A techno-economic assessment of residential building energy retrofits in Canada’s remote communities: A case study

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Abstract

There are roughly 300 remote communities in Canada that face a number of energy system related concerns including high fuel costs, high electricity rates, leaky and inefficient housing, and air pollution. Residential building energy retrofits can address many of these concerns. Moreover, these measures can reduce fossil fuel consumption, and improve a community’s overall housing stock. In the current study, the techno-economic feasibility of implementing a wide range of energy retrofits on a subset of building archetypes commonly found in northern Canadian remote communities is investigated. The EnergyPlus building simulation tool is used to analyse several combinations of residential building energy retrofits with the objective of maximizing energy savings and thermal comfort, and minimizing project costs. The indigenous community of MoCreebec Eeyoud, located on Moose Factory Island in northern Ontario is used as the case study. Findings from the study suggest that increasing the attic floor insulation thickness and upgrading windows and doors are the most effective building energy retrofit measures to undertake.

Introduction

Diesel is currently the primary source of energy in Canada’s remote northern communities. The use of diesel generators contributes to several economic, social, and environmental challenges faced by these communities (Fitzgerald & Lovekin, 2018). These challenges include, but are not limited to, high pollution and noise levels, high diesel plant operational and fuel transportation costs, and high utility electricity costs (McFarlan, 2018; NRCan, 2011). Prolonged diesel fuel dependency also drastically impacts community energy security and increases vulnerability to diesel supply volatility. The true cost of electricity in many remote communities is as high as $1.14/kWh; this is nearly ten times greater than the average price paid by Canadians (Lovekin & Heerema, 2019). Moreover, these communities face long and harsh winters. This not only contributes to higher space heating demands, but also accelerates the degradation of the community building stock, which consequently proliferates the already elevated space heating demand (Polar Knowledge Canada, 2019).

Consequently, the cost of electricity in many of these communities is heavily subsidized to reduce the financial burden on the consumer. Electricity subsidies currently account for roughly 74% of a typical consumer’s electricity bill (Lovekin & Heerema, 2019). If these subsidies were instead redirected towards improving a community’s building stock, the net effect would potentially lead to a decrease in total annual consumer energy demand. Additional benefits would include an increase in occupant thermal comfort, and a decrease in annual diesel fuel consumption and associated fuel shipments to the community.

Canada has a long history of residential energy retrofit (ER) incentive programs. One of the most noteworthy and successful of these programs is the *home-as-a-system* program launched by Natural Resources Canada (NRCan) in April of 1998 (Parekh et al., 1998). Although the program was marketed under several different names throughout its roughly 13 year duration such as *EnerGuide for Houses*, or *ecoEnergy*, the underlining structure of the program essentially remained the same. This program differs substantially from typical list-based incentive programs, in which fixed financial incentives are given to specific stand-alone retrofits regardless of building type and location. The *home-as-a-system* program is more detailed in scope and comprises a three-step process. The first step involves a personalized home energy audit conducted by a home energy advisor. Advisors then create an energy model of the building using building simulation software (often HOT2000 (NRCan, 2020)). The second step involves creating a custom-tailored packaged list of recommended home ERs from the information gathered through the energy model. The homeowner, with the assistance of an advisor, is then able to act on any number of the ERs recommended within the package. The final step involves a follow-up evaluation to assess the effectiveness of the ERs, which is required to occur within 18 months of the ERs being implemented (Gamtessa, 2013; Hoicka, Parker, & Andrey, 2014).

The *home-as-a-system* program and other similar programs have been extensively studied by a number of researchers, and were found to be highly effective at promoting customer participation and reducing annual energy use (Gamtessa, 2013; Hoicka & Parker, 2018; Hoicka et al., 2014). Hoicka & Parker (2014) wrote "…when homeowners make decisions based on the *home-as-a-system* approach and act on the totality of advice given to them, it is more likely that greater energy and greenhouse gas savings will be achieved.". Similarly, Gamtessa (2013) wrote "high ratios of pre-retrofit to post-retrofit energy consumption and cost generally correspond to homeowners undertaking more upgrades." The conclusions of these studies are straightforward; the more custom tailored ERs applied on a home, the more energy savings will be achieved. Unfortunately, for these programs to be implemented successfully they require a home energy advisor to complete personalized home energy evaluations for all participants. This can be both costly and time consuming, especially in a remote community setting.

