonstrate the value of demand response and stress the importance of models such as this to explore the specific effects of proposed changes to the building and electricity sectors.

Introduction

Buildings are responsible for roughly 40% of greenhouse gas emissions globally [94]. In Canada, two-thirds of residential energy is used for heating, and natural gas (NG) is the primary heating fuel for over half of households [95–97]. Increasing building efficiency and switching to electric heating therefore represents a large potential for the reduction of greenhouse gas emissions, especially when that electricity is powered by renewable generation. Building electrification and efficiency upgrades also provide an opportunity to co-optimize the operation of electricity and building systems.

Due to rapidly declining costs combined with the Paris Agreement [98] and other global efforts to reduce carbon emissions, variable renewable generation technologies such as wind and solar have been gaining prominence in markets and contributing increasingly more electricity to grids worldwide. However, the reliance of these technologies on weather conditions complicates supply and demand balancing, particularly on grids that have little storage capacity and inflexible generation needs [99,100]. Electrification of building heating and cooling systems provides an opportunity to reduce the severity of these problems through demand response (DR) strategies that make electricity demand responsive to the conditions of power availability, for example by heating or cooling in advance, or changing the internal temperature setpoints of buildings [101]. Such actions take advantage of buildings' thermal mass to change the timing of building energy load and, if implemented correctly, can have only a moderate impact on the comfort of building occupants.

Energy flexibility in buildings is a widely studied topic, but a few key shortcomings make it difficult to understand how building electrification and DR might impact an electricity grid with the degree of spatial and temporal granularity needed to make planning and operational decisions. Research focused on buildings lacks a common metric for flexibility that can be used across different technologies and building types [102]. The field also generally fails to explore how a market might be created to realistically harness the benefits of building flexibility [102,103]. Additionally, meaningful building-grid interactions involve whole communities of buildings, but a review by Li et al. [103] found that a majority of papers focus on individual buildings, rather than on aggregations of buildings or their effect on their electricity systems.

On the other hand, research focusing on the electricity system tends to represent buildings in a similarly simplified fashion. In a review of 54 different energy system modeling tools, Chang et al. found that only half of these included a representation of heating demand [104]. Even when heating demand was modelled, it was almost always used as an estimated input, rather than modelled in operational detail, making these models unable to explore building-centric questions such as efficiency upgrades and demand response. A review by Savvidis et al. likewise identified demand-side changes and demand-side grid flexibility as two questions that energy system models were not well-equipped to address [105].

In Canada specifically, despite an abundance of models investigating a renewable transition, studies tend to be siloed between sectors, either focusing directly on buildings but with no consideration of electricity system impacts, or containing high-level building representations that omit operational detail [33]. This perspective makes it difficult to study demand response, electrification, and other cross-sectoral synergies [106,107].

Internationally, some papers exist that link detailed building-side models to supply-side considerations. For example, Wang et al. [108] and McPherson and Stoll [47] apply detailed constraints representing the operation of different demand response sensitive devices. Wang et al. models time-shiftable appliances by representing their time of use as optimization variables that are constrained to ensure completion within a certain time frame. McPherson and Stoll apply five energy-based constraints to ensure that shifted power is recovered within a certain time interval, and that shifts are sufficiently spaced in time to allow for proper device operation. Although both formulations represent the general concept of demand response in a power system model, they both rely on a fixed and static parameterization to represent building system demands and constraints. This fails to capture the dynamic nature of buildings, which are able to change their demand in response to grid requirements, and may experience changing energy needs in response to both global climate change and building-side technology upgrades.

Several authors have developed methodologies to represent the dynamic nature of building energy demand. Papaefthymiou et al. [109] apply detailed thermodynamic modeling to investigate heat pump operation and building temperature within a set of reference buildings and establish a maximum and minimum energy usage needed to ensure comfort. Building demand is then allowed to vary within these bounds as part of a unit commitment model. Magni et al. use a state space model to represent temperature change as a function of ambient conditions and building properties; like Papaefthymiou et al., they also allow building energy use to vary within comfort limits as part of a unit commitment representation of the electricity system [110]. However, both these analyses assume that building thermodynamic load is always available for utility control, which may not be the case for residential buildings.

Part of the reason for the sector-specific analyses and lack of integrated modelling is the high computational expense of single-building methods. Yin et al. [111] and Zhu et al. [112] attempt to overcome this barrier by repeatedly simulating demand response events over a wide range of varied conditions to create databases. However, these methods require an extremely large number of simulations, which is not practical for larger-scale groups of buildings.

Finally, despite the high potential utility of DR, there are currently very few active demand response policies in Canada [113]. Exploring the policy space with modeling could not only be informative, but could also motivate the development and implementation of demand response programming in Canada.

This paper simultaneously addresses methodological gaps in the literature and branches into previously unexplored scenario space at the intersection of building efficiency and electrification, demand response, and increased grid reliance on VRE generation. On the methodological side, we enact a novel information transfer framework between an operational building model and an operational model of an electricity system, which overcomes the sector-specific focus that limits many existing papers. Within this model linkage, a detailed set of operational constraints captures the dynamic nature of buildings better than previous models, while also ensuring that consumer comfort is continuously maintained. To address the issue of a metric for building flexibility, this value is straightforwardly quantified as the amount of building load available to the grid for demand response shifts throughout the year. As well, our novel parametrization of building flexibility limits computational expense, allowing the simulation of an entire city's building stock, rather than a small number of buildings as seen in some previous studies. On the scenario side, we investigate the combined effects of increased building envelope efficiency, the deployment of high-efficiency electric heat pumps, and increased solar and wind capacity, which answers open questions regarding the interactions between these various upgrades. We also shed light on the potential value and operational specifics of demand response by comparing three levels of energy shifting across two building stock and grid compositions. Our hope is that the model and results presented in this paper will help cities and utilities move towards their decarbonization goals.

The rest of this paper is organized as follows. First, we describe our detailed thermodynamic model of building heat use. Next, normal building energy use is contrasted with demand response through the simulation of a number of demand response events. The observed energy differences between normal and demand response operation are then used to formulate a series of constraints in an operational model of an electric grid. A validation of the model is presented, and a case study is then performed that explores the effects of building stock modernization (envelope upgrades and the installation of highly efficient ground source heat pumps) and varying demand response magnitudes (degree change and event frequency and duration). Finally, our results show that changes in the timing of building energy use due to building efficiency increases can cause significant changes in the timing and impact of demand response events. We also show that shifting large amounts of energy at once is advantageous, and that start-up costs as well as costs per megawatt-hour (MWh) are important in determining how the capacity factors of different energy sources are impacted by the implementation of demand response.

Methods

This paper passes information between two sector-specific operational models, allowing us to understand how fluctuations in building load affect power system operation. On the building side, a detailed representation of the residential building stock in the city of Regina, Saskatchewan is formulated using the building energy simulation program EnergyPlus [56]. Next, DR parameters are extracted from this model by simulating a series of representative DR events and contrasting them with regular building operation. For simplicity and since Regina is a strongly heating-dominated climate, we focus only on heat load during this study. The DR parameters are then used to formulate a series of constraints for SILVER [40], a linear optimization model describing the dispatch of generation assets on Regina's electric grid. Finally, SILVER is run to determine the optimal operating schedule for the grid's generation assets, which now include building demand response. These steps as well as the inputs and outputs of each are shown in Figure 4-1, and are described in more detail in the sections below.

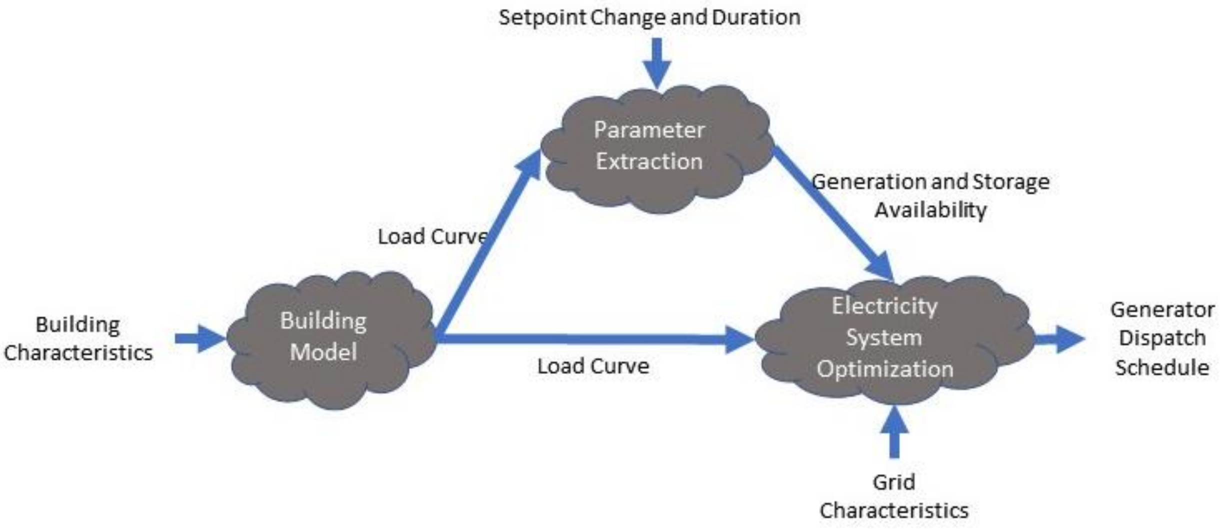


Figure 4-1: Model workflow for this study. Bubbles represent primary models or formulations, while arrows are labeled with inputs/outputs for each step.

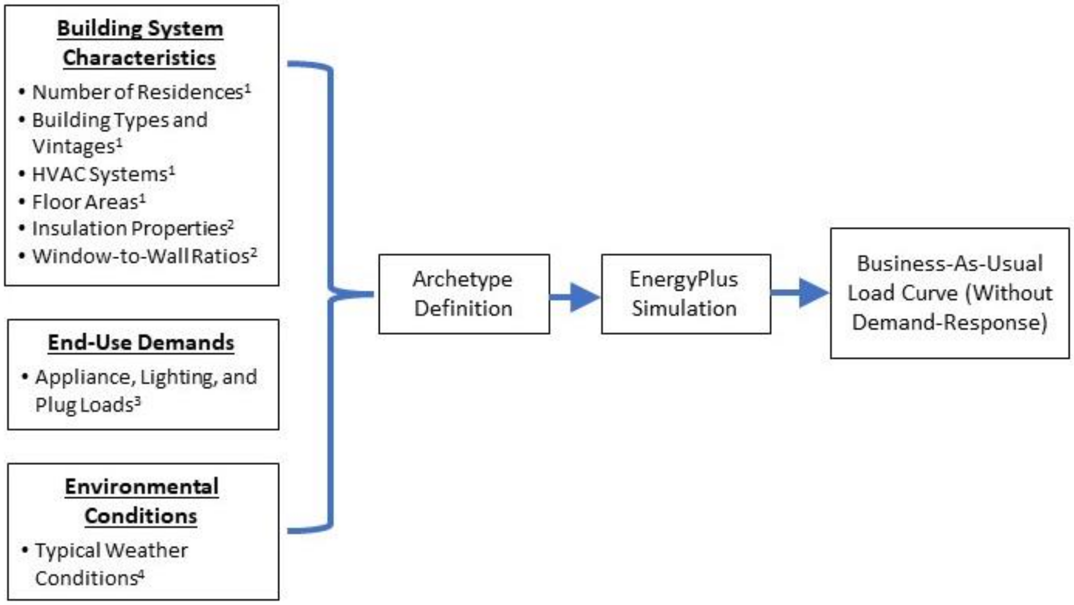
Step 1: Building Model

Engineering models represent building energy use as a function of the physical factors directly affecting that use [18]. These factors include constant thermal exchange with the environment, the energy input into heating and cooling systems to maintain appropriate temperatures, and occupant behavior such as the use of lighting and other appliances. A larger set of buildings, such as a residential community or a city, can be represented via archetype-based aggregation, in which a few representative buildings are modeled in detail via simulation engine, and the results are then scaled by the number of each building type to match the size of the target building stock [17,20].

For this study, EnergyPlus [114] was used as the simulation engine for two configurations representing the city of Regina, Saskatchewan using archetype-based aggregation. First, the residential building stock of present-day (2020) Regina was modeled using the methodology in [46]**.** Most input parameters, such as the number of buildings of each type, building vintage, floor area, and type of heating appliance were taken from national and provincial census data [115–117]**.** For each building, thermal heat transfer properties were estimated based on its vintage according to the formula proposed by Tooke et al. [54]. In addition, a static load curve representing plug loads such as lighting and appliance use was included based on the work of Armstrong [58], and weather information was taken from the Canadian Weather Energy and Engineering Datasets [61]. Parameter descriptions for the major archetypes used are given in Table 4-1, and a graphic depicting the flow of information through this model is shown in Figure 4-2.

Table 4-1: Defining parameters of the archetypes used for the 2020 version of the Regina. The 2050 version was based on this model, but with updated heating systems and envelope thermal properties as described in the text.

