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Effectiveness of single and multiple energy retrofit measures on the energy consumption of office buildings

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ABSTRACT

Energy retrofit measures (ERMs) are applied to reduce the energy consumption of buildings. The effectiveness of any ERM depends on many building specific factors, such as location, size, operation, building envelope, electrical, heating, cooling and ventilation system properties. It is common for multiple ERMs to be applied to a building to reduce its energy consumption. However, the reduction in energy consumption when multiple ERMs are applied is not the sum of the impact of individual ERMs. Effectiveness of multiple ERMs depends upon their interactive effects. Using representative office buildings and an energy modelling computer program, the effectiveness of individual and multiple ERM was assessed providing a better understanding of their interactive effects.

1. Introduction

Energy has become an expensive commodity for at least two fronts, economical and environmental [1]. For office buildings, there are varying energy retrofit measures (ERMs) that can be implemented to reduce energy consumption [2]. Financial justification remains the sole criterion that owners and property managers of office buildings will apply before implementing ERMs, i.e. balancing the implementation cost of ERMs with their respective savings due to energy conservation. In this regard, the government is providing financial incentive to offset the implementation cost of ERMs and adding a financial bonus for implementing multiple ERMs [3,4].

The effectiveness of multiple ERMs due to interactive effects is not well documented. For the building envelope where the thermal efficiency of the walls, roofs and windows were studied; the optimum cost effective ERMs was possible only when ERMs are implemented with proportioned budget allocations to the efficient ERMs [5]. Furthermore, the results revealed that the most efficient ERM is not always derived from a cost effective energy saving strategy. For example, improvement in the windows thermal efficiency can result in the largest energy savings whereas improvement in the walls may yield the maximum energy savings at low budgets, i.e. largest energy saving measures are not necessarily the most cost effective ERMs. A European study carried out in 2002 to evaluate energy retrofitting strategies designed for office buildings, considered combinations of ERMs – building envelope improvements, HVAC improvements, use of passive cooling technologies, and lighting improvements [6]. The results showed that the selection of ERMs should be based on the specific energy characteristics of the building and that measure sets need to be carefully selected to avoid using measures that attempt to save the same energy and therefore have no additional impact on energy reduction.

This current study was carried out with the goal of assessing the changes in energy consumption that occur due to the application of various measure sets. Chidiac et al. [7] outlined a methodology for analyzing the cost/benefit relationship of applying ERMs to various types of Canadian office buildings. The potential of energy efficient technologies applied to new building design had previously been treated for Canadian buildings [8]. The effectiveness of both individual ERM application as well as the application of multiple sets of retrofits was determined. The simulation results confirmed previous findings [5,6], namely the effects of individual ERMs are

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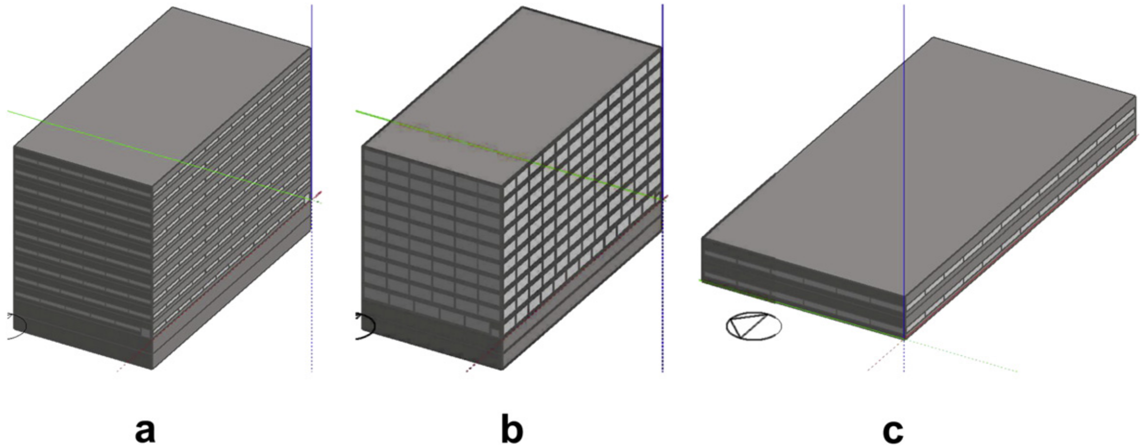