Literature Review

A number of studies have investigated the cost and energy saving potential from implementing several individual and/or packaged residential building ERs. An early study by Cohen, Goldman and Harris (1991) assessed energy and cost savings from retrofitting a typical single-family home in northern USA. Both individual and packaged retrofit options were considered in the study, and the retrofit performance was assessed based on pre and post-construction cost and metered data. Increasing ceiling and wall insulation levels was found to be the most cost-effective envelope retrofit with energy savings ranging from 12-21%. Upgrading windows was found to be the least cost-effective retrofit with energy savings ranging from 2-5%. Another study by Guler et al. (2001) compared the economic feasibility and annual energy savings of a wide range of ERs in the Canadian housing stock. The researchers modelled a number of homes with the modelling software HOT2000 using surveyed housing energy consumption data from 1993. They found that only minimal energy savings of approximately 0-8% were possible across the ERs considered. Upgraded basement wall insulation and windows were identified as being the most and least effective at reducing annual energy savings, respectively.

Oberegger, Pernetti & Lollini (2020) developed calibrated bottom-up building models to estimate the cost and energy savings from implementing individual and packaged ERs in a number of homes located in northern Italy. The researchers subdivided the homes in terms of size, age, and location, and used the modelling software PHPP (Passive House Canada, 2020) to estimate the energy savings incurred. They found that façade and roof insulation upgrades were the highest priority ERs with respect to both annual energy savings and project cost. Asadi et al. (2012) conducted a study in which they developed a multi-objective optimization model to assess the feasibility of several residential building energy retrofits for a single-family home located in Portugal. The objective of the study was to identify the most optimal building energy retrofit packages which offered the highest energy savings at the lowest cost. They found that packages with high levels of added exterior wall insulation and minimal upgrades to both window and roof insulation led to the most economically feasible scenarios. Streicher et al. (2017) completed a thorough analysis of over 6000 recently renovated homes in Switzerland to assess the techno-economic impact of implementing individual and combined ER packages. The retrofitted homes were part of an energy efficiency program in which households were given suggested retrofits by home energy advisors. Although the advisors prioritized upgrading exterior building façade insulation, results showed that these retrofits were not cost-effective over their projected lifetime. The most cost-effective retrofits included increased insulation on unheated slabs and upgraded windows. Hoicka & Parker (2018) conducted a survey-based study in which they asked several Canadian home energy advisors which residential building energy retrofits they recommended to the majority of clients. Their recommendations in order of decreasing importance were air sealing, increased attic/roof insulation, increased basement insulation, increased exterior wall insulation, upgraded windows, and installation of high efficiency mechanical systems (Hoicka & Parker, 2018).

The studies shown above, whether they are based on expert recommendations, modelling predictions, or post retrofit data analysis, demonstrate that there are no clear building ERs that are consistently superior to others across different building types and climate regions. The techno-economic feasibility of the retrofits considered in these studies vary substantially based on building type, envelope construction, age, and location, as well as the cost and performance of the ERs themselves. Moreover, the majority of homes assessed in these studies utilize both heating and cooling systems and are located in relatively mild climates. To the authors' knowledge, no other studies have been conducted to assess the techno-economic impacts of residential home ERs in communities located in northern heating-only climates.

The objective of this study is to conduct a multi-objective techno-economic assessment of a wide range of building ERs on a subset of building archetypes commonly found in northern Canadian remote communities. The multi-objective techno-economic assessment will aim to identify the most economically feasible ER combinations, with the largest increases in both annual energy savings and thermal comfort. The EnergyPlus (U.S. Department of Energy, 2019) building performance simulation tool is used to construct the building energy models. For each building archetype, optimal ER packages are identified that maximize energy savings, thermal comfort, and project economics. These packages are useful to policy makers and community leaders in remote northern communities who can potentially use them for the planning of future residential housing stock and/or ER incentive programs. The indigenous community of MoCreebec Eeyoud, located on Moose Factory Island in northern Ontario (see Figure 2) is used as the case study in the analysis.

Methods

MoCreebec Eeyoud residential building energy models

The MoCreebec Eeyoud community is relatively small in size with a population of approximately 1000 (MacLeod Farley & Associates, 2015). As the community is grid connected, the majority of its power demand is met via grid electricity. However, the community's far northern location and housing stock profile is representative of a typical remote Canadian diesel-powered community, and thus serves as an accurate case study for this analysis.