Archetype	Vintage	Floor Area (m)	Height (m)	Special Wall Features	Heating System	Envelope Thermal Properties	Number of Residences of Type
Old House	1970	10 x 14	3	None	NG forced-air furnace based on EnergyPlus template	Roof, wall, and window U-values, window solar heat gain coefficient, window-to-wall ratio, and infiltration rate calculated based on vintage according to formula from Tooke et al. [54]	40,667
New House	2010	11 x 15	3	None			15,723
Apartment	1965	9 x 12	3	2 Walls Adiabatic			30,994



[1] *From Canadian census* [115–117]
[2] *From Tooke et al.* [54].
[3] *From Armstrong et al.* [58]
[4] *From government dataset* [61]

Figure 4-2: Information and steps used to model Regina before demand response. Main input data sources were Canadian government datasets and two supplementary research papers (leftmost column). This information was used to define a set of archetypes, which were then modeled in EnergyPlus to produce a business-as-usual load curve.

Second, a highly-efficient or "2050" version of Regina was simulated by modifying the "2020" model. To simulate a highly-optimized future version of the city, all buildings were assumed to have complete envelope retrofits so that the thermal insulation properties of the windows, walls, basement, and roofs met the highest tier of the BC Step Code, which represents one of the highest national standards for building envelope efficiency [118,65]. As well, the thermal system of every building was assumed to be replaced with a highly-efficient ground source heat pump based on a template from EnergyPlus [119].

Step 2: Extraction of Demand Response Parameters

During normal operation, energy is continuously consumed by buildings for heating and other loads. In a cold environment, much of this energy is used to replace heat that the buildings have lost to their surroundings. Due to their thermal inertia, if the input of heat were to suddenly stop, the buildings would cool down slowly as the furniture, walls, and other components gradually released stored energy. The lag between heating being turned off and buildings becoming an uncomfortable temperature can be taken advantage of to reduce building energy demand at times when power availability (e.g. wind and solar) is low. This energy can then be recovered later when power availability is high.

In this formulation, a demand response event affects only building heating systems and is defined as a setpoint decrease which lasts for a prescribed period of time, followed by a rebound period in which buildings consume additional energy to return to their original temperature. All buildings participating in DR are assumed to participate simultaneously in both the setpoint change and the rebound. The general effects of both the setpoint change and the rebound on building energy use is explained in detail in the following paragraph. Of note, other strategies for demand response are possible, but are not represented in this study.

Our DR formulation results in two periods during which the energy use of the buildings differs from normal operation. First, the setpoint is relaxed, and the buildings use less energy than they would normally use; the energy difference between the regular and relaxed-setpoint energy use can be conceptualized as “generation” because additional energy is now available for the grid (Figure 4-3, middle). Secondly, as soon as the setpoint ceases to be relaxed, the buildings use some additional energy relative to the business-as-usual case. From the building perspective, this energy is needed to bring the building from the relaxed temperature back to the normal temperature. From the perspective of the electric grid, the energy difference between the post-DR and the business-as-usual cases can be thought of as a “replenishment” of the building stock’s energy storage bank, or a “recovery” of lost energy (Figure 4-3, right).

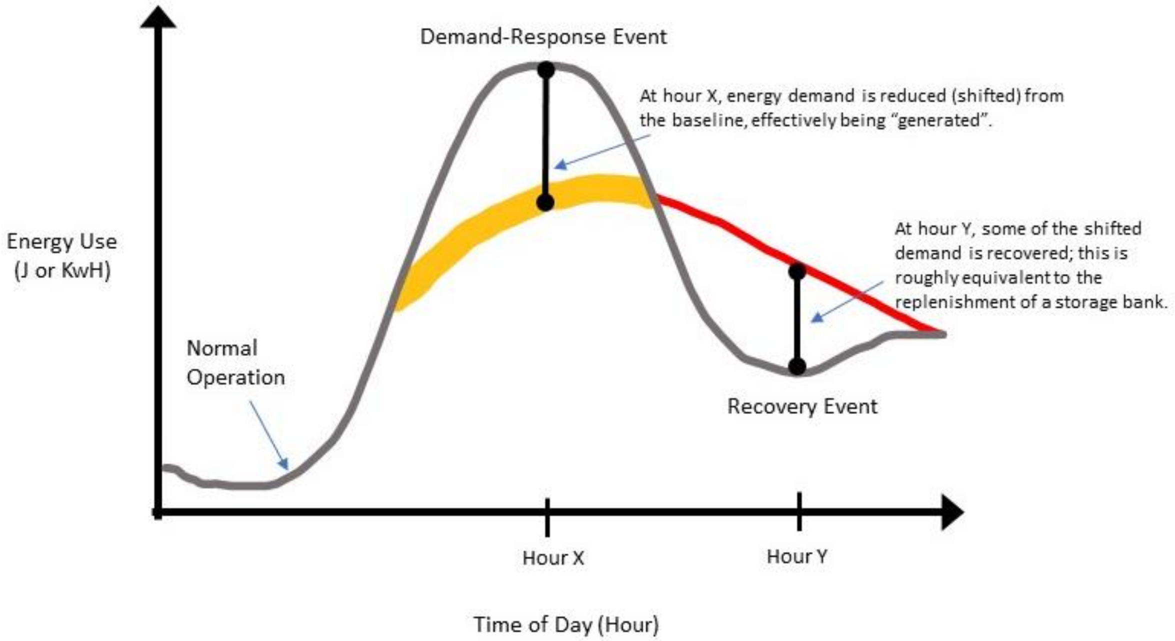


Figure 4-3: Conceptual illustration of demand response. The gray line represents the regular load curve of the building stock. When a demand response event occurs, the building stock first uses less energy than it ordinarily would (thick orange line). After the event ends, more energy relative to the regular load curve is used (red line) as the building stock consumes extra energy to return to normal temperatures. For the purposes of this study, we are interested in the energy available at hour X and the energy recovered at hour Y.

Parameter values for generation and recovery events were calculated via the following steps:

a) Simulate the business-as-usual building heating load for an entire community over the course of the year.

b) Identify several characteristic temperature conditions throughout the year. Each characteristic temperature condition consists of a starting temperature and a direction of temperature change, and demand response events are simulated at each characteristic condition in the following step. To select the characteristic conditions, we use the Profile feature of EnergyPlus, which produces temperature graphs representing an average day for each month. Months with similar average days are grouped, resulting in four groups for this study; the summer months of June, July, and August are excluded as heating load during those months is negligible. Next, two timepoints for each group are selected for demand response simulation: “morning” temperatures are cold but increasing, while “evening” temperatures are warm but decreasing. This results in a total of eight characteristic temperature conditions, which are shown in Table 4-2.

c) Simulate DR events at the characteristic temperature conditions: first, “generation” is modelled by relaxing (lowering) the heating setpoint and re-calculating the building load curve for the community. Following each simulated generation event, “recovery” is modelled by returning the setpoint to its business-as-usual temperature after five generation hours. This amount of time is significantly longer than any of the demand response events modelled in this study and ensures that all buildings are completely at the lowered temperature when the storage event begins.

d) Calculate the difference in energy use between normal operation and while generating and storing, respectively. In reality, the difference between normal operation and demand response operation will change during each hour of a demand response event. However, to accommodate the formatting of the optimization problem, we assume that the amount of energy able to be shifted is constant for the duration of the shift. This value is extracted from the building model by keeping the building at the relaxed setpoint for four hours (which is significantly longer than any generation event in this study) and finding the energy difference between normal operation and the demand response event during the first hour of the shift.

e) Prepare values for input into the electricity system model. To formulate a yearly matrix of hourly generation and storage availability, each hour of the year is assigned a generation and a storage value based on its month and the time of day. Between 4:00 and 15:59, the morning values for that month are used, while the evening value is used from 16:00 until midnight and from midnight until 3:59. The months and times of day represented by each characteristic temperature condition are shown in Table 4-2.

Table 4-2: Characteristic temperature conditions and the months and times of day that are represented by each. Note that June, July, and August are not represented because heating load during those months is negligible.

Characteristic Temperature (°C) at Start of Simulated Period	Direction of Temperature Change During Simulated Period	Months Represented	Time of Day Represented
-20	Increasing	Jan/Dec	"Morning": 4:00 - 15:59
-14		Feb/Mar/Nov	
2		Apr/Oct	
16		May/Sep	
-12	Decreasing	Jan/Dec	"Evening:" 16:00 - midnight; midnight - 3:59
-7.5		Feb/Mar/Nov	
8.5		Apr/Oct	
19.5		May/Sep	

Step 3: Electricity System Model

This study utilizes SILVER, an open-source production-cost model developed by McPherson and Karney [40], as its electricity system model. SILVER uses linear programming to determine the optimal (least-cost) dispatch of a fixed set of electricity system assets in a region. Within this framework, the amount of energy generated during each hour must be enough to meet the total hourly demand of the system. When variable renewable assets are included, their hourly production is determined as a function of weather conditions.

In this paper, we make three key modifications to the baseline SILVER from [40]. First, as seen in our previous work [46], we directly include business-as-usual (no demand response) building load from EnergyPlus as part of the hourly energy demand. Secondly, we introduce two new decision variables to determine the hourly demand response status of the building stock. Alongside these variables, the hourly generation and storage availabilities taken from the building model in the Step 2 are used to specify the power generated or stored via DR during each applicable hour. Similar to the application of a top-down utility control scheme, this allows the electricity system model to decide when, for how long, and by how many degrees to change building setpoints in response to a grid requirement for energy generation. Third and finally, to ensure occupant comfort during DR, we implement the constraints proposed by McPherson and Stoll in [47]. A schematic of SILVER including our modifications is shown in Figure 4-4, and our new decision variables and constraints are described below.

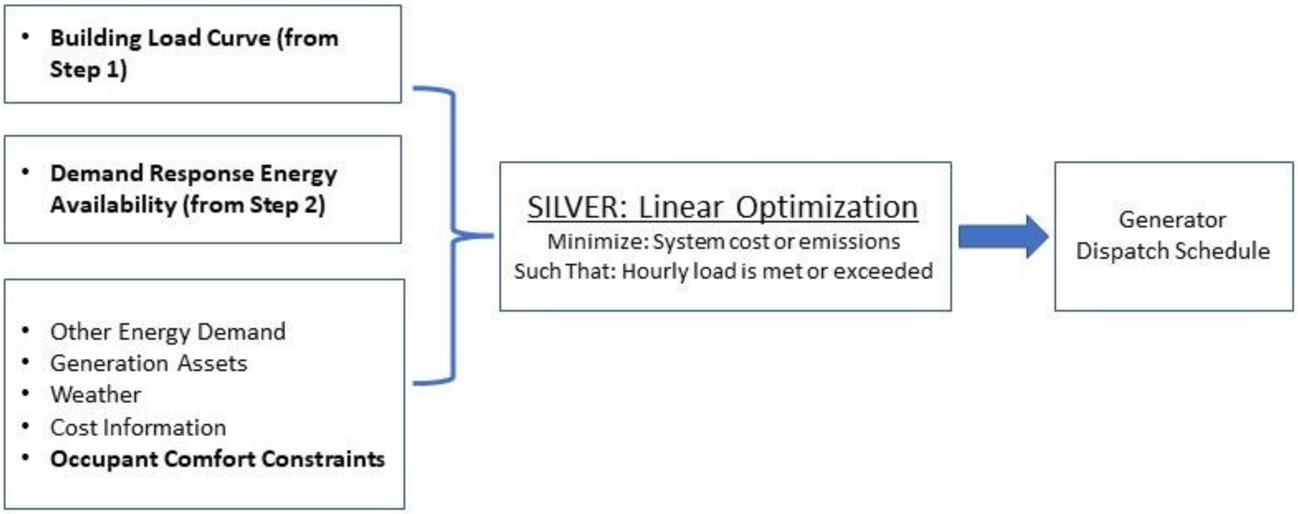


Figure 4-4: Inputs and output of the SILVER electricity system model. Bold text indicates important modifications made in this paper. More information about SILVER and our modifications can also be found in a recent work by Seatle and McPherson [120]. Inputs not addressed in this work are identical to those used in [46].

Decision Variables

To allow SILVER to determine when the building stock is participating in demand response, we define two new decision variables. G_t represents the generation status of the building stock, and S_t represents the storage status of the building stock:

$$G_t = \begin{cases} 1, \text{if the building stock is generating at time } t \\ 0, \text{otherwise} \end{cases} \tag{1}$$

$$S_t = \begin{cases} 1, \text{if the building stock is storing energy at time } t \\ 0, \text{otherwise} \end{cases} \tag{2}$$

Incorporation of Demand Response Energy Availability

Next, the hourly generation and storage availability taken from the building model are used to guide the actual generation and storage prescribed by SILVER:

$$G_t\, P_{g,t} \leq \hat{P}_{g,t}, \text{ and} \tag{3}$$

$$S_t\, P_{s,t} \geq \hat{P}_{s,t} \tag{4}$$

where $\hat{P}_{g,t}$ and $\hat{P}_{s,t}$ are the time-specific generation and storage availabilities extracted from the building model, and $P_{g,t}$ and $P_{s,t}$ are the scheduled generation and storage amounts as prescribed by SILVER's optimization algorithm.

Preservation of Occupant Comfort

Finally, four additional constraints proposed by McPherson and Stoll [47] are applied to ensure occupant comfort. These constraints limit the length of a DR event, the number of hours between events, the number of occurrences within a set period, and the amount of time that can elapse before shifted energy is recovered.