Fig. 1. Representative buildings, (a) building LV, (b) building LC, (c) building S.

not additive. To gain insight on how individual and ERM sets influence energy consumption, three different building types were modelled, each possessing envelope and system properties designed to represent the wide variety of building properties found in the typical Canadian office building stock [7,9]. By comparing the simulated results to the respective summations, estimations of the effectiveness of measure sets can be made.

Table 1
Building LV – pre-1950 and 1950–1975 archetype descriptions (7).

Item	Pre-1950	1950–1975
Description of building: # of storeys: 10 above and 2 below ground Floor area: 24,150 m^2 Volume: 84, 525 m^3	Heating fuel: natural gas Cooling fuel: electricity External wall: brick veneer on concrete block with 1/2 plaster, rigid insulation Roof: metal roofing deck Windows: single glazed No blinds	Heating fuel: natural gas Cooling fuel: electricity External wall: brick veneer on concrete block with 1/2 plaster, rigid insulation Roof: metal roofing deck Windows: double glazed Medium reflectivity blinds
Guides/standards	ASHVE – 1939	ASHVE – 1950, ASHRAE – 1961
Lighting load (W/m^2)	26	17.8
Lighting level (Lux)	500	500
Equip/appliance load (W/m^2)	10	20
Elevator load (kW)	4 × 30	4 × 30
Occupant density (m^2/person)	30	25
Fenestration (%)	30	40
Fenestration *U*-value (W/m^2 C)	6.42 (SHGC = 0.81)	4.50 (SHGC = 0.68)
Wall *U*-value (W/m^2 C)	1.21	1.21
Roof *U*-value (W/m^2 C)	1.41	0.74
Below grade wall (RSI)	No insulation	No insulation
Perimeter floor insulation (RSI)	No insulation	No insulation
Floor on ground	Tile on 8 in. concrete slab	Tile on 8 in. concrete slab
Infiltration (ACH)	1.0	0.75
Outdoor air (l/s/person)	10	10
HVAC system	Ventilation type: CAV Heating efficiency: 0.75 Cooling COP: 1.8 Cooling type: chilled water	Ventilation type: CAV Heating efficiency: 0.75 Cooling COP: 2.5 Cooling type: chilled water
SHW system	Electric storage heater	Electric storage heater

2. Energy modelling

The analysis procedure put forward by Chidiac et al. [7] to assess the energy consumption of Canadian office buildings was adopted

Table 2
Building LV – post-1975 and current levels (7).

Item	Post-1975	Retrofit
Description of building: # of storeys: 10 above and 2 below ground Floor area: 24,150 m^2 Volume: 84, 525 m^3	Heating fuel: natural gas Cooling fuel: electricity External wall: brick veneer on concrete block with 2.5 in air space 1/2 plaster, rigid insulation Roof: metal roofing deck Windows: double glazed Medium reflectivity blinds	Daylighting with light dimming 60% air to air heat recovery
Guides/standards	ASHRAE – 1977, MNECB – 1997	ASHRAE – 1977, MNECB – 1997
Lighting load (W/m^2)	17.8	10.0
Lighting level (Lux)	500	500
Equip/appliance load (W/m^2)	30	30
Elevator load (kW)	4 × 30	4 × 30
Occupant density (m^2/person)	20	18
Fenestration (%)	50	50
Fenestration *U*-value (W/m^2 C)	3.40 (SHGC = 0.47)	1.8 (SHGC = 0.41)
Wall *U*-value (W/m^2 C)	1.16	0.55
Roof *U*-value (W/m^2 C)	0.64	0.47
Below grade wall (RSI)	No insulation	No insulation
Perimeter floor insulation (RSI)	No insulation	No insulation
Floor on ground	Tile on 8 in. concrete slab	Tile on 8 in. concrete slab
Infiltration (ACH)	0.5	0.5
Outdoor air (l/s/person)	10	10
HVAC system	Ventilation type: VAV (Turndown ratio = 0.3) Heating efficiency: 0.75 Cooling COP: 5.2 Cooling type: chilled water	Heating efficiency 0.95 w/gas preheat Add economizer
SHW system	Electric storage heater	Electric storage heater

Table 3
Building LC – 1950–1975 and post-1975 levels (7).