A large number of MoCreebec Eeyoud community homes were built in the early 1990s, and consist primarily of detached, semi-detached and row homes. Archived construction drawings for each of these building types were collected from the community and used to develop three building energy models in EnergyPlus (see Figure 1 and Table 1 for building profile views and housing data). As all homes in this study were built roughly during the same period and by the same builder, there was little to no deviation in the construction materials used. Envelope construction specifications are shown in Table 2. All material thermal properties are taken from the *National Renewable Energy Laboratory – Building Component Library* (NREL, 2020). As the current study focuses exclusively on building envelope retrofits, improvements in air tightness and building mechanical systems are neglected. The buildings' mechanical heating systems consist of a 15kW electric forced-air furnace with an outdoor-air heat recovery ventilator. Occupant-based passive cooling control is employed in the cooling season: when zone temperatures exceed 24°C, windows are opened and slated blinds are shut.

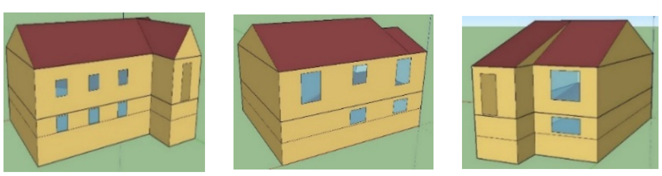

Figure 1: Building archetype profile views. From left to right: Detached, Semi-Detached, and Row Home

All building models are subdivided into three zones: basement, main level, and attic. It is assumed that the thermal mass of internal objects (*e.g.* walls, furniture etc…) and air transfer in between zones is negligible. Furthermore, internal gains and occupant presence are based on fixed schedules. Internal gains are obtained from ASHRAE's Handbook of Fundamentals (ASHRAE, 2017b), and typical residential schedules are obtained from COMNET codes and standards (COMNET, 2016). Although these assumptions oversimplify temporal heat and mass transfer processes during simulation, and as a result may lead to increased error in energy use and thermal comfort results, they are deemed warranted as 1) the assumptions are constant for all scenarios and thus relative changes from implementing ERs will be reflected accordingly, and 2) model complexity and corresponding simulation run time are reduced considerably enabling a larger dataset to be assessed in the study.

Table 1: Community housing data by building type

Building Type	Floor Area (m^2)	Window Area (m^2)	No. of Doors	Year Built
Detached	206	9.5	2	1990
Semi-Detached	175	12.4	1	1992
Row	143	8.8	1	1990

Building envelope energy retrofit scenarios

The list of building envelope ERs considered in this study is shown in Table 3. The ER scenarios comprise every single packaged combination of these retrofits implemented on the base case models of all three building types, amounting to a total of 324 ER scenarios per building type. An iterative simulation process is conducted using the python *idf* editing package Eppy (Philip, 2019). EnergyPlus *idf* files are first edited by the Eppy script to implement the desired energy retrofit scenario. The newly edited *idf* file is then run in EnergyPlus and the results are stored in a separate folder.

The ER scenarios are based on the ENERGY STAR® *for New Homes Standard* program (NRCan, 2015). This program is a collaboration between NRCan and ENERGY STAR® that promotes energy efficiency of new homes built in Canada through an accreditation process that certifies homes that meet predetermined minimum standards. Minimum insulation envelope standards vary depending on region. The program subdivides Canada into several climate zones based on their annual heating degree days (HDD) as shown in Figure 2. HDDs are equivalent to the number of degrees Celsius a given day's mean temperature is below 18°C (NRCan, 2015). The MoCreebec Eeyoud community is located in climate Zone 3. For the purposes of this study, the authors only analyse the impact of upgrading envelope insulation to ENERY STAR® climate Zones 2 and 3, as climate zone 1 is only applicable to a small region in southern British Columbia. Climate zones are indicated for each retrofit as a subscript of the retrofit labels (*i.e.* column 2) shown in Table 3. For example, the label $exWall_{Z2}$ is representative of exterior walls that meet ENERGY STAR® climate Zone 2 minimum insulation requirements. Building component labels that correspond to the base case (*i.e.* pre retrofit) buildings are indicated with the subscript "BC" (not shown in Table 3)

Column 4 of Table 3 indicates the cost of the ER which has been extrapolated from the *RSMeans* construction database, and adjusted for northern Ontario prices using the *RSMeans* location factor correction data sheet (RSMeans, 2018). The cost shown accounts for all phases of the construction process. For example, the cost associated with the $exWall_{Z2}$