Maximum Uptime

First, to prevent DR events from persisting too long, we limit the maximum uptime M, which represents the maximum length of time for which generation can occur. No more than M hours of generation are allowed to occur during the interval from $t - M$ hours until the current time t:

$$\sum_{t-M}^{t} G_t \leq M \tag{5}$$

Minimum Downtime

Similar to the maximum uptime, occupant comfort is further preserved by requiring that a certain number of hours m passes between subsequent generation events. After a generation event, generation cannot occur again during the interval from the current time t until the future time $t + m$:

$$\sum_{t}^{t+m} 1 - G_t \geq (-1)(m\,\Delta_G) \tag{6}$$

where Δ_G is defined as the status change at time t:

$$\Delta_G = G_t - G_{t-1} \tag{7}$$

Maximum Number of Events

Next, existing DR policies (e.g., [120]) usually assure consumers that there will only be a limited number of demand response events every month. To approximate this, the third occupant comfort constraint limits the amount of energy expended within each month to less than the product of the maximum number of starts $\$_m$ and the average amount $\bar{P}_{g,t}$ of energy shifted during each generation event:

$$\sum_{t \in month} G_t\, P_{g,t} \leq \$_m\, \bar{P}_{g,t} \tag{8}$$

This constraint is also applied each day by the daily equivalent of the above inequality.

Recovery Interval

Finally, to ensure that shifted energy is returned to consumers within a reasonable time interval, we track dr_t, the amount of generation energy available before recovery is needed:

$$dr_t = dr_{t-1} - S_t\, P_{s,t}\, F_s - G_t P_{g,t} \tag{9}$$

where F_s is calculated from the demand response availabilities and represents the proportion of shifted energy that is ultimately recovered. This fourth constraint ensures that recovery will be completed within *R* hours by forcing dr_t to equal some initial value dr_0:

$$dr_{t+R-1} \geq (-1)(\, dr_0 \, \Delta_G) \tag{10}$$

Final Output

Taking these constraints into account, the final output of the solved SILVER model is a yearly dispatch schedule for the grid's generation assets, which now include building DR. Importantly, other parameters of interest, such as associated costs, emissions, and updated (including demand response) building load are *not* output by SILVER; however, these can be easily calculated based on the dispatch schedule.

Case Study

Six scenarios are developed to address two questions regarding the value of demand response: three scenarios exploring the impacts of demand response magnitude (degree change and event frequency) in two building stocks differentiated by envelope and heating system upgrades.

First, to determine how the timings of demand response events might affect the value provided to the system, three levels of demand response magnitude (i.e., degree change and event frequency) are envisioned (Table 4-3). In the *baseline* scenario, building temperatures are dropped by 1 degree Celsius for up to 3 hours in response to a grid requirement for generation. This event is allowed to occur up to 1 time per day, up to a maximum of 20 times per month. Next, in the *high-energy* scenario, building temperatures are dropped by 4 degrees Celsius for 3 hours. Since a 4-degree temperature change reduces energy usage by slightly more than 3 times that of a 1-degree temperature change, this event is only allowed to occur 6 times per month. This ensures that a comparable amount of total energy is shifted in each case, and only the timing of when that shift occurs is varied[1].

Third, in the *frequent* scenario, building temperatures are again reduced by 1 degree Celsius, but for only 2 hours up to 4 times per day, and up to 30 times per month. In this scenario, the lowering of the event duration to 2 hours is balanced out by the higher monthly maximum of 30 events per month, allowing the same approximate amount of total energy to be shifted as in the other two scenarios. Meanwhile, the increased daily maximum of 4 events per day allows shifting to occur more frequently if that is found to be optimal.

Next, these three levels of DR event magnitude are simulated in two different building stock configurations in Regina, Saskatchewan. First, existing 2020 data is used to construct a *present-day* version of the city. Since only 10% of homes in Saskatchewan have electrified heating systems [95], 10% of the building stock is assumed to contribute to electric heating load and participate in demand response. Second, a *highly efficient* city is modeled assuming extensive envelope retrofits and the

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[1] As seen in Table 4-3, the average monthly amounts of energy shifted are only roughly similar. However, the high-energy case shows consistent performance between years despite shifting the most energy of all the cases in 2020 and the least energy of all the cases in 2050. This suggests that the values are close enough for the purposes of this study.

installation of high-efficiency ground source heat pumps in every building. In this version of Regina, 50% of the building stock is assumed to contribute to electric heating load and participate in DR. This proportion ensures that total heating load remains roughly similar between both cases.

Clean electricity is necessary for building electrification to have a positive environmental impact. Thus, before extensive electrification takes place, the power system should be decarbonized. For this study, additional renewable capacity is added to the existing grid in Regina. Like Regina today, the modelled grid for all six scenarios has a generation capacity of 88 MW hydro and 218 MW NG. Then, an additional 100 MW wind farm is installed, and 25% of Regina rooftops are outfitted with solar panels. These capacities were chosen based on our previous work [46], and because they represent a transitional situation which is less carbon-reliant than the existing grid, but not completely decarbonized. Transitional situations are important to explore because they represent the short-term decisions that are necessary in sequence to achieve long-term and deeper decarbonization scenarios [121,122]. In the specific scenario for this study, an increase in renewable capacity without phasing out any traditional generation allows the grid to use variable renewables when available, but still be able to fall back to traditional generation resources if needed.

Table 4-3: Setup of the 6 building-side scenarios explored in this study.

	Infrastructure Parameters		*Demand Response Parameters*				
Scenario Name	**City Year**	**% of Building Stock Participating**	**Temperature Change (°C)**	**Maximum Event Duration (Hours)**	**Maximum Number of Events Per Day**	**Maximum Number of Events Per Month**	**Average Monthly Energy Shifted (MWh)**
Baseline: Present-day	2020	10	1	3	1	20	235
Frequent: Present-day	2020	10	1	2	4	30	198
High-Energy: Present-day	2020	10	4	3	1	6	257
Baseline: Highly Efficient	2050	50	1	3	1	20	274
Frequent: Highly Efficient	2050	50	1	2	4	30	220
High-Energy: Highly Efficient	2050	50	4	3	1	6	174

Model Validation

SIVER and the building model were both validated in previous work in the absence of DR. SILVER was developed and validated in [40]. Meanwhile, in a previous work [46], the building model was compared to real utility data from SaskPower, and found to be representative.

To determine the accuracy of the impact of DR on demand load, two sets of building load curves for the present-day building stock in the presence of baseline DR were constructed and compared. First, the direct result from SILVER was calculated by adding the demand response component of the dispatch schedule from Step 3: Electricity System Model to the pre-DR load curve from Step 1: Building Model. Second, a higher-resolution version of the same load curve was produced by running the computed dispatch schedule at an individual building level in EnergyPlus. Validating the model at this scale determines the exact amount of energy shifted and recovered during each DR event, and can therefore be used as a ground truth to which the parameterized events can be compared: the closer the two load curves, the better the approximation provided by the parameterization method. It was found that the two load curves exhibited an R^2 value of 0.99 and differed by only 1.45% on average for each hour (Figure 4-5), indicating that the parameterization is a very good estimate for the available shiftable energy.

Finally, our values were compared to those found in the literature. O'Dwyer et al. [123] modelled shiftable heating load and estimated that around 75 MW could be shifted during a demand response event involving 2 million homes. When scaled down to Regina's building stock count of 80 thousand, their shiftable amount comes out to 3 MW total, which is similar in scale to the 6 MW we predicted for 1-degree shifts in 2020. Similarly, Zhou et al. [124] found that 0.12 KW per home could be shifted by cycling heating devices off for short periods during a single hour of utility load control. In our study, home energy use could be reduced by 0.75 KW per home, which is the same order of magnitude. Although our values are only within ballpark of the literature, this is acceptable because building flexibility estimates vary widely between models and scenarios – for example, Li et al. observed power reductions ranging from 0.5% to 65% of peak load among 85 papers reviewed [103].

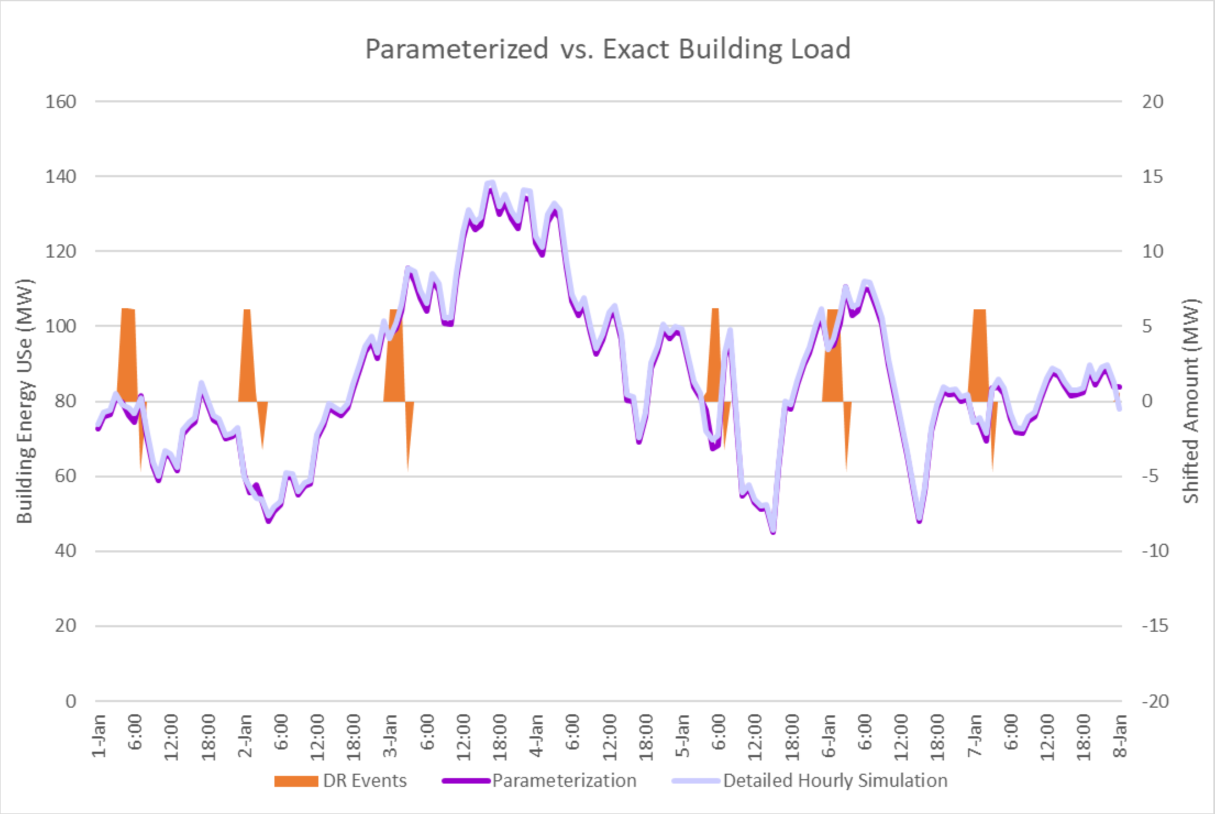

Figure 4-5: Building load in the presence of demand response events as estimated at characteristic timepoints (dark purple) versus directly simulated in the building model (light purple). Little difference can be seen between the two curves, regardless of when DR occurs (orange).

Assumptions and Limitations

Before discussing the results, it is important to keep in mind the limiting assumptions that were made during the modeling process. Most notable is our deterministic representation of all loads and variable renewable sources. On the building side, we assume that in the absence of demand response, all buildings are kept at a constant heating setpoint of 21°C in accordance with ASHRAE comfort standards [125]. We further assume that all buildings have one of three non-heating electric load profiles as simulated by Armstrong et al. [58]. Similarly, on the electricity side, SILVER optimizes each month while having complete information for that month. This means that electric demand and variable renewable availability are known with 100% certainty within our model, whereas in reality, future weather and future electric demand are uncertain until they occur, and generator dispatch levels are constantly adjusted in real time based on instantaneous changes in demand and VRE availability. Across both sectors, our assumptions of set schedules with little variation between individual buildings result in a modelled grid whose operation may differ slightly from and be less complex than that of a real grid. However, by reducing the computational intensity of the model, our simplifications facilitate the novel model linkage that is achieved in this work. Additionally, over- and under-predictions of values are likely to cancel each other out when looking at a full year of operation [126,127]. Due to these factors, we assume that our assumptions are justified for the purposes of this paper.

Finally, one additional important limitation is the specificity of this study. We only investigate a few simple DR strategies, and only one type of load – heating – is impacted by those strategies. Thus, our study represents only one specific case of demand response. Other DR schema and the inclusion of other loads can certainly be envisioned, and will be addressed in future work.

Results

Effects of Building Stock Upgrades

Before demand response is introduced to the system, both building stocks perform as expected. On an individual level, the envelope and heating system upgrades result in substantial energy savings, with the average highly efficient house using around 5x less energy than the average present-day house (Figure 4-6). Meanwhile, as specified by the study design, both the highly efficient (assuming 50% of all homes contribute to heat load) and the present-day (assuming only 10% of all homes contribute to heat load) building stocks use very similar amounts of energy (Figure 4-7).