Item	1950–1975	Post-1975
Description of building: # of storeys: 10 above and 2 below ground Floor area: 24,150 m^2 Volume: 84, 525 m^3	Heating fuel: natural gas Cooling fuel: electricity External wall: curtain wall with aluminum siding and 100 mm insulation Roof: metal roofing deck Windows: double glazed Medium reflectivity blinds	Heating fuel: natural gas Cooling fuel: electricity External wall: curtain wall with aluminum siding and 100 mm insulation Roof: metal roofing deck Windows: double glazed Medium reflectivity blinds
Guides/standards	ASHVE – 1950, ASHRAE – 1961	ASHRAE – 1977, MNECB – 1997
Lighting load (W/m^2)	17.8	17.8
Lighting level (Lux)	500	500
Equip/appliance load (W/m^2)	20	30
Elevator load (kW)	4×30	4×30
Occupant density (m^2/person)	25	20
Fenestration (%)	85	100
Fenestration *U*-value (W/m^2 C)	4.50 (SHGC = 0.68)	3.40 (SHGC = 0.47)
Wall *U*-value (W/m^2 C)	0.37	0.37
Roof *U*-value (W/m^2 C)	0.74	0.64
Below grade wall (RSI)	No insulation	No insulation
Perimeter floor insulation (RSI)	No insulation	No insulation
Floor on ground	Tile on 8 in. concrete slab	Tile on 8 in. concrete slab
Infiltration (ACH)	0.75	0.5
Outdoor air (l/s/person)	10	10
HVAC system	Ventilation type: CAV Heating efficiency: 0.75 Cooling COP: 2.5 Cooling type: chilled water	Ventilation type: VAV (Turndown ratio = 0.3) Heating efficiency: 0.75 Cooling COP: 5.2 Cooling type: chilled water
SHW system	Electric storage heater, 95% efficiency	Electric storage heater, 95% efficiency

Table 4
Building LC – current levels (7).

Item	Retrofit
Description of building: # of storeys: 10 above and 2 below ground Floor area: 24, 150 m^2 Volume: 84, 525 m^3	Daylighting with light dimming 60% air to air heat recovery
Guides/standards	ASHRAE – 1977, MNECB – 1997
Lighting load (W/m^2)	10.0
Lighting level (Lux)	500
Equip/appliance load (W/m^2)	30
Elevator load (kW)	4×30
Occupant density (m^2/person)	18
Fenestration (%)	100
Fenestration U-value (W/m^2 C)	1.8 (SHGC = 0.41)
Wall U-value (W/m^2 C)	0.37
Roof U-value (W/m^2 C)	0.47
Below grade wall (RSI)	No insulation
Perimeter floor insulation (RSI)	No insulation
Floor on ground	Tile on 8 in. concrete slab
Infiltration (ACH)	0.5
Outdoor air (l/s/person)	10
HVAC system	Heating efficiency 0.95 w/gas preheat Add economizer
SHW system	Electric storage heater, 95% efficiency

Table 5
Building S – Pre-1950 and 1950–1975 (7).