Table 2: Building component construction material details

Building Component	Material components (from exterior to interior)	Insulation Value (m^2K/W)
Attic floor	Gypsum board, wood stud, batt insulation (0.3 m)	6.10
Main level floor	Gypsum board, wood stud, OSB sheathing, vinyl flooring	0.24
Above-grade exterior wall	Vinyl siding, OSB sheathing, wood stud, batt insulation (0.152 m), gypsum board	3.26
Above-grade portioning wall	Gypsum board, wood stud, batt sound insulation (0.152 m), gypsum board	3.25
Below-grade basement wall	Reinforced concrete, wood stud, batt insulation (0.102 m)	2.79
Basement floor	Reinforced concrete slab-on grade (0.102 m)	0.34
Windows	Double glazed wood sliders	0.41[a]
Doors	Insulated steel door	0.54[a]

[a] *Insulation values are obtained from various MoCreebec Eeyoud community home energy audit reports*

retrofit includes the removal of the existing vinyl siding, the installation of the added rigid board insulation, and the reinstallation of new vinyl siding.

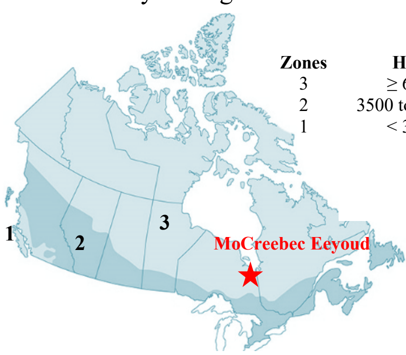

Figure 2: ENERGY STAR® Canadian climate zones (NRCan, 2014)

Technical metrics

Annual energy savings (AES) and thermal comfort (TC) are used as the metrics to assess the technical performance of each ER scenario in this study. The annual energy savings by ER scenario is calculated using the following equation:

$$AES_i = AE_{pre-retrofit} - AE_{post-retrofit,i} \quad (1)$$

where, AES_i is the annual energy saved by ER scenario i, $AE_{pre-retrofit}$ and $AE_{post-retrofit}$ are the annual energy (AE) consumptions for the base case and post-retrofit scenario i, respectively.

Thermal comfort is measured using the Fanger comfort model (Fanger, 1970). This model is widely used amongst practitioners and has been adopted by ASHRAE 55 (ASHRAE, 2017a). The Fanger comfort model uses the occupants predicted mean vote (PMV) to quantify the level of discomfort experienced. PMV scores TC on a scale from -3 (too cold) to 3 (too hot); with a score of 0 being ideal TC. The score is generated by the EnergyPlus *People* object. The object requires many user inputs from the modeller such as occupant presence, metabolic rate, and zone air velocity. Occupant presence and metabolic rate are input as fixed schedules (as discussed in the previous section) and zone air velocity is assumed to be constant at 0.1 m/s. The latter assumption is supported through a sensitivity analysis conducted by the author with a range of published residential indoor air velocities (Olesen, 2004) and found very little deviation in TC. A notable difficulty in comparing the TC across PMV scores, is that the PMV scale views a score of -1 and +1 to be as equally uncomfortable. To overcome this issue, the annual mean squared PMV score ($\overline{PMV_i}^2$) is used as the TC indicator for each ER scenario in this study.

Economic Metrics

The net present value (NPV) is used as the metric to assess the economic performance of each ER scenario in this study. The NPV is a measure of the current value of a project over its expected lifetime considering all project cash flows and time value of money. A positive NPV implies that a project is economically feasible, whereas a negative NPV implies that a project is not economically feasible. The NPV is expressed as

$$NPV_i = \sum_{j=0}^{n} \frac{(Benefit_i - Cost_i)_j}{(1+i_d)^j} \quad (2)$$

where NPV_i is the NPV of ER scenario i, j is the year, n is the total lifetime of the project in years, i_d is the discount rate, $Cost_i$ is the total ER cost for scenario i (only applied at year 0), and $Benefit_i$ is the annual cost savings accrued from the implementation of ER scenario i (applied from years 1 to n). This term is expressed as

$$Benefit_i = AES_i * Cf_i \quad (3)$$

where Cf_i represents the fuel cost. This study assumes that all projects have a lifetime of 30 years, and a discount rate of 6%. Fuel cost is assumed to be 32 ¢/kWh; *i.e.* the average rate of electricity in remote northern communities (NRCan, 2011).