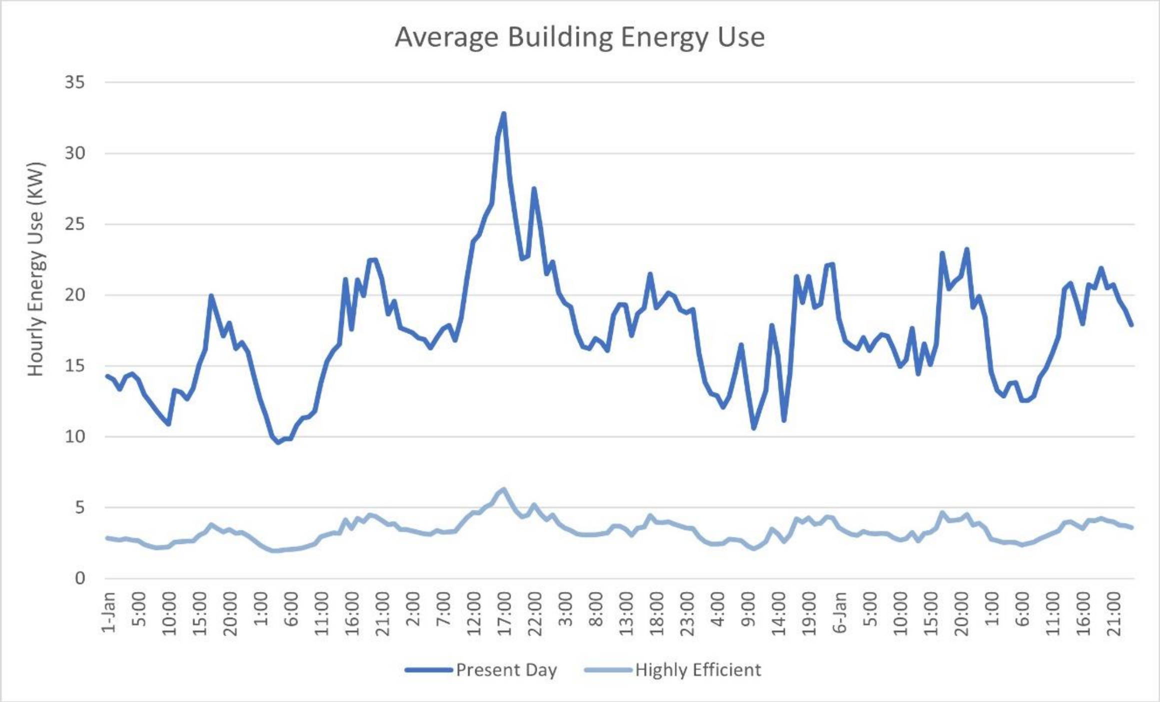

Figure 4-6: Energy use for an average building from each building stock composition during one week in the coldest month of the year. Both buildings use electricity for heating.

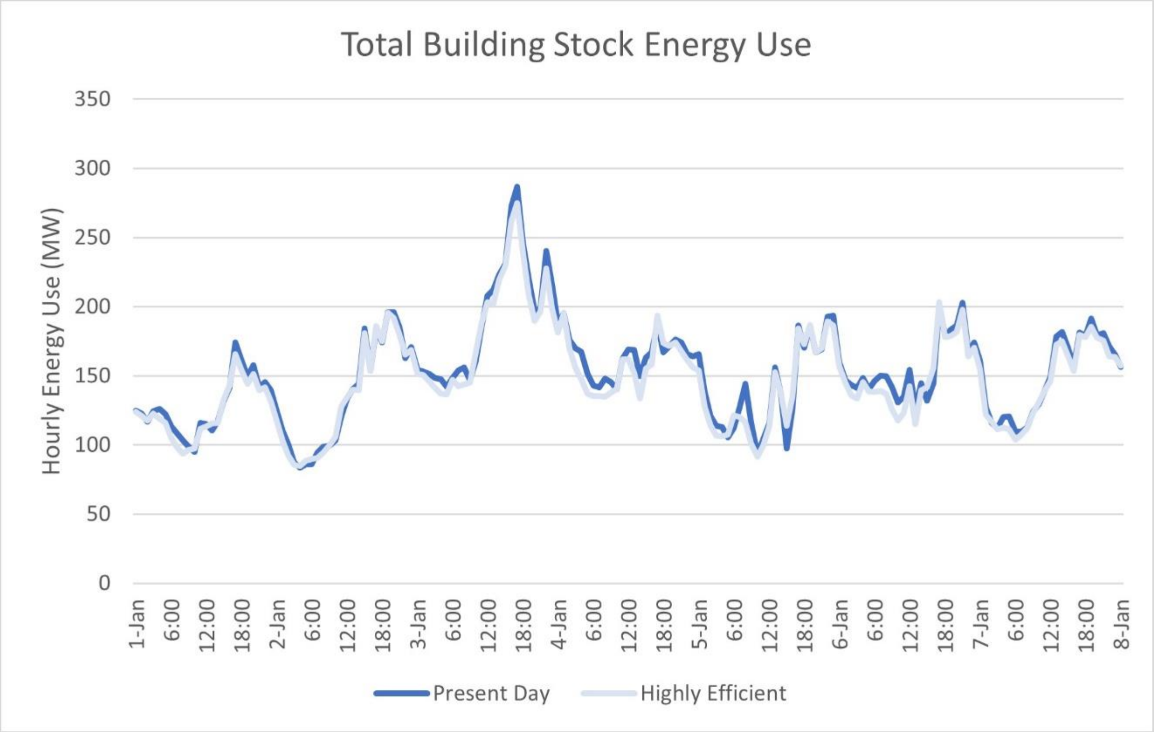

Figure 4-7: Total building stock energy use during one week in the coldest month of the year. The highly efficient building stock includes a greater number of buildings to account for increased penetration of electric heating technologies.

However, the similarity in total energy usage between the two building stocks does not translate to similar performance in the presence of DR. Within each strategy, the generation available from demand response varies by time of day, building stock composition, and month (Figure 4-8). Overall, the highly efficient building stock tends to have more morning availability, while the present-day building stock has more evening availability. Both trends are due to the effects of increased insulation efficiency, with greater generation availability seen in whichever stock reduces consumption more during demand response. Since the highly efficient buildings have more insulation, they are less able to be warmed by their environment in the morning half of the day, when temperatures are cold but increasing.
This results in greater energy savings – and therefore greater amounts of shiftable energy – from demand response during the mornings for this building type. Conversely, less insulation in present-day buildings means that those buildings lose more heat to the environment in the evening half of the day, when temperatures are warm but decreasing; as a result, evening DR events generate more energy in present-day buildings.

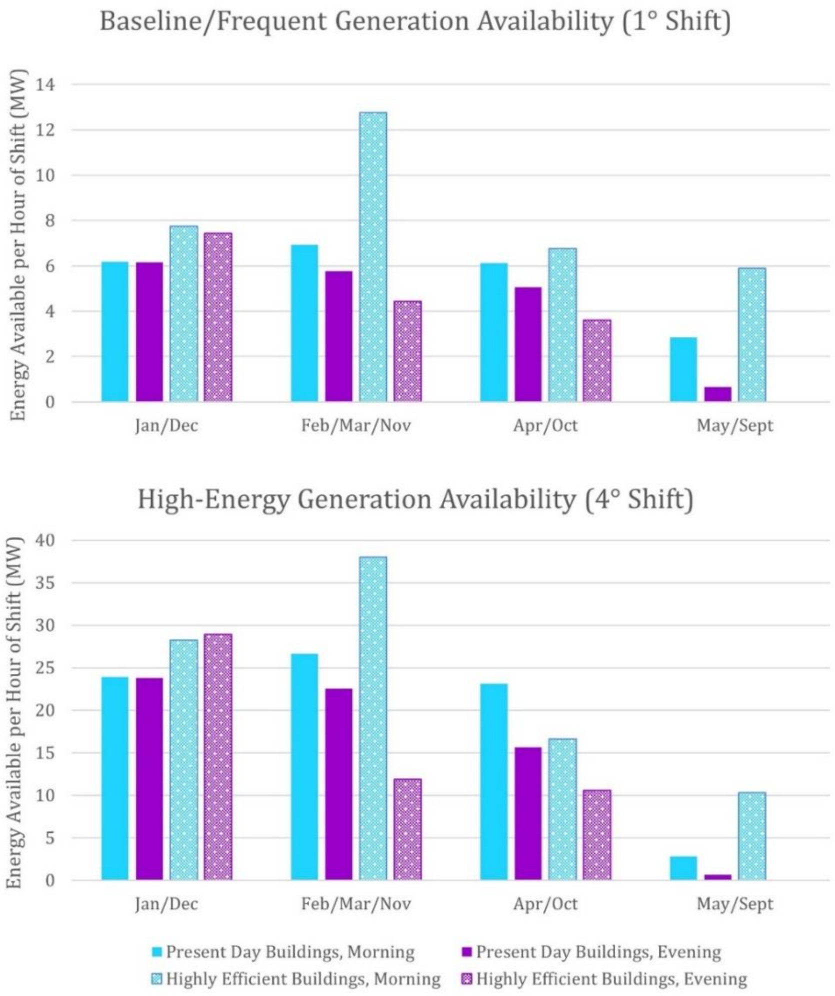

Figure 4-8: Energy available for generation shift events during each hour of DR. During the "morning" half of the day, which lasts from 4:00 until 15:59, temperatures are relatively cold, but increasing. Meanwhile, the "evening" half of the day lasts from 16:00 until 3:59 the next day, and temperatures are relatively warm, but decreasing. Grouped months were parameterized together and shift the same amount of energy at each time of the day; June, July, and August are not represented as heating is negligible during those months.

Effects of Demand Response Magnitude

Comparing the overall performance of the different demand response magnitudes and building stock compositions, it can be seen that high-energy shifts (changing setpoints by 4°C) are the most effective in terms of both cost and emission savings for both the present-day (2020) and highly efficient (2050) building stocks. Shifts of this magnitude are almost twice as impactful as the other two strategies, saving a rough annual total of $CAD 200K and 450 tonnes of CO_2 equivalence for each building stock (Figure 4-9).

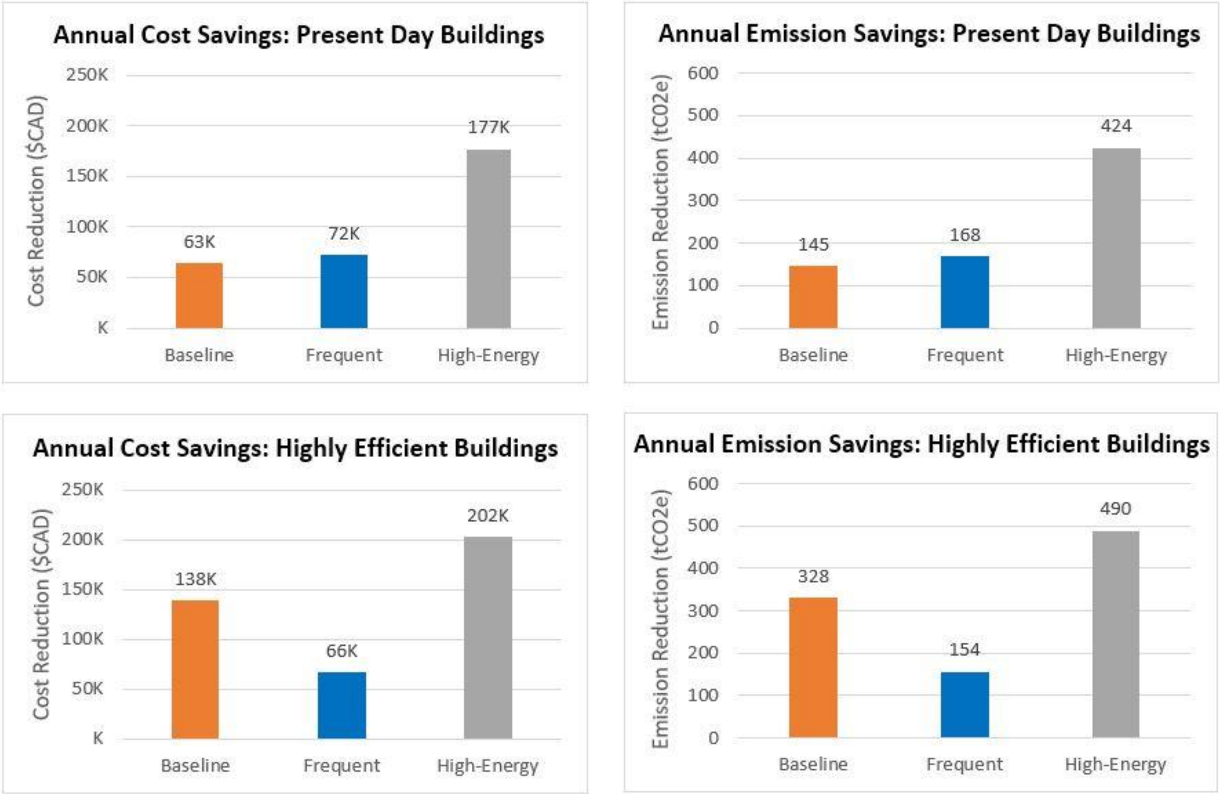

Figure 4-9: Annual operating cost and emission reductions for the modelled building stocks in the presence of demand response events of the modelled magnitudes.