Item	Pre-1950	1950–1975
Description of building: # of storeys: 2 above ground Floor area: 4200 m^2 Volume: 14,700 m^3	Heating fuel: natural gas Cooling fuel: electricity External wall: brick veneer on concrete block with 1/2 plaster, rigid insulation Roof: 2 in. built-up concrete on 1 in. rigid insulation Windows: single glazed	Heating fuel: natural gas Cooling fuel: electricity External wall: brick veneer on concrete block with 1/2 plaster, rigid insulation Roof: 2 in. built-up concrete on 1 in. rigid insulation Windows: double glazed Medium reflectivity blinds
Guides/standards	ASHVE – 1939	ASHVE – 1950, ASHRAE – 1961
Lighting load (W/m^2)	26	17.8
Lighting level (Lux)	500	500
Equip/appliance load (W/m^2)	10	20
Elevator load (kW)	1×30	1×30
Occupant density (m^2/person)	30	25
Fenestration (%)	30	40
Fenestration *U*-value (W/m^2 C)	6.42 (SHGC = 0.81)	4.50 (SHGC = 0.68)
Wall *U*-value (W/m^2 C)	1.21	1.21
Roof *U*-value (W/m^2 C)	1.36	0.74
Below grade wall (RSI)	No insulation	No insulation
Perimeter floor insulation (RSI)	No insulation	No insulation
Floor on ground	Tile on 8 in. concrete slab	Tile on 8 in. concrete slab
Infiltration (ACH)	1.0	0.75
Outdoor air (l/s/person)	10	10
HVAC system	Ventilation type: CAV Heating efficiency: 0.75 Cooling COP: 1.8 Cooling type: chilled water	Ventilation type: CAV Heating efficiency: 0.75 Cooling COP: 2.6 Cooling type: chilled water
SHW system	Electric storage heater	Electric storage heater

in this study. It includes the selection of an appropriate energy modelling software package, the definition of representative buildings and a simulation strategy. Accordingly, EnergyPlus [10,11] was adopted to estimate the energy consumption of office buildings.

Recognizing that office buildings vary by fuel source used, age, size, occupancy characteristics, HVAC system, location and building envelope construction practices, it was proposed that these buildings be grouped as follows. First, the representative buildings need to account for the major changes in construction practices that have occurred. Accordingly, three building archetypes were proposed:

- Archetype #1 – buildings that were constructed prior to 1950,
- Archetype #2 – buildings constructed between 1950 and 1975, and
- Archetype #3 – buildings constructed post-1975.

For each of the archetype classifications, a set of predefined building types was developed. Two of these predefined buildings possess brick veneer/concrete block exterior walls with a low window to wall ratio. This building type is currently typical for low-rise structures and was common in older medium-rise structures. A third building type, composed primarily of curtain-walls with a high window to wall ratio, was chosen to represent the majority of newer high-rise office buildings. Therefore, the three representative buildings adopted for this study are (as illustrated in Fig. 1),

Table 6
Building S – post-1975 to current levels (7).

Item	Post-1975	Retrofit
Description of building: # of storeys: 2 above ground Floor area: 4200 m^2 Volume: 14,700 m^3	Heating fuel: natural gas Cooling fuel: electricity External wall: Brick veneer on concrete block with 2.5 in air space 1/2 plaster, rigid insulation Roof: 2 in. built-up concrete on 1 in. rigid insulation Windows: double glazed Medium reflectivity blinds	Daylighting with light dimming 60% air to air heat recovery
Guides/standards	ASHRAE – 1977, MNECB – 1997	ASHRAE – 1977, MNECB – 1997
Lighting load (W/m^2)	17.8	10.0
Lighting level (Lux)	500	500
Equip/appliance load (W/m^2)	30	30
Elevator load (kW)	1 × 30	1 × 30
Occupant density (m^2/person)	20	18
Fenestration (%)	50	50
Fenestration *U*-value (W/m^2 C)	3.40 (SHGC = 0.47)	1.8 (SHGC = 0.41)
Wall *U*-value (W/m^2 C)	1.16	0.55
Roof *U*-value (W/m^2 C)	0.64	0.47
Below grade wall (RSI)	No insulation	No insulation
Perimeter floor insulation (RSI)	No insulation	No insulation
Floor on ground	Tile on 8 in. concrete slab	Tile on 8 in. concrete slab
Infiltration (ACH)	0.5	0.5
Outdoor air (l/s/person)	10	10
HVAC system	Ventilation type: VAV Heating efficiency: 0.75 Cooling COP: 2.6 Cooling type: chilled water	Heating efficiency 0.95 w/gas preheat And economizer
SHW system	Electric storage heater	Electric storage heater

- Building type LV – large (12-storey; 24,000 m^2) with a brick veneer and concrete block exterior walls,
- Building type LC – large (12-storey; 24,000 m^2) with an exterior curtain wall, and
- Building type S – small (2-storey; 4200 m^2) with brick veneer and concrete block exterior walls.