Multi-objective optimization analysis

The technical and economic metrics noted in the sections above are used to develop the following multi-objective problem statement:

Table 3: Building envelope energy retrofits

Building Component	Retrofit label	Retrofit description	Cost ($/m^2)
Above-grade exterior walls	$exWall_{Z2}$	Add exterior wall rigid board insulation: 57.15 mm	77.6
	$exWall_{Z3}$	Add exterior wall rigid board insulation: 69.85 mm	80.8
Below-grade basement walls	$bWall_{Z2}$	Add interior wall rigid board insulation: 12.7 mm	42.3
	$bWall_{Z3}$	Add interior wall rigid board insulation: 38.1 mm	47.6
Basement floor	$bFloor_{Z2}$	Add floor rigid board insulation: 57.15 mm	71.9
	$bFloor_{Z3}$	Add floor rigid board insulation: 120.65 mm	90.6
Attic floor	$aFloor_{Z2}$	Increase batt insulation: 431.8 mm	26.0
	$aFloor_{Z3}$	Increase batt insulation: 433.4 mm	28.6
Door	$door_{Z3}$	Replace door(s) with high-efficiency door(s): U-factor: 1.2 W/m^{2}K	$531/unit
Window	$window_{Z3}$	Replace window(s) with high-efficiency window(s): U-factor: 1.2 W/m^{2}K	$515/unit

- $Maximize\{AES\}$
- $Maximize\{NPV\}, while\ ensuring\ NPV > 0$
- $Minimize\{\overline{PMV}^2\}$

Although meeting all three objectives would in theory lead to optimal ER scenarios, these objectives often conflict with one another (*i.e.* higher NPVs do not necessarily correlate to higher AES and/or lower $\overline{PMV}^2$ values). Building upon previous work conducted by Asadi et al. (2012), the Tchebycheff method (otherwise known as the weighted min-max method) is used to solve the multi-objective problem stated above. The method is programmed in the python environment and formulated using the following set of equations:

$$Min\{\alpha_i\} \qquad (4)$$

$$\alpha_i \geq (AES_{max} - AES_i) \cdot (\sigma_{aes}/AES_{max})$$

$$\alpha_i \geq (\overline{PMV}^2 - \overline{PMV}^2_{min}) \cdot (\sigma_{pmv}/\overline{PMV}^2_{min})$$

$$\alpha_i \geq (NPV_{max} - NPV_i) \cdot (\sigma_{npv}/NPV_{max})$$

$$\alpha_i \geq 0$$

$$\sigma_{aes} + \sigma_{pmv} + \sigma_{npv} = 1$$

AES_{max}, and NPV_{max} represent the maximum AES and NPV, respectively, and $\overline{PMV}^2_{min}$ represents the minimum $\overline{PMV}^2$ value across all ER scenarios. Parameters σ_{aes}, σ_{pmv} and σ_{npv} are the weights of each objective. These weights can be adjusted depending on the relative importance of each objective. α is calculated for each ER scenario i, and the ER scenario with the lowest α_i value is considered to be the 'non-dominant' solution to the multi-objective problem. That is, there exists no other ER scenario that can optimize any one objective (*e.g.* maximize AES, maximize NPV and/or minimize $\overline{PMV}^2$) without negatively impacting another objective (Asadi, da Silva, Antunes, & Dias, 2012).

Results

Figures 3 through 5 show the impact of individual ERs on TC, AES and NPV, respectively, across all scenarios comprising each stated ER. The ER labels used in each figure correspond to the retrofit labels shown in Table 3. Results are shown for the row home building type. Since the semi and detached homes experience similar trends to the row home, they are excluded from the analysis to avoid redundancy. Each box plot shown in these figures represents a statistical distribution of results obtained across ER scenarios, and indicates the minimum, lower quartile, median, upper quartile, and maximum values obtained, from bottom to top, respectively.

Figure 3 shows that increased insulation to basement floors and upgraded windows have the largest impact on $\overline{PMV}^2$. A reduction of 0.43 (21%) in the median $\overline{PMV}^2$ is observed for $bFloor_{Z3}$ relative to $bFloor_{BC}$, whereas an 11% reduction in the median $\overline{PMV}^2$ is observed for $window_{Z3}$ relative to $window_{BC}$. Therefore, increased basement floor insulation and windows have a significant impact on the buildings TC. ER $bFloor_{Z3}$ has the smallest median $\overline{PMV}^2$ with a value of 1.63. For ERs $bFloor$, $exWall$, $aFloor$, $window$, and $door$, lower $\overline{PMV}^2$ values are shown relative to the base case respectively. However, this isn't true for ER $bWall$.