For the frequent and high-energy shifting magnitudes, there is little difference in performance between the two building stocks. However, performance at the baseline magnitude dramatically increases as the building stock becomes more efficient. In the highly efficient building stock, emissions savings increase from around 150 to over 300 tonnes of CO_2 equivalence, while cost savings also doubled from around $CAD 65K to almost $CAD 140K (Figure 4-10).

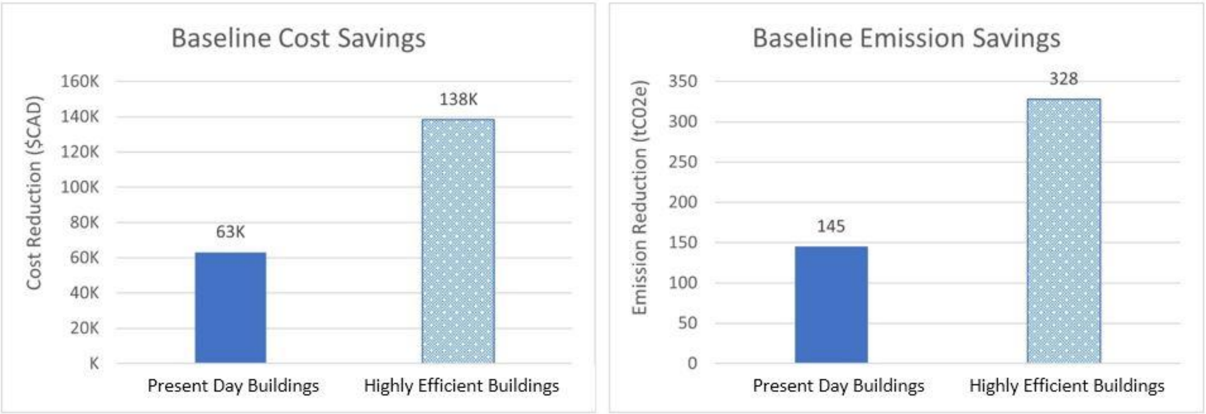

Figure 4-10: Performance comparison for the baseline case between the two building stock compositions. Both cost savings and emissions savings are approximately doubled as buildings became more efficient.

Explanatory Factors

The varying performance of the different DR magnitudes can be explained by the available shiftable energy under different conditions, the timing of demand response events as a function of VRE availability, and the differential impact of demand response events on NG and hydro generation.

First, although the present-day buildings generally have greater generation availability during the evenings, the morning generation availability tends to be larger overall (Figure 4-8), which contributes to the performance difference in the baseline case.

However, the algorithm is not always able to shift at the times with the most generation available because shifts need to align with specific timings in VRE availability. Since each generation shift is immediately followed by a recovery hour, the best timing for a shift is when renewable generation is low but increasing soon. Thus, in addition to the frequency constraints already imposed by the various strategies, the timing of DR events is selected by the algorithm from the small pool of favorable timepoints based on VRE (Figure 4-11). Since high-energy events are so infrequent, there are relatively more times at which these events could be scheduled, allowing the high-energy shifts for both building stocks to occur exclusively at times with the greatest generation availability. Frequent shifts in contrast are more constrained by VRE availability patterns and sometimes have to occur at times when the generation availability is lower, resulting in poorer performance for both building stocks. At the baseline magnitude, the higher generation availability during mornings in the highly efficient building stock combined with the somewhat-smaller number of shifts (as compared to the frequent strategy) results in increased performance for the highly efficient building stock, which can preferentially shift during mornings only.

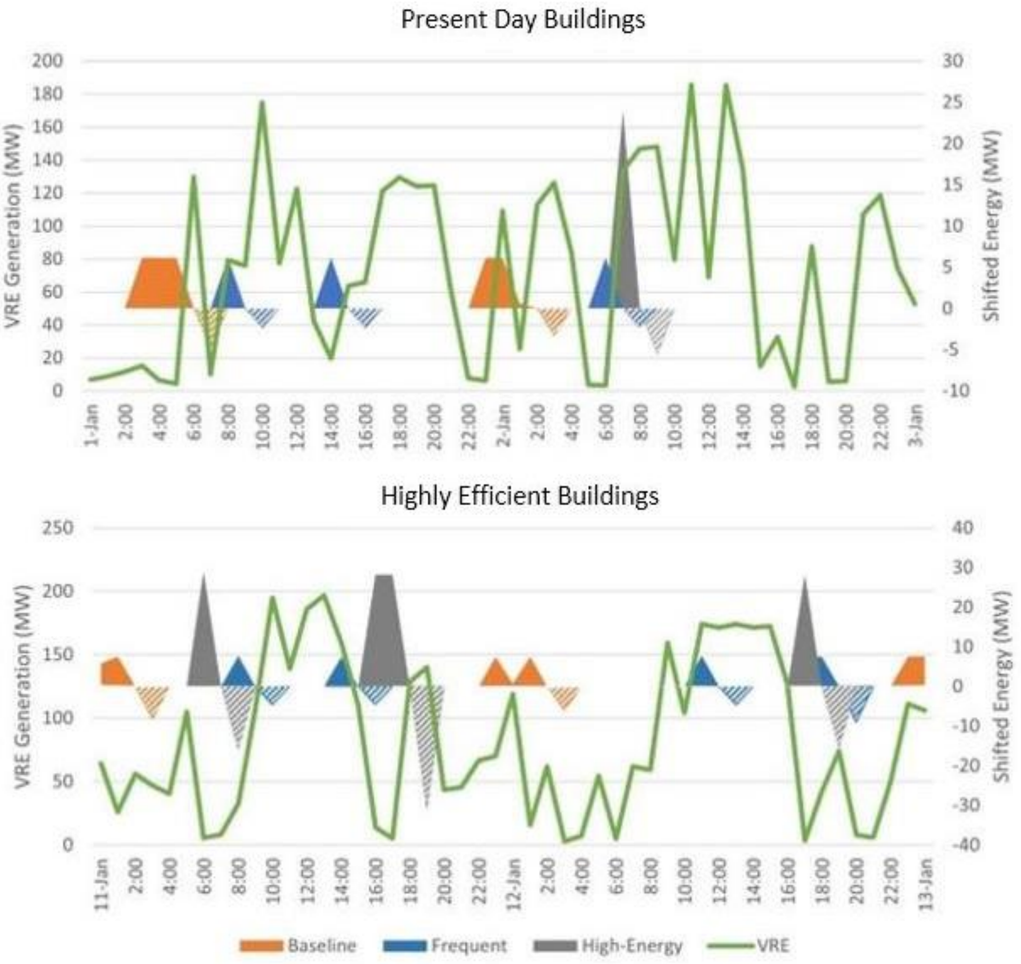

Figure 4-11: Demand response events (shading) and VRE generation (green line) in the coldest months for each building stock composition. Solid-colored shapes (positive) represent generation events, and striped shapes (negative) represent recovery. Generation is often aligned with dips in renewable energy production.

Finally, an important factor which exacerbates performance differences is how demand response impacts the capacity factors of natural gas and hydro, respectively. Since NG is much more expensive per megawatt-hour than hydro, the capacity factor of NG generation is lowered in all scenarios. However, for both building stocks, frequent shifts also significantly lower the capacity factor of hydro, while the high-energy strategy has very little impact on the capacity factor of hydro (Figure 4-12). This behavior can be explained by the association of NG generators with a start-up cost. After a certain reduction in NG generation, additional reduction requires at least one NG generator to turn off and be powered on again later, incurring the start-up cost. If only a small amount of DR generation is still available, the algorithm will choose to reduce (displace) hydro, thus avoiding the start-up cost. However, if the amount of available demand response generation is enough to offset the start-up cost, NG will be displaced instead. At the high-energy magnitude, the large amounts of energy able to be generated by demand response in a single event enable NG generation to be displaced almost exclusively, while the small amounts of energy available per shift in the frequent strategy have the opposite effect. For the baseline magnitude, the poorer-performing present-day buildings displace much more hydro than the highly efficient buildings (Figure 4-12); this is a ramification of the baseline magnitude’s ability to preferentially shift during the mornings, when available generation is significantly higher for the highly efficient buildings than for the present-day building stock.

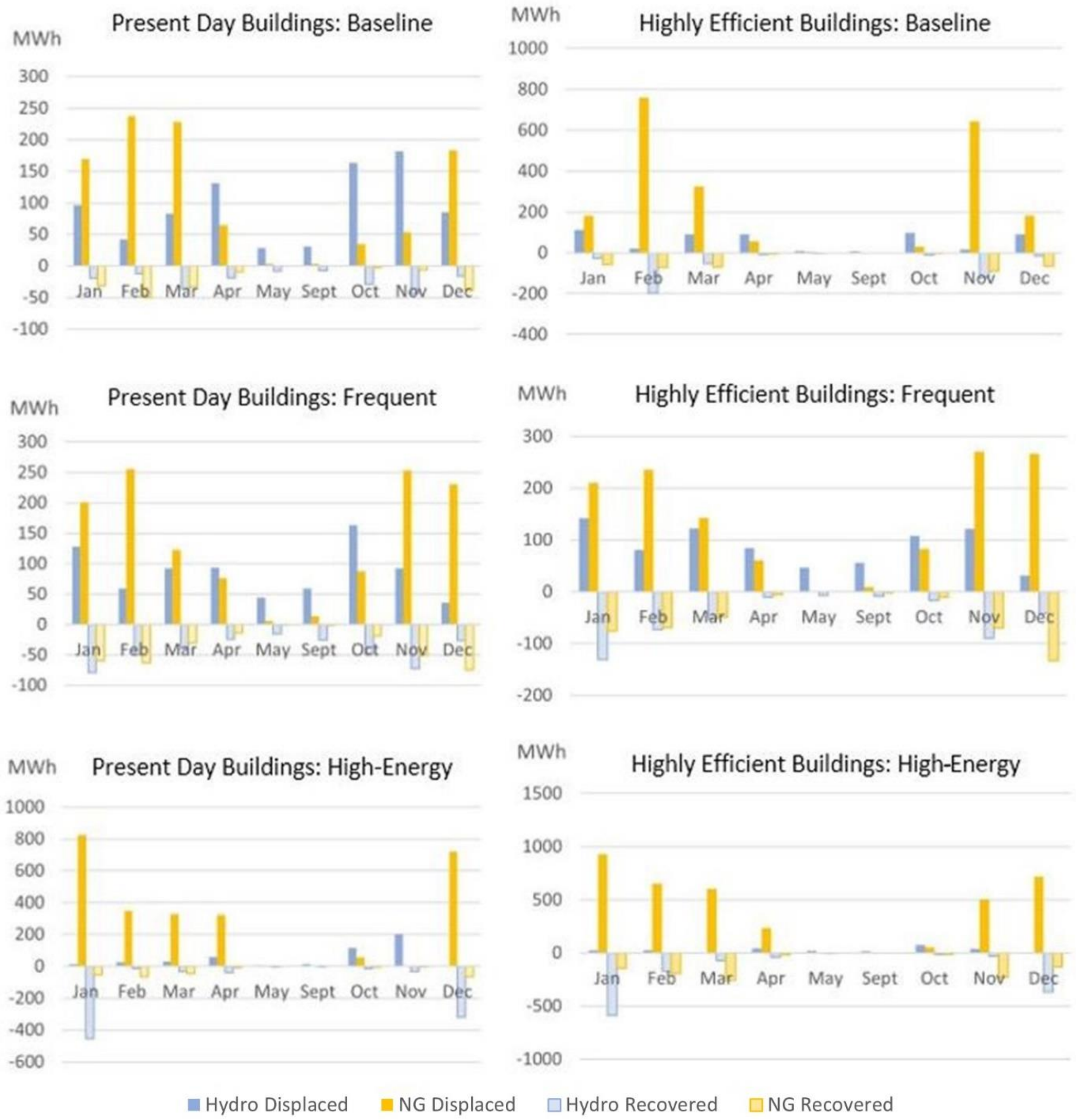

Figure 4-12: Amount and type of generation displaced (positive values) and recovered (negative values) by building demand response events of each event magnitude and for each building stock composition. June, July, and August are not shown because heating demand is negligible during those months.

Discussion

Generation Mix: Role of Natural Gas, Hydro, and Renewables

As expected, demand response had a positive impact on renewable utilization. By shifting energy when VRE generation was low and recovering energy when VRE generation was high, demand response replaced a significant amount of NG generation with VRE. However, as the results showed, renewable utilization is not the only factor in reducing the cost and emissions associated with energy use: the tradeoff between NG and hydro illustrates some of the difficulties in ensuring lowered carbon emissions. NG is more expensive per megawatt-hour, but is associated with a start-up cost when powering on a generator. In contrast, hydro is cheaper per megawatt-hour but freely able to turn on or off as needed. As a result of these characteristics, the capacity factor of hydro as well as NG was reduced by DR, especially when the number of DR events was high. This result is not ideal from an emissions standpoint, and it underlines the importance of coordination between demand-side electrification and supply-side decarbonization efforts. Simply adding renewables to the generation mix and replacing NG-powered appliances with electric ones does not by itself guarantee that emissions or operational costs will decrease. Instead, generation availability and demand requirements should be aligned to the greatest extent possible, to ensure that the use of low-cost and low-emission generation is maximized. This can be accomplished by continued scenario exploration through models such as the one used herein, or the use of different criteria to determine when shifting should occur (such as minimizing emissions instead of costs).