Moreover, ASHVE [12,13] and ASHRAE [14–16] guides were used to define the construction characteristics of the walls, roof and fenestration. The details associated with each building type's construction and equipment properties are presented in Tables 1–6. The buildings were heated using natural gas.

Table 7
Parameter range.

Parameters	Range
Lighting load (W/m^2)	10–26
Equipment load (W/m^2)	15–65
Occupancy density (m^2/person)	18–30
Fenestration %	85–100% (large curtain wall building) 30–50% (large concrete panel building) 30–50% (small building)
Fenestration *U*-value	1.8–6.42
Wall *U*-value	0.37 (large curtain wall building) 0.35–1.21 (large concrete panel building) 0.55–1.21 (small building)
Roof *U*-value	0.47–0.74 (large curtain wall building) 0.47–1.41 (large concrete panel building) 0.47–1.36 (small building)
Infiltration rate (ACH)	1.0–0.1
Heating efficiency	75–95%
Cooling COP	1.7–5.2
Blinds?	Yes/No
Turndown ratio	Yes/No
Daylighting?	Yes/No
Heat recovery efficiency	0–60%
Gas pre-heat w/economizer?	Yes/No

To capture the effect(s) of changing individual and/or multiple variables on the energy consumption of a building, a method for simulating each variable change was developed [7]. This simulation strategy centres on how the archetype scheme was developed. Since three main vintages were chosen as representative stages in building construction practices, the variables associated with these three time periods were first defined and set as a starting point for variables alteration.

First, the "Base Level" model was simulated for its energy consumption. A study on Canadian commercial building sector revealed that the mean and standard deviation of the final delivered energy use intensity of government office space in Canada is 1.3078 GJ/m^2 and 1.1657 GJ/m^2, respectively [17]. The mean and standard deviation of the computed energy intensity for each of the "Base Level" representative building was found to be 1.3993 GJ/m^2 and 0.2913 GJ/m^2 and therefore fits well within the average of the Canadian office building stock.

The "Base Level" variables were then adjusted, individually, to reflect a change in the archetype vintage. This process was repeated for each of the variables and for each of the archetype periods, including a "Retrofit" vintage that contained additional upgraded levels. Furthermore, considerations were made to account for changes that may occur to the usage of the office buildings. These include an increase in the occupant density of the building and additions to the equipment and appliance loads. The complete list

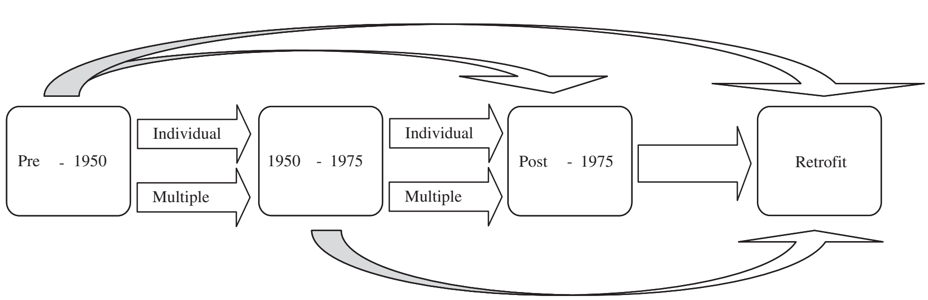


Fig. 2. Simulation scheme.

of variables explored and the range of values used in the simulations are given in Table 7.

The simulation scheme as summarized in Fig. 2 shows that the effects of both individual measures and measure sets on the energy consumption of the buildings were studied. Measure sets were limited to those with a greater than 10% effect on energy consumption. The sets were limited to three measures. The simulations were performed using three cities representing different climatic regions, namely, Edmonton, Ottawa and Vancouver. The average annual temperature fluctuation for each of these cities is presented in Figs. 3 and 4.