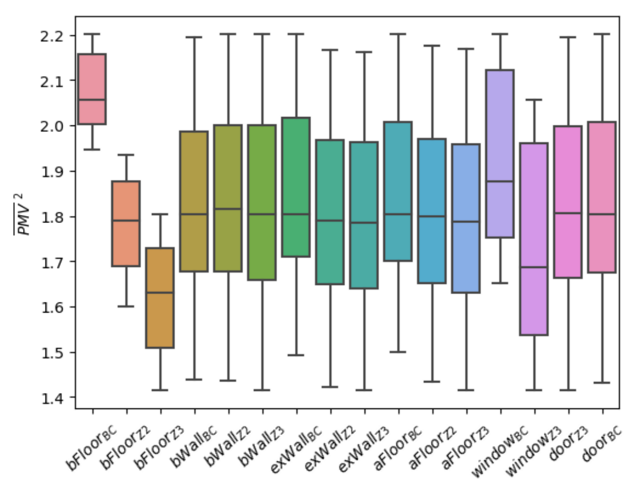

Figure 3: Impact of individual ERs on TC across all "row home" scenarios comprising stated ER

Figure 4 shows that AES are most sensitive to upgrades in basement floor insulation and windows. An increase from 5.2 to 10.5 GJ (102%) in median AES is observed for

$bFloor_{Z3}$ relative to $bFloor_{BC}$, whereas a 77% increase is observed for $window_{Z3}$ relative to $window_{BC}$. More modest increases in median AES are observed for $aFloor_{Z3}$ relative to $aFloor_{BC}$ (33%) and for $exWall_{Z3}$ relative to $exWall_{BC}$ (22%). ER $window_{Z3}$ demonstrates the largest median AES of 11.3 GJ.

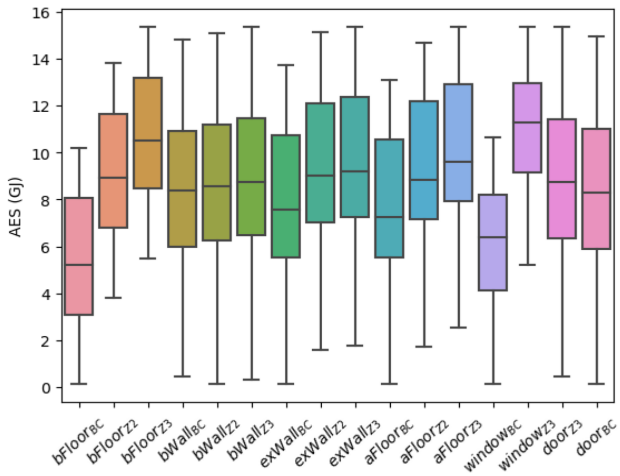

Figure 4: Impact of individual ERs on AESs across all "row home" scenarios comprising stated ER

Figure 5 shows that the only ERs (excluding base case insulation levels $bWall_{BC}$ and $exWall_{BC}$) that resulted in a positive median NPV across all ER scenarios are the $window_{Z3}$, and $aFloor_{Z3}$ retrofits. ER scenarios that include the $bWall_{BC}$ retrofit have the highest median NPV ($1730). This suggests that in most cases increasing basement wall insulation is not a cost effective measure.

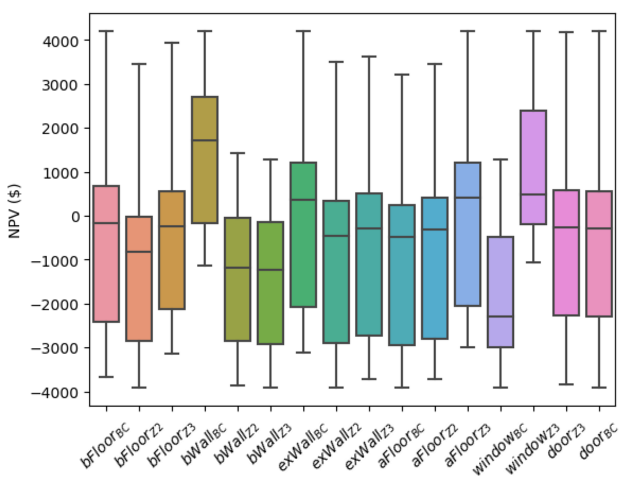

Figure 5: Impact of individual ERs on NPV across all "row home" scenarios comprising stated ER