Large Impact of Infrequent, High-Energy Shifts

One might expect that frequent shifts of smaller magnitude would respond more often to changing grid conditions and thus contribute more flexibility to the grid. However, this flexibility ultimately proved to be a liability due to the large number of events scheduled. Because shifts occurred so frequently and needed to align with specific trends in VRE generation, not all such shifts were able to occur at the times with the highest demand response generation availability. In contrast, the high-energy magnitude shifts were much more impactful for reducing both costs and emissions. Since fewer shifts of high-energy magnitude occurred, these shifts were able to selectively occur only when demand response generation availability was at its highest. These effects were compounded by the algorithm's choice to reduce the capacity factor of NG instead of hydro. When demand response shifted small amounts of energy, inexpensive hydro was sometimes reduced rather than NG, to avoid incurring the start-up fee for turning a NG generator off and on. On the other hand, when DR shifted large volumes, NG was reduced instead.

These results have two important implications. First, the difficulty of scheduling: since DR recovery entails the use of additional energy relative to the baseline, additional generation costs will be incurred whenever recovery does not align with increased renewable production. Therefore, a well-designed DR program should seek to minimize the total number of recovery shifts required, or to pursue other strategies to mitigate the impact of recovery. Although some recovery is inevitable, the ratio of energy shifted (generated) to energy recovered can be increased through strategies such as shifting more energy at once, having fewer events, or allowing events to last for longer lengths of time, the latter of which also increases flexibility by allowing more possible hours during which recovery can occur. Secondly and relatedly, longer generation shifts that move greater amounts of energy at once are generally going to be the most effective for reducing both costs and emissions: when larger volumes of expensive or carbon-intensive generation are replaced by renewable generation via DR, associated start-up costs and ramping limitations become inconsequential. Additionally, since DR events are allowed to end early, generation events that last for longer numbers of hours will have more possible hours during which recovery might occur, which increases the probability of using renewable rather than traditional generation resources to recover previously-shifted energy. Longer, higher-energy generation events are inherently more intrusive to consumers, which may result in lower participation or require larger incentives; however, as has been shown, even a small number of yearly events can have a large impact on the system.

Mixed Effects of Building Stock Composition Changes

Surprisingly, a significant difference in the effectiveness of DR between the two building stock compositions was only observed in the baseline case. At the other DR magnitudes, changes to the composition of the building stock did not have a consistent effect on the amount of generation available for demand response. Compared to present-day generation availability, the highly efficient building stock sometimes had more energy and sometimes had less energy available for DR generation events, depending on the time of day, the month, and the degree change. This is due to the interplay of different factors relating to increased building efficiency: better heating systems reduce generation availability because less energy is needed to produce required indoor temperatures, but better envelopes allow heat to be retained for longer, which increases generation availability and reduces recovery costs. These mixed signals make it important for jurisdictions and energy distributors to perform exploratory studies before implementing policy changes. Only through detailed operational modeling can potential effects and trends be determined.

Policy Implications

A 2018 report by NRCan estimated that over 82% of buildings in Canada were outfitted with smart meters [128], which connect to the internet and allow utilities to remotely control building temperature setpoints. However, as seen in the appendix of this thesis, there are very few residential demand response programs available in Canada today. One reason for this may be the underwhelming per-household financial benefit of demand response. In this study, the most effective demand response strategy per household was the high energy shifting strategy in the present day buildings, wherein operating costs associated with approximately 8,700 homes were reduced by a total of $CAD 177,000 annually. On a per-home basis, this represents a saving of only $20 per home per year, which is very small and may not suffice as an economic motivation for consumer participation in demand response. Thus, if DR programs are to become widespread, is it crucial to come up with additional motivators beyond simple financial ones. This could be accomplished by promoting cultural values regarding the importance of reducing carbon emissions by every little bit possible, through legislation, or by coming up with DR control strategies that are increasingly less noticeable to occupants and are thus more likely to be accepted as a normalized part of building operation.

Comparison to the Literature

Several other works exhibit results that are consistent with our findings. Relating to our observed displacement of NG rather than hydro, Zhao et al. [129] noted that ramping constraints make thermal generators less flexible than pumped hydro, leading to potential cost increases when variable renewables are prioritized in the generation mix. Similarly, Imcharoenkul and Chaitusaney [130] found that as renewable penetration increases, the inflexibility of coal and NG leads to these generators being less affected by DR programs than other, more-flexible non-VRE sources. As well, Péan et al. [131] compared a price signal and an emissions signal for scheduling DR events, and found that although both of these decreased both the costs and the emissions associated with grid operation, the price-based signal produced a greater price decrease at the expense of some emissions savings. On the topic of varied results due to changes in building stock characteristics, Satchwell et al. [91] found that increasing envelope efficiency sometimes increased and sometimes decreased DR availability, and that the timing of building energy demand – especially whether building demand coincides with VRE generation – is important for determining the associated costs and emissions. Finally, Salo et al. [132] investigated several demand response strategies and found that the most effective involved substantial (43-50%) peak power limiting, which reduced internal temperature significantly; this supports our result that shifting more energy at once is better than smaller, more frequent shifts.

Limitations and Future Work

As mentioned previously, this study investigates only a few very similar DR strategies, and only one type of load. Therefore, future work should investigate different shifting strategies and include other potential sources of flexibility. Alternative shifting strategies could involve preheating buildings to a higher temperature when renewable generation is high, allowing less energy to be used for heating later. Or, generation events could be allowed to last for longer periods of time, which would allow for more options when scheduling the recovery hour. Another strategy could explore staggering setpoint changes to slightly reduce load when renewable availability is low, as opposed to shifting all at once as seen in this work. Staggering setpoint changes could result in a diminished rebound effect after load is shifted.

Also of note, other thermodynamic loads not covered in this study, such as water heating, refrigeration, commercial and industrial space heating, and cooling loads during the warmer months, could be used as additional sources of flexibility. Shifting strategies similar to those investigated for residential heating could be enacted in these loads. Incorporating these additional sources into a city’s demand response reservoir would result in increased flexibility.

One final potential source of flexibility which could be addressed in future work is the smart scheduling of appliances, in which certain loads that are not time-sensitive, such as dishwashers or laundry machines, are scheduled to occur at optimal times for the grid. Our current formulation does not apply to these types of loads since they are not thermodynamic, but rather are discretely scheduled (i.e., either on or off) and operate only for short periods during the day. However, these could be included in a future version of our model by representing relevant shiftable loads in more detail and applying additional constraints to describe when and how these loads can be shifted and rescheduled. One example of constraints for non-time-sensitive, non-thermodynamic loads is seen in the previously-referenced work by McPherson and Stoll [47].

Conclusions

This paper demonstrates the effectiveness of building DR and has important implications for policymakers drafting regulations at the intersection of demand electrification and grid decarbonization.

- *Building demand response can provide valuable flexibility to the grid, but the most effective strategies for shifting energy rely on shedding large amounts of energy at once, rather than shifting small amounts of energy with greater frequency.*

Building demand response in the form of global setpoint changes can mitigate the unpredictability of VRE by reducing the building load when VRE generation is low, and increasing the load when VRE generation is high. This can result in substantial operational cost savings and emissions reductions. However, setpoint changes are most effective when building temperatures are allowed to vary several degrees at once, as this offsets potential costs associated with changing the on/off status of generators. Since large setpoint changes have greater impacts on occupant comfort, generous incentives may be required to ensure consumer participation.

- *In a cost-driven market, the pricing schemes of different assets determine when and how they are used.*

Despite NG being significantly more expensive than hydro, the start-up costs associated with NG generation sometimes caused the system to reduce the capacity factor of hydro rather than NG generation. This was one of the most unexpected results of the study, and it also had a significant impact on the emission and cost savings associated with demand response. For policy makers, this result suggests that the inflexibility of NG generation may pose a challenge as grids transition to increased reliance on renewable sources. Imposing steep emissions taxes on high-carbon generation may help meet this challenge, but it is also important to increase the capacity of other reliable sources (for example, by adding storage) so that NG generators can stay off once they are turned off.

- *Building stock upgrades require higher participation rates in demand response programs, but do not necessarily decrease the value or flexibility that demand response can provide.*

As buildings increase in efficiency, the shrinking size of the total building load means that a higher number of buildings must participate in DR to achieve the same capacity of available shiftable energy. However, better insulation also allows energy to be stored for longer periods of time, and causes buildings to take longer to be passively heated by the environment, but retain heat for longer once they have reached their setpoint. This results in larger differences between daytime and nighttime demand response availability, which can be exploited to achieve larger cost and emissions reductions. More generally, building upgrades do not result in buildings that cannot contribute to increased grid flexibility via demand response.

- *Exploratory modelling studies are needed to determine the specific effects of intended demand response schemes, building stock upgrades, or other changes potentially affecting electricity supply and demand.*

Changes in the shape of the building load curve can have large effects on DR availability and on the timing of energy shifts. Further, although renewables with no operation costs will always be utilized when available, the pricing dynamics of the rest of the grid can play a large role in determining which types of generation will be reduced when renewable energy becomes available, and which types of generation are relied on when little renewable energy is available. This means that the impacts of electrification and decarbonization may vary based on the details of the changes being made. As buildings and electricity systems gradually transition to higher efficiencies and higher renewable penetration, models can play an important role in determining the best strategies for modernization.

Through the novel model linkage proposed herein, computationally-inexpensive parameterization of yearly demand response availability, and detailed exploration of scenarios relating to both demand response event magnitude and building stock upgrades, this work provides an important contribution to both methodological literature and policy applications. We hope that researchers and policy-makers alike can use our results and modelling framework to answer important questions relating to residential building efficiency, demand response, and renewable energy integration.

Chapter 5: Conclusion

In this thesis, a detailed model of building energy use was developed, linked to an operational model of an electricity system, and used to study the impacts of building efficiency increases and demand response on the building system's ability to be powered by an increased share of variable renewable energy. This was accomplished through three major phases of development. First, the building model was created and was linked to the electricity system model via a curtailment signal, in which building setpoints were adjusted based on the presence or absence of excess renewable generation (curtailment). During this development step, increased building efficiency was shown to limit the additional electricity demand associated with increased penetration of electric heating and cooling systems. It was also shown that demand response could effectively use almost all the curtailed renewable generation, and that building pre-heating and cooling combined with relaxed setpoints could reduce overall building energy use.

Second, the model was validated in multiple ways. During theoretical and physical validation, the model was compared to real measured data and was found to be sufficiently matching per existing industry standards. Then, sensitivity analyses were conducted to determine the effects of various input parameters, and it was shown that envelope and heating system upgrades resulted in the expected effects on building electricity use. After this, important constraints which linked the building and electricity system model in the third phase of development were examined in detail to determine that these constraints were having their intended effect within the model linkage. Next, the case studies explored and general conclusions drawn by the model were compared to existing literature and found to be in line with current theory.

Third and finally, an improved version of model linkage was enacted by a multistep procedure in which important information was extracted from the building model and passed into the electricity system model during optimization, enabling the timing of building demand response events to be directly optimized alongside the grid's generation and transmission assets. This version of the model linkage was similar in accuracy to the first version, but took a much more practical approach to this issue of demand response, as it maximized the utility of building flexibility and changed building setpoints only sometimes, rather than controlling them at every hour of the year. Case studies were then performed to compare the value of different demand response strategies in both a contemporary building stock and a building stock which was retrofitted with highly insulating envelope materials and high efficiency ground source heat pumps. The results indicated that demand response events shifting more energy at once were better able to reduce emissions by allowing natural gas generators to turn off, that building efficiency increases sometimes increased and sometimes decreased available shiftable energy, and that demand response was effectively able to shift building energy use towards times with higher variable renewable availability.

The most important contribution of this thesis is its methodology, specifically its integration of two detailed models from different sectors into a single workflow. To the author's knowledge, this broad of a perspective – incorporating an entire building community AND a provincial electric grid – is very rarely taken in modeling works. Thus, the method presented within this thesis is an important blueprint for how to achieve model integration for large-scale models.

However, there are three main areas in which this model framework can be improved. The first area is the inclusion of additional technologies and other sources of flexibility which could further increase the performance of the electric grid. These can include the detailed representation of other shiftable loads such as appliance use and water heating, the inclusion of battery storage technologies, and the incorporation of technologies such as dynamic thermal rating of transmission lines, which can improve the performance of existing electricity infrastructure. The second main area in which this model framework can be improved is by increasing model robustness and accuracy, which can be achieved by accounting for uncertainty within the model and/or by representing certain model features in greater detail, for example by directly incorporating building comfort metrics into the electricity system model. Third, the case studies presented in this thesis are limited, and additional case studies as well as the application of this model framework to other cities and other configurations of the electric grid could be very informative. Potential ways to incorporate these developments into future work are discussed below.

Inclusion of other shiftable load types has the potential to greatly increase the flexibility associated with residential energy use. Examples of demand response involving time-shiftable household appliance loads are seen in [133–135], all of which describe constraints that enforce appliance energy use in the context of optimized energy management for single buildings. Constraints such as these could be written to account for appliance loads in the archetypal homes used in this thesis, and these constraints could then be aggregated to the community level and included within the electricity system model, which would allow the represented appliances to be operated at times optimal for the grid. Another way to incorporate appliance usage is through non-intrusive load decomposition as seen in [136–139], in which signal processing is used to extract appliance load profiles from aggregate electricity use data. These load profiles could also be used to write appliance-usage constraints that could be included within the electricity system model.