3. Effects of retrofit implementation

The proposed energy modelling strategy employed a discrete jump in the buildings' characteristics as they moved from one level of archetype to the next. However, for each archetype level, measures were applied individually and in sets to assess the combined effect of two or more measures. For example, two individual retrofit measures may reduce consumption by 15% respectively. If both measures are applied in a set, the result might be less than the 30% sum of the two measures. When simulation is used to assess this measure set, the combined effect might be less than 20%. Knowledge of the combined effects can aid in the selection of cost effective retrofit measures, either as single measures or in measure sets.

3.1. Single ERM application

Model results for individual ERM application that have yielded at least a 10% reduction in the energy consumption are presented for each city in Figs. 5–7 corresponding to building types LV, LC and S, respectively. These bar plots highlight the impact of the ERM on the electrical and natural gas consumption of each building. The plotted data were normalized using the archetype's base case consumption data, i.e.

$$\text{Change in energy consumption} = \frac{\text{Archetype retrofitted energy consumption } (\text{GJ/m}^2)}{\text{Archetype base level energy consumption } (\text{GJ/m}^2)} \times 100\% \quad (1)$$

Table 8 summarizes the significant observations from the simulations. From the results, the retrofits that have the highest

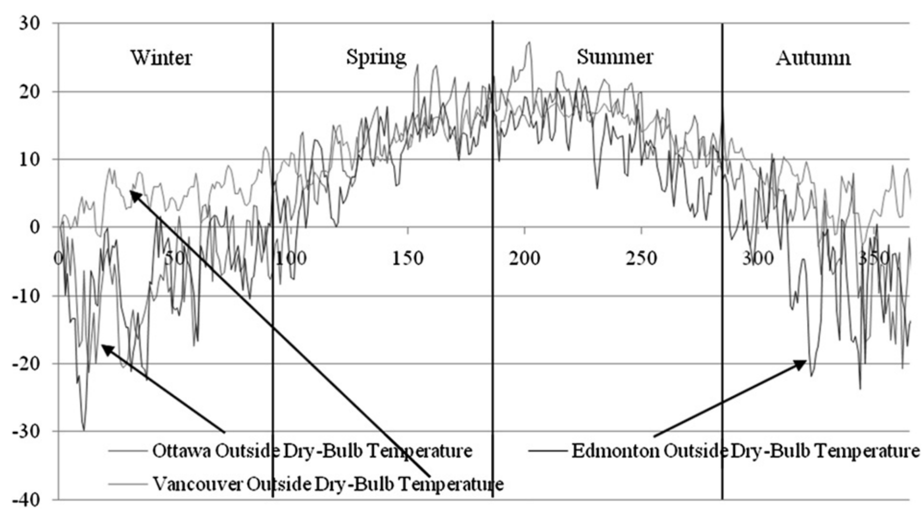


Fig. 3. Daily dry bulb temperatures for Edmonton, Ottawa and Vancouver.

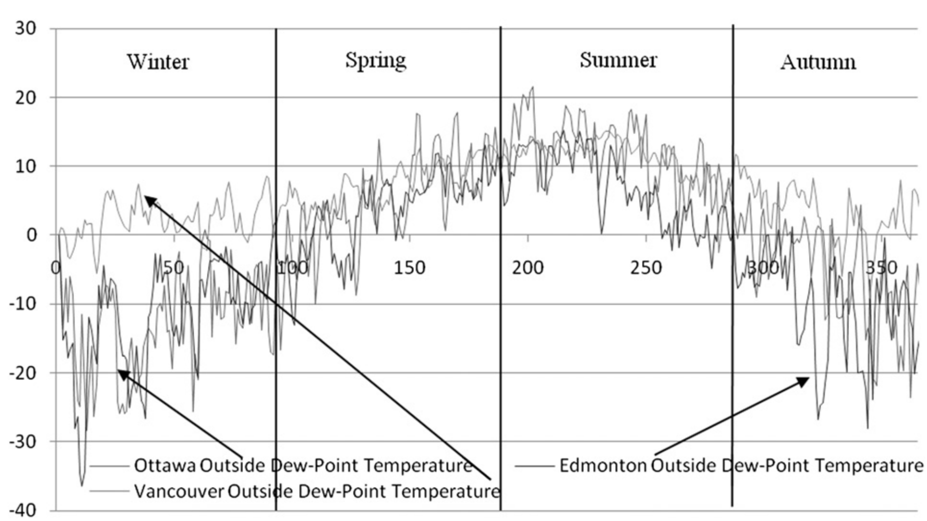


Fig. 4. Daily dew point temperatures for Edmonton, Ottawa and Vancouver.