Overall, the implementation of upgraded doors has very little impact on either $\overline{PMV}^2$, AES and NPV. Though semi and detached homes have very similar findings from what is shown in Figure 3 through 5, there are a few notable differences. For example, ERs are generally considerably more effective at increasing AES and decreasing $\overline{PMV}^2$ in the row home as compared to both the semi and detached homes. On the other hand, insulation improvements to both basement and exterior walls are much more effective at decreasing $\overline{PMV}^2$ and increasing AES in the semi and detached homes relative to the row home. The reason for this is likely due to the walls of both the semi and detached homes having more overall exposure to the outdoor environment. As a result, these homes experience greater benefits from increased wall insulation.

Figure 6 shows a positive relationship between the NPV of each ER scenario and the AES. The ER scenario cost (equivalent to $Cost_i$ as defined in the Technical metrics section) is also plotted for comparison. A least squares regression analysis is used to plot both lines of best fit shown on Figure 6. While a strong Pearson correlation between AES and ER (*r*= .88) suggests an increase in cost as AES rises, there is also a moderately strong positive correlation (*r*= .47) between AES and NPV. Thus, implying that as the AES of ERs increase, the economic benefits will also increase in spite of higher costs. However, positive NPVs only occur above AES of 10.3 GJ. Conversely, the ER scenario cost at this value becomes significant (>$97k) and may deter homeowners to undertake ERs.

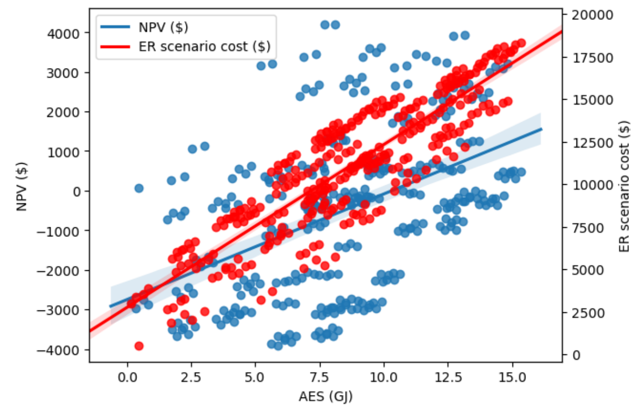

Figure 6: NPV of each energy retrofit scenario compared against annual energy savings and retrofit cost: Row home

Table 4 shows the results of the multi-objective analysis. The table shows the ER scenarios selected by building type for three different multi-objective weighting schemes. Each multi-objective weighting scheme prioritizes one techno-economic metric. Metrics that are prioritized have their objective weights set at 0.6, whereas the remaining objective weights are set at 0.2. Across all building types and weighting schemes, the selected ER scenarios all consist of both $window_{Z3}$ and $aFloor_{Z3}$. Upgraded doors are included in all but one ER scenario; *i.e.* the semi-detached home under the TC prioritized weighting scheme. Under the NPV prioritized weighting scheme, the basement walls are left unchanged across all building types. The AES prioritized weighting scheme favours $exWall_{Z3}$ as it is selected across all building types. Although improvements