If the functions of existing components of the electric grid are able to be improved, this could provide a pathway to increase grid performance while limiting the costs associated with grid improvement. One way to accomplish this is by using a dynamic thermal rating system as seen in [140–142]. Using this method, transmission line capacities change dynamically based on temperature conditions, which often increases their capacity since non-dynamic rating of transmission lines must account for unlikely worst-case scenarios [143]. This innovation could be incorporated into the electricity system model by allowing transmission line capacity to vary based on current weather conditions, and would allow the model to import more energy from further away to mitigate against fluctuations in renewable generation or in demand.

One other important technology which is not included in this work is battery storage. The electricity system model used in this work has incorporated battery storage in other publications such as [46,144], and battery storage has been shown to greatly increase the ability of the electric grid to use variable renewable energy [46]. Additional case studies to the ones performed in Chapter 4 can be explored using the aforementioned framework and can elucidate how the addition of a battery storage system affects the utility of demand response and enables building electric demand to be met with renewable generation.

As mentioned in Chapter 4, one conceptual limitation of the model framework is that it is deterministic: it is assumed that electricity demand and weather conditions are known with 100% certainty while the model is solved, but in reality this is not the case. To increase the robustness and accuracy of the model, techniques such as stochastic programming or robust optimization could be used (i.e., [135]), which incorporate probability values for uncertain parameters or provide approximate solutions that take into account the likelihood of actual values being different from assumed values. These methods could be implemented within the electricity system model during the solving process, or could be applied to the building model by adjusting the results of the simulation software.

It could also be possible to further the integration between the electricity and building systems. One way to do this could be by directly incorporating comfort level and customer utility into the electricity system model's objective function, as seen in [133]; or, building temperatures could be directly controlled within the electricity system model, as seen in [134]. For both methods, thermodynamic information could be extracted from the building model by simulating building load at different operating temperatures, and then constraints could be written that restrict the energy use of the building sector to specify when target temperatures are maintained and when temperature relaxation is allowed. Rather than specifying that demand response occur as a series of discrete events as seen in this thesis, the new strategies listed here would allow the electric grid to directly manage the timing of building energy use. This doesn't necessarily improve the accuracy of the model, but it does present different ways to conceptualize temperature-based demand response, which are interesting to consider and could potentially lead to different results.

Finally, the case studies performed in this thesis are all focused on the city of Regina and consider only a small set of building retrofits and demand response strategies. Exploring additional ways to implement demand response, such as those discussed in Chapter 4 and in the previous paragraph, could unlock more opportunities for the electric grid to benefit from building flexibility. Similarly, other changes in the building stock, such as the building of new homes, increasing population density, or exploring changes to city layout, could have important implications in the future of building energy use. Likewise, applying this model framework to other locations could be helpful to jurisdictions seeking to reduce their carbon emissions, and could even inform provincial or national decarbonization policy if applied to many cities. Given the useful effects of building demand response and the high carbon emission reduction potential of coordinated building-side electrification and supply-side variable renewable integration, this model framework should continue to be used in the pursuit of decarbonization goals.

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Appendix

A1: Policy Review

The tables below (Tables A-1 through A-5) contain a review of building-level demand-side management, decentralized generation, envelope and appliance upgrades, and other related policies currently available in Canada. The heat pump chart in particular was contributed to a report on energy systems integration initiatives conducted by the Canadian Institute for Climate Choices [113].

Historically, decarbonization efforts in the building sector have not always gone well for Canada. Because of the conflicting roles of the national government (which can sign treaties such as the Kyoto Protocol) and the provincial governments (which are in control of their natural resources, including electricity), Canada's initial attempt to develop demand-side management resources in the 1990s was centered around voluntary policies that focused on educating people and promoting energy efficiency as a moral and cultural value [145]. This approach was ineffective, in part because policies were not adopted at a high enough rate to cause widespread change [9].

Similarly, a 2004 attempt by the province of Ontario to implement widespread demand-side management also suffered poor results due to a reliance on voluntary actions. Although smart meters became widespread in homes and businesses by 2010 as a result of the policy, energy prices rose and peak demand was often not reduced as intended [146]. Among other issues, the involvement of a large number of distribution companies resulted in high implementation costs and difficulties in integrating essential data sources for the devices [147]. As well, the time-of-use pricing schemes employed failed to consistently align with electricity needs and did not offer large enough price differentials to effectively motivate large-scale changes in consumer behavior [148].

Unfortunately, existing policies aimed at building-side decarbonization in Canada today continue to focus on increasing the efficiency of envelopes or appliances through voluntary changes. For example, in the residential sector, many existing policies offer financial incentives supporting the installation of high-efficiency heat pumps. In the commercial sector, demand-response plans are common and offer a number of different pricing schemes and possible consumer actions. While the existence of these policies is certainly a step in the right direction, mandatory legislation may be required to ensure that participation levels are high enough to have a significant impact on Canada’s carbon emissions.

Table A-1-1: Canadian policy initiatives focused on increasing building efficiency.

Efficiency Programs

Definition and Comments: These are targeted at increasing the efficiency of new or existing building envelopes, building systems, and appliances. A plethora of similar programs exist nationally, but this chart provides sufficient examples of what these might look like. A related concept is that of "net zero buildings," which are so highly efficient that they are able to produce as much energy as they need.

Entity	**Entity Level or Type**	**Policy Name**	**Years**	**Category**	**Target**	**Description**	**Link**
NRCan	National government	EnerGuide	2006-present	Envelope and Appliance Efficiency	Homeowners, Consumers, Manufacturers	Products and homes are inspected and rated to certify their efficiency.	https://www.nrcan.gc.ca/energy-efficiency/energuide/12523
NRCan	National government	EnergySTAR Certified Homes	present	Envelope and Appliance Efficiency	Homeowners; Builders	Builders can be licensed and homes can be certified for meeting certain efficiency standards	https://www.nrcan.gc.ca/energy-efficiency/energy-star-canada/energy-star-for-new-homes/22179
NRCan	National government	R-2000 Net Zero Energy Pilot	2013-2016	Net Zero Building	Builders	Educated, certified, and recognized builders for constructing net-zero homes that met a strict set of performance standards, including EnerGuide (see above), appropriate use of on-site PV, and envelope and insulation requirements.	https://www.nrcan.gc.ca/energy-efficiency/energy-efficiency-homes/buying-energy-efficient-new-home/netzero-future-building-standards/20581
NRCan	National government	Energy Savings Rebate program – Ontario	2019-2021	Appliance Efficiency	Retailers	Offered rebates for the sale of products promoting energy-efficiency in Ontario	https://www.canada.ca/en/environment-climate-change/services/climate-change/low-carbon-economy-fund/energy-savings-rebate.html

Efficiency Programs

Definition and Comments: These are targeted at increasing the efficiency of new or existing building envelopes, building systems, and appliances. A plethora of similar programs exist nationally, but this chart provides sufficient examples of what these might look like. A related concept is that of “net zero buildings,” which are so highly efficient that they are able to produce as much energy as they need.

Entity	**Entity Level or Type**	**Policy Name**	**Years**	**Category**	**Target**	**Description**	**Link**
NRCan, on behalf of Régie du bâtiment du Québec	Collaboration between national and provincial government	Quebec Construction Code, Chapter I.1 – Energy Efficiency of Buildings, and National Energy Code of Canada for Buildings 2015 (amended)	2021-present	Envelope Efficiency	Builders	“Sets out technical requirements for the energy-efficient design and construction of new buildings, additions and public swimming pools in Quebec”	https://nrc.canada.ca/index.php/en/stories/now-available-quebec-construction-code-chapter-i1-energy-efficiency-buildings-national-energy-code
Canada Green Building Council	National nonprofit	Various programs	2002-present	Envelope and Appliance Efficiency	Homeowners and Builders	Supports various green building standards, such as LEED for Canada, and the WELL Building Standard (both of which certify buildings based on their performance)	https://www.cagbc.org/
Built Green Canada	Industry standards organization partnered with national government	Various programs	Present	Envelope Efficiency	Builders	Third-party independent certification for sustainable home construction	https://www.builtgreencanada.ca/
British Columbia	Provincial government	BC Step Code	2014-Present	Envelope Efficiency	Builders, Homeowners	Voluntary standard that provides incremental and measurable energy-efficiency requirements for new constructions and retrofits. Local governments choose whether to adopt.	http://www.energystepcode.ca/
Quebec	Provincial government	Novaclimat	2008-present	Envelope Efficiency; Building System Efficiency	Home and Building Owners; Builders	Certifies new buildings; inspects existing buildings and provides funding to improve insulation and ventilation systems	https://transitionenergetique.gouv.qc.ca/en/residential/programs/novoclimat

Efficiency Programs

Definition and Comments: These are targeted at increasing the efficiency of new or existing building envelopes, building systems, and appliances. A plethora of similar programs exist nationally, but this chart provides sufficient examples of what these might look like. A related concept is that of “net zero buildings,” which are so highly efficient that they are able to produce as much energy as they need.

Entity	Entity Level or Type	Policy Name	Years	Category	Target	Description	Link
BC Hydro	Utility company	Electrification Engagement Plan	2021-2026	Appliance Electrification; Building System Efficiency	Consumers (both businesses and individuals)	Increase load by increasing electrification, which will allow grid to benefit from economies of scale.	https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/electrification/Electrification-Plan-Engagement-20210414-Buildings-Presentation.pdf
BC Hydro	Utility company	Appliance rebates	Present	Appliance Efficiency	Homeowners	Offers rebates on new appliances if they are efficient enough	https://www.bchydro.com/powersmart/residential/savings-and-rebates/current-rebates-buy-backs/appliance-rebates.html

Table A-1-2: Canadian policy initiatives relating to the installation and deployment of smart grids.

Smart Grid Programs

Definition and comments: These programs all deal with the installation or use of smart grids, which include advanced control features such as advanced metering if energy use, remote or programmable control, and user-friendly analytics.

Entity	Entity Level or Type	Policy Name	Years	Target	Description	Link
NRCan	National government	Smart Grid Program	2020-2024	Utility Companies	Funds the widespread installation and deployment of smart meters in homes by utility companies. Seventeen projects collectively received $100M over four years; projects ranged from exploratory to operational.	https://www.nrcan.gc.ca/sites/nrcan/files/environment/Smart-Grid-2020-en.pdf
BC Hydro	Main electric utility in BC	Smart Metering Program	2010-2012	Customers	Replaced 1.8 million existing customer meters with digital smart meters. Objectives: allow consumers to be informed about their energy use; reduce operating costs.	https://www.infrastructurebc.com/projects/operational-complete/smart-metering-program/
Ontario	Provincial government	Ontario Smart Metering Initiative	2004-2010	Business and residential electricity consumers	Install smart meters in all Ontario homes and businesses	http://www.ic.gc.ca/app/oca/crd/dcmnt.do?id=2660&lang=eng

Table A-1-3: Canadian policy initiatives supporting distributed generation.

Distributed Generation Programs

Definition and comments: These programs support the installation and deployment of renewable generation resources close to where the generated energy will be used.

Entity	Entity Level or Type	Policy Name	Years	Target	Description	Link
Alberta	Provincial government	Micro-generation regulation	2008-present	Homeowners, Businesses, Small Power Plants	Allows Albertans to generate their own energy, and to receive a credit for energy they sell back to the grid	https://www.alberta.ca/micro-generation.aspx
British Columbia	Provincial government	2002 Energy Plan: Energy for Our Future	2002-2019	Homeowners, Businesses, First Nations Communities	Funding for distributed-connected generation and smart meters	https://ceri.ca/assets/files/CERI%20Electricity%20Report%20%20-%20January%202020.pdf
New Brunswick	Provincial government	Embedded Generation program	Present	Small-scale Generators	Fixed price for selling electricity back to the grid	https://www.nbpower.com/en/products-services/embedded-generation/
Nova Scotia	Provincial government	Enhanced Net Metering and Solar for Community Buildings (two programs)	2015-present	Small Generators, Homeowners, Businesses	Long-term fixed price contracts for selling back to grid	https://ceri.ca/assets/files/CERI%20Electricity%20Report%20%20-%20January%202020.pdf
Nova Scotia	Provincial government	Community Feed-In Tariff	2010-2016	Community Distribution Infrastructure	Added renewable generation capacity	https://energy.novascotia.ca/renewables/programs-and-projects/comfit

Distributed Generation Programs

Definition and comments: These programs support the installation and deployment of renewable generation resources close to where the generated energy will be used.

Entity	Entity Level or Type	Policy Name	Years	Target	Description	Link
Manitoba Hydro	Provincial utility company	Technical requirements for connecting distributed resources to Manitoba Hydro distribution system	2003-present	Consumers; Site Owners	Regulatory framework for consumers to produce their own electricity	https://ceri.ca/assets/files/CERI%20Electricity%20Report%20%20-%20January%202020.pdf
SaskPower	Provincial utility company	Small Power Production Program	2007-2018	Small Power Plants	Allow small power plants to generate clean energy for their own usage	https://ceri.ca/assets/files/CERI%20Electricity%20Report%20%20-%20January%202020.pdf
SaskPower	Provincial utility company	Net Metering program	2019-2021	Consumers, Homeowners, Businesses	Customers can receive credits for generating excess power	https://www.saskpower.com/Our-Power-Future/Powering-2030/Generating-Power-as-an-Individual/Using-the-Power-You-Make/Net-Metering

Table A-1-4: Canadian policy initiatives relating to demand response.