Fig. 5. Effects of single ERM on electrical and natural gas consumption of building LV.

and lowest impact on energy consumption were different for each building archetype. The improvement that led to the largest reduction in energy consumption for building LV over all archetype years was the reduction of the infiltration rate of the building. Reducing the infiltration rate can be accomplished by improving the overall air tightness of the building envelope. The savings in natural gas experienced varied between 64% in Ottawa, 65% in Edmonton and 51% in Vancouver of the original consumption levels for buildings constructed between 1950 and 1975. A similar trend was found for buildings LC and S where the maximum savings in natural gas resulted from reducing the infiltration. The electrical consumption savings that result from an improvement in the tightness of a building are negligible in comparison.

Improvements in the wall and window thermal efficiencies yielded the second largest reduction in energy consumption with the greatest benefits observed in building LC. This is likely due to the large percentage of windows possessed by this building type. A 30–40% reduction in natural gas usage was noted.

Improvements in the roof thermal efficiencies for building type S built pre-1950 yielded a 14% and 9% increase in natural gas for the cities of Ottawa and Vancouver, respectively, and a 1% decrease for the city of Edmonton. Closer examination of the monthly natural gas consumption and solar gains input for the three cities reveal that the roof acted as a solar collector and transmitted the solar gains to the building. Improving the thermal resistance of the roof impacted the transfer of solar gains to the building. The corresponding electrical consumption decreased by 18%, 19%, and 24%, respectively, for Vancouver, Edmonton, and Ottawa. It should be noted that the building overall energy consumption decreased by 15% on average when the roof was upgraded.

Largest reduction in the electrical consumption was noted for all three buildings when the constant air volume (CAV) fan system was replaced with variable air volume (VAV). The reduction varied from 30% to 40% depending on the type and location of the building.

3.2. ERM sets

The effectiveness of individual measures has been documented for the different types of office building and shown in Figs. 5–7. However, the effectiveness of single measures needs to be extended to measure sets. The differences in energy consumption, in the form of percentage changes from base case, between these two modelling approaches are presented in Figs. 8–13. The results have been organized per building type and climate zone. Only those measures whose impact on consumption exceeded 10% (positive or negative) were considered.

An examination of the modelling results reveals that the reductions are not necessarily a linear addition of the savings from each ERM. For example, the implementation of light dimming features with more efficient lighting fixtures is not as effective in reducing consumption as a linear addition would indicate. On the other hand, the implementation of building envelope improvements, combined