Table 4: Building retrofit multi-optimization results

	Basement Floor	Basement Walls	Exterior Walls	Attic Floor	Windows	Doors	NPV ($)	AES (GJ)	$\overline{PMV}^2$
AES prioritized solution: $\sigma_{aes} = 0.6$, $\sigma_{npv} = 0.2, and\ \sigma_{pmv} = 0.2$									
Row	$bFloor_{Z3}$	$bWall_{BC}$	$exWall_{Z3}$	$aFloor_{Z3}$	$window_{Z3}$	$door_{Z3}$	3207	14.81	1.44
Semi	$bFloor_{BC}$	$bWall_{Z3}$	$exWall_{Z3}$	$aFloor_{Z3}$	$window_{Z3}$	$door_{Z3}$	2990	17.13	2.03
Detached	$bFloor_{BC}$	$bWall_{Z3}$	$exWall_{Z3}$	$aFloor_{Z3}$	$window_{Z3}$	$door_{Z3}$	2201	20.04	2.23
NPV prioritized solution : $\sigma_{aes} = 0.2$, $\sigma_{npv} = 0.6, and\ \sigma_{pmv} = 0.2$									
Row	$bFloor_{Z3}$	$bWall_{BC}$	$exWall_{BC}$	$aFloor_{Z3}$	$window_{Z3}$	$door_{Z3}$	3935	13.16	1.52
Semi	$bFloor_{BC}$	$bWall_{BC}$	$exWall_{Z3}$	$aFloor_{Z3}$	$window_{Z3}$	$door_{Z3}$	5458	15.88	2.04
Detached	$bFloor_{BC}$	$bWall_{BC}$	$exWall_{Z3}$	$aFloor_{Z3}$	$window_{Z3}$	$door_{Z3}$	4750	18.04	2.25
Thermal Comfort prioritized solution : $\sigma_{aes} = 0.2$, $\sigma_{npv} = 0.2, and\ \sigma_{pmv} = 0.6$									
Row	$bFloor_{Z3}$	$bWall_{BC}$	$exWall_{Z3}$	$aFloor_{Z3}$	$window_{Z3}$	$door_{Z3}$	3207	14.81	1.44
Semi	$bFloor_{Z2}$	$bWall_{BC}$	$exWall_{BC}$	$aFloor_{Z3}$	$window_{Z3}$	$door_{BC}$	3025	13.96	1.93
Detached	$bFloor_{BC}$	$bWall_{Z3}$	$exWall_{Z3}$	$aFloor_{Z3}$	$window_{Z3}$	$door_{Z3}$	2201	20.04	2.23

to the basement floor have mixed success across the weighting schemes, these retrofits are preferred under the TC prioritized weighting scheme as $bFloor_{Z3}$ and $bFloor_{Z2}$ are selected for the row and semi homes, respectively.

Discussion & Conclusion

The current study shows that ERs can be an attractive solution for policy makers and community leaders to reinvest energy subsidies towards ERs that are not only economically feasible, but will lead to reductions in energy consumption and improvements in TC.

Findings from the multi-objective analysis (see Table 4) suggest that regardless of building type, improvements to attic insulation and upgraded windows and doors are economically feasible ERs that will increase both TC and AES. This is further supported by Figure 3 through 5 which shows that increased attic insulation and upgraded windows lead all other ERs with respect to increases in AES and NPV, and improvements in TC. The large selection of ER $door_{Z3}$ in the multi-objective analysis came as a surprise as upgraded doors are shown to have minimal impact on either TC, AES or NPV (see Figure 3 through 5). However, as the installation cost to upgrade doors is substantially lower than all other ERs, these upgrades were found to be favourable in the analysis.

If policy makers and northern community leaders sought to prioritize AES above all else, for reasons such as reduction in diesel fuel use and/or transportation, the following ERs should be prioritized in order of decreasing importance: windows, basement floor insulation, attic floor insulation, above grade exterior walls, below grade exterior walls and doors. This recommendation is supported by comparing the median AES for each ER in Figure 4. However, in the semi and detached homes, where a larger portion of the exterior walls are exposed to the outdoor environment, increased insulation to exterior walls should be prioritized above increased attic insulation as the former leads to higher AES in these homes.

The maximum ER scenario NPV for the row, semi and detached homes are $4,200, $5,974 and $5,176, respectively; a modest return for a project with such a significant lifespan (30 years). However, to some degree these results are expected given the considerable need for government initiatives in Canada to promote residential energy efficiency measures through incentive based programs (Hoicka et al., 2014). These returns exclude any form of carbon taxation. If carbon taxation were to be included, the income accrued from diesel generator emissions could increase the financial benefits of ER scenarios. Further work should be conducted to look into carbon taxation policies in northern communities, and assess how these policies affect the economics of different ER scenarios.

It is important to note that the recommendations presented in this study should only be considered for buildings with similar archetype, age and location. When comparing these recommendations to those suggested by advisors in previous studies (Hoicka & Parker, 2018), there are noticeable differences. Although both prioritize attic insulation, the advisors recommend prioritizing increased basement and exterior wall insulation over upgraded windows. To the advisors' credit it is difficult to determine what exactly the homeowner's priorities are when these recommendations are given. Regardless, what is evident from these findings and those from the literature is that a simple 'one size fits all' ER recommendation for residential buildings is ill advised. Further work should be done too asses even further northern remote homes; such as in artic regions. The findings of this modelling study should also be compared with post and pre-retrofit energy consumption data in retrofitted homes in remote northern communities to reinforce the validity of the findings.

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