Demand-Response Programs

Definition and comments: These programs all incorporate some form of real-time demand response, in which an entity (usually a utility company) attempts to manipulate short-term demand via changing prices and/or pre-defined agreements allowing direct utility control of some end uses.

Entity	Entity Level or Type	Policy Name	Years	Target	Description	Link
Alberta Electric System Operator	Provincial grid and market operator	Load Shield Service for Imports	2011-present	Businesses	Based on Alberta-British Columbia interconnection conditions, participants will sometimes be asked to "arm" certain loads, which can be turned off immediately if needed. Plans are tailored to each participant.	https://www.enelx.com/n-a/en/faq/eindustry/alberta-lssi-dr
Alberta Electric System Operator	Provincial grid and market operator	Operating Reserves Program	present	Large Consumers	Participants are on standby to reduce load within minutes of notification.	https://www.enelx.com/n-a/en/faq/eindustry/aeso-operating-reserves-program
Capital Power	Power management service in Alberta	Coincident Peak Demand Management Tool	Present	Consumers	Smart dashboard informs customers of approaching peak demand periods, allowing customers to avoid charges	https://www.capitalpower.com/who-we-are/energy-services/
BC Hydro	Provincial utility company	Automated Demand Response trial	2021-2022	Businesses	Pilot program: participants have devices installed and will follow a customized and automatic demand-response program during the trial period.	https://www.bchydro.com/powersmart/business/programs/auto-demand-response.html?WT.mc_rd=rd_autodemandresponse
Newfoundland Labrador Hydro	Provincial utility company	Demand Charges	present	Businesses	Customers are charged if their instantaneous demand ever exceeds a certain amount.	https://nlhydro.com/customer-service/commercial-customers/demand-charges/

Demand-Response Programs

Definition and comments: These programs all incorporate some form of real-time demand response, in which an entity (usually a utility company) attempts to manipulate short-term demand via changing prices and/or pre-defined agreements allowing direct utility control of some end uses.

Entity	Entity Level or Type	Policy Name	Years	Target	Description	Link
New Brunswick Power Corporation, University of New Brunswick, and several other utility companies	Multi-utility consortium in Maritime Provinces (New Brunswick, Nova Scotia, and Prince Edward Island)	PowerShift Atlantic	2010-2015	Residential Consumers; Businesses	Pilot/demonstration project. Participants received smart devices with some energy storage capabilities. An energy management system connected to these devices shifted load without customers being affected.	https://www.nrcan.gc.ca/science-and-data/funding-partnerships/funding-opportunities/current-investments/electricity-load-control-demonstration/4975
Ontario	Trend observed in province as result of Smart Metering Initiative (see above)	Time of use (ToU) pricing	2010-2016	Consumers	ToU pricing became standard once smart meters became widespread in Ontario. However, peak demand was often not curtailed, and electricity prices grew overall.	https://www.cbc.ca/news/canada/toronto/smart-meters-hydro-bills-ontario-time-of-use-pricing-1.3862462
Hydro One	Major utility company in Ontario	ToU pricing	Present	Consumers	Time-of-use periods are defined for each day in a six-month interval based on the time of day and the type of day (weekday or weekend/holiday). Each period is associated with a pre-defined price.	https://www.hydroone.com/rates-and-billing/rates-and-charges/electricity-pricing-and-costs
Independent Electricity System Operator (IESO)	Government-owned regulatory body (specifically, it is a Crown corporation and ISO) in Ontario	ToU and tiered pricing	Present	Consumers	Some consumers pay ToU rates, such as the ones described above. There is also a tiered pricing scheme, in which the electricity rate price is based on monthly usage.	https://ieso.ca/en/Learn/Electricity-Pricing/For-Residents-and-Small-Businesses

Demand-Response Programs

Definition and comments: These programs all incorporate some form of real-time demand response, in which an entity (usually a utility company) attempts to manipulate short-term demand via changing prices and/or pre-defined agreements allowing direct utility control of some end uses.

Entity	**Entity Level or Type**	**Policy Name**	**Years**	**Target**	**Description**	**Link**
Hydro Quebec	Electric utility in Quebec	Winter Credit Option	Present	Consumers	Customers' typical energy use is measured, and customers are notified of peak demand events one day in advance. When peak demand occurs, customers receive a credit based on how much they reduce their energy usage relative to their own normal usage.	https://www.hydroquebec.com/residential/customer-space/rates/winter-credit-option.html
Hydro Quebec	Electric utility in Quebec	Rate Flex D	Present	Consumers	Customers pay extra-low price during "regular" times, and pay an extra-high price during peak demand events, which are announced in advance.	https://www.hydroquebec.com/residential/customer-space/rates/rate-flex-d.html
SaskPower	Electric utility in Saskatchewan	Demand Response Program	Present	Large Consumers	Contract-based program with 1-2 year terms. Participants reduce load or shift power use according to a customized plan.	https://www.saskpower.com/Efficiency-Programs-and-Tips/Saving-Power-At-Work/Savings-Programs/Business-Programs/Demand-Response-Program
Yukon Energy and NRCan	Utility company in Yukon (with funding from national government)	Peak Smart	2018-2021	Consumers	Part of NRCan Smart Grid Program. Consumers given smart thermostat or water tank controller that can be controlled remotely in order to manage peak demand	https://yukonenergy.ca/energy-in-yukon/saving-energy/peak-smart

Table A-1-5: Canadian policy initiatives relating to heat pumps.

Heat Pump Programs

Definition and comments: This chart lists all available incentives towards high-efficiency heat pump installation available in Canada at time of writing.

Entity	Entity Level or Type	Policy Name	Years	Target	Description	Link
NRCan	National government	Install or replace a ground Source Heat Pump	Present	Homeowners in all provinces	$5000 towards the new installation of a full heat pump system, or $3000 towards the replacement of a heat pump unit. The new system must meet efficiency standards, be purchased in Canada, and be installed by a licensed professional	https://www.nrcan.gc.ca/energy-efficiency/homes/canada-greener-homes-grant/make-your-home-more-energy-efficient/plan-document-and-complete-your-home-retrofits/eligible-grants-for-my-home-retrofit/23504#s5
NRCan	National government	Install or complete new or replacement air source heat pump (ASHP) system	Present	Homeowners in most provinces	Either $2500 or $4000 towards a new or replacement air source heat pump that meets certain criteria. Funding amount depends on system size, and residents of Quebec and Nova Scotia may face more stringent requirements in order to receive funding.	
NRCan	National government	Cold Climate Heat Pumps (CCHP)	Present	Homeowners	$5000 towards a new or replacement cold climate heat pump system that meets performance and other standards and is used to service the entire home.	
Royal Bank of Canada	Multinational bank	RBC Energy Saver Loan	Present	Homeowners	Discounted interest rate or discounted home energy audit for customers who upgrade their home, including the purchase of energy-efficient products	https://www.rbcroyalbank.com/personal-loans/energy-saver-loan.html
Enbridge Gas Inc.	Major utility company in Ontario	Home Efficiency Rebate Plus	Present	Homeowners	Up to $10000 for retrofits that improve home efficiency, including but not limited to heat pumps; also offers $600 additional rebate for home evaluation	https://www.enbridgegas.com/en/residential/rebates-energy-conservation/home-efficiency-rebate-plus

Heat Pump Programs

Definition and comments: This chart lists all available incentives towards high-efficiency heat pump installation available in Canada at time of writing.

Entity	**Entity Level or Type**	**Policy Name**	**Years**	**Target**	**Description**	**Link**
Enbridge Gas Inc.	Major utility company in Ontario	Affordable Multi-Family Housing Program	Present	Owners of multi-family buildings	Up to $9000 for upgrading to condensing or high-efficiency boiler or furnace	https://www.enbridgegas.com/business-industrial/incentives-conservation/programs-and-incentives/retrofits-custom-projects
Enbridge Gas Inc.	Major utility company in Ontario	ERV/HRV Incentives	Present	Commercial property managers/ owners	Per-unit installation incentives may be offered to commercial buildings that install new energy recovery ventilators (ERV) or heat recovery ventilators (HRV)	https://www.enbridgegas.com/business-industrial/incentives-conservation/energy-solutions-by-equipment/space-heating-ventilation-building-envelope/erv-hrv
Ontario	Municipal and provincial governments	Ontario Renovates Program	Present	Low-to-moderate income households and people with disabilities	Details depend on the municipality, but homeowners can receive $15,000-30,000 of assistance towards repairs and renovations that may include increasing energy efficiency	https://showmethegreen.ca/home/home-improvement/ontario-renovates-program/

Heat Pump Programs

Definition and comments: This chart lists all available incentives towards high-efficiency heat pump installation available in Canada at time of writing.

Entity	Entity Level or Type	Policy Name	Years	Target	Description	Link
BC Hydro	Provincial utility company	Home renovation rebates	Present	Homeowners	Up to $10,000 in rebates for various home efficiency improvements (including heater upgrade)	https://www.bchydro.com/powersmart/residential/savings-and-rebates/current-rebates-buy-backs/home-renovation-rebates.html
Fortis BC	Provincial utility company	Natural Gas Furnace Rebate	Present	Homeowners	Up to $1000 rebate for ENERGYStar certified natural gas furnace, plus $150 more for eligible thermostats.	https://www.fortisbc.com/rebates/home/natural-gas-furnace-rebates
Fortis BC	Provincial utility company	Heat pump service rebate	Present	Homeowners, Property Maintainers	$50 for service on your heat pump	https://www.fortisbc.com/rebates/home/heat-pump-service
CleanBC	Provincial government initiative	Better Homes Combined Space and Hot Water Heat Pump Rebate	Present	Homeowners	“The CleanBC Better Homes and Home Renovation Rebate Program is offering a rebate of up to $4,300 for installing a combination space and water heat pump system. A $500 electrical service upgrade rebate is available when converting your fossil fuel primary space or water heating system to an electrical primary space or water heating system.”	https://betterhomesbc.ca/rebates/combination-space-and-water-heat-pump-rebate/
CleanBC	Provincial government initiative	Better Homes and Home Renovation Rebate	Present	Residents of RDN Electoral Areas and the District of Lantzville	$250 for switching from oil heating to a heat pump	https://www.rdn.bc.ca/oil-to-heat-pump

Heat Pump Programs

Definition and comments: This chart lists all available incentives towards high-efficiency heat pump installation available in Canada at time of writing.

Entity	Entity Level or Type	Policy Name	Years	Target	Description	Link
Efficiency Manitoba	Provincial government corporation	Ground Source Heat Pump Program	Present	Homeowners	Participants apply through their installer to receive funding. Once they are pre-approved, participants must front the money for the project, but will receive an incentive of unspecified value once the pump has been installer	https://efficiencymb.ca/business/ground-source-program/
Daikin	Multinational conglomerate company	Heat Pump Rebates in New Brunswick	Present	Homeowners	$1,550 from manufacturer towards purchase of select heat pumps	https://daikinatlantic.ca/2019/08/16/heat-pump-rebates-in-new-brunswick/
NB Power	Provincial utility	Total Home Energy Savings Program	Present	Homeowners	Money towards renovations to increase energy efficiency	https://www.saveenergynb.ca/en/save-energy/residential/total-home-energy-savings-program/
Newfoundland Power	Provincial utility	Electric Heating Systems & Heat Pumps	Present	Homeowners	Up to $10,000 for electric heating systems, including heat pumps	https://www.newfoundlandpower.com/My-Account/Services/Financing-Plans
takeCHARGE	Utility initiative in Newfoundland	Rooftop Air Source Heat Pumps Rebate	Present	Commercial buildings	$300 per ton on rooftop air source heat pumps	https://takechargenl.ca/business/product-rebates/rooftop-air-source-heat-pumps/

Heat Pump Programs

Definition and comments: This chart lists all available incentives towards high-efficiency heat pump installation available in Canada at time of writing.

Entity	Entity Level or Type	Policy Name	Years	Target	Description	Link
Efficiency Nova Scotia	Nonprofit organization	Home Energy Assessment	Present	Homeowners	$300 to $600 per ton on heat pump installation/upgrade (up to a max of $5000)	https://s3-ca-central-1.amazonaws.com/ens-efficiency-ns-prod-offload-647701102377-ca-central-1/wp-content/uploads/2019/08/02161415/HEA-Rebate-Guide-WEB.pdf
efficiencyPEI	Provincial government	Energy Efficient Equipment Rebates	Present	Homeowners	$1200 to $2500 on upgrading to (or improving existing) heat pumps	https://www.princeedwardisland.ca/en/information/environment-energy-and-climate-action/energy-efficient-equipment-rebates
Énergir	Provincial government	Chauffez vert	Present	Homeowners	up to $1,650 for eligible low temperature heat pumps that are ENERGY STAR certified	https://transitionenergetique.gouv.qc.ca/en/residential/programs/chauffez-vert/financial-assistance#c11037
City of Toronto	Municipality	Home Energy Loan Program (HELP)	Present	Homeowners	Low interest loan of up to $75,000 for home energy improvements	https://www.toronto.ca/services-payments/water-environment/environmental-grants-incentives/home-energy-loan-program-help/