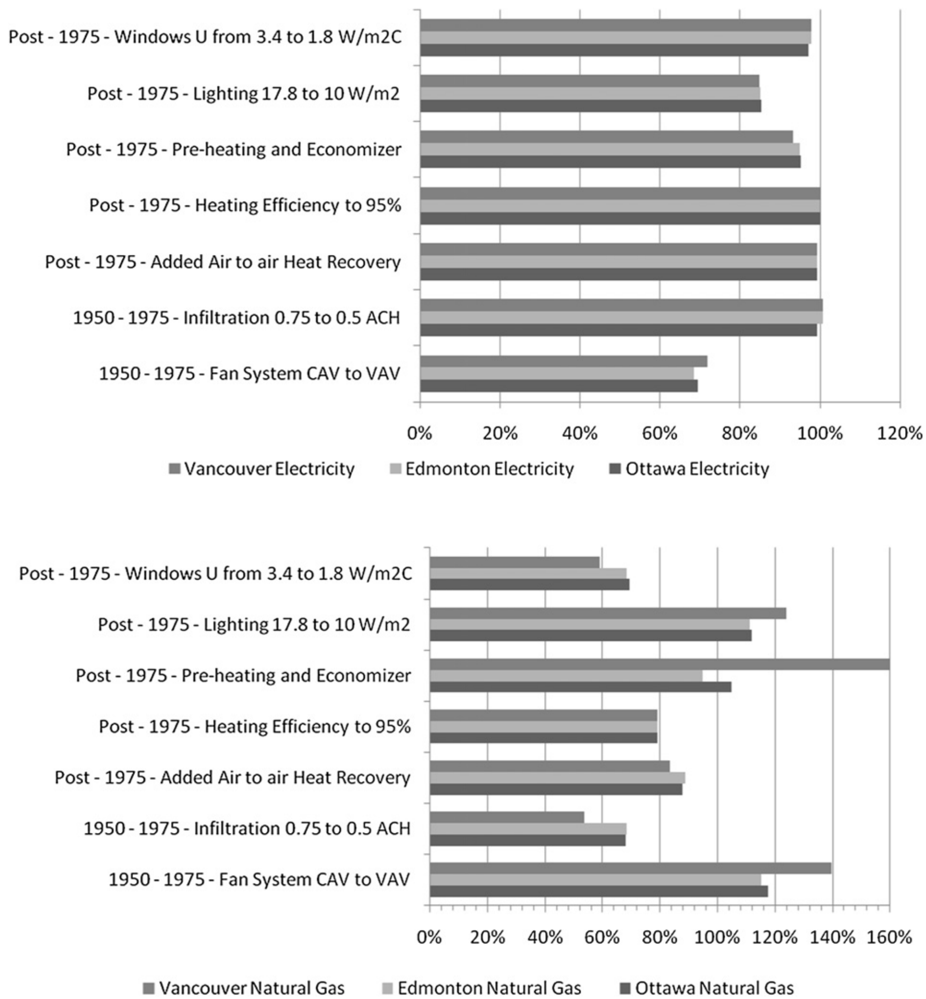


Fig. 6. Effects of single ERM on electrical and natural gas consumption of building LC.

with an HVAC upgrade which includes improved boiler efficiency, economizer and preheating system, provides a greater reduction in energy consumption.

4. Observations and discussion

4.1. Building LV

Focusing first on the changes to the electrical consumption of building type LV for each of the cities modelled, Ottawa, Edmonton and Vancouver, several observations can be made. For the majority of measure sets, the modelled reduction in energy consumption was found to be generally less than the linear addition of the individual simulations. Only two retrofit measures applied as a set, resulted in a larger reduction in energy consumption than the sum of each measure. These two measures were a new HVAC system and an improvement in building envelope *U*-values. This stems from the fact that the insulating capacities of the walls, roof and windows of a building have a direct impact on the amount of heating and cooling required [7]. The HVAC system upgrades were designed to incorporate three measures, namely the combination of a high efficiency boiler, an economizer and a preheating system. The inclusion of an economizer in this set reduces overall cooling requirements by allowing an increase in the usage of outside air to aid in the cooling of the internal spaces. From Table 9 and Fig. 8, one observes that the reduction in electrical consumption occurs for all three cities only when the windows' thermal performance improves and for Ottawa and Vancouver when the walls' thermal performance improves. Results for select retrofits have been summarized in Table 9; all combinations, which were assessed, have been included in Fig. 8.

The largest difference between additive and modelled electrical consumption reductions occurred for sets with measures that reduce lighting loads and add light dimming controls with daylighting. Since daylighting techniques substitute natural sunlight for electrically supplied lighting, the reduction in consumption is a function of the electricity consumed by the lamps currently installed. Eq. (2) has been taken from the EnergyPlus Reference Manual [18] where f_P is the fractional electric lighting input and f_L is the fractional electric lighting output.

$$f_P = f(x) = \begin{cases} f_{P,\min}, & f_L < f_{L,\min} \\ \dfrac{f_L + (1 - f_L) f_{P,\min} - f_{L,\min}}{1 - f_{L,\min}}, & f_{L,\min} \le f_L \le 1 \end{cases} \quad (2)$$

If the steady state consumption of the lighting system is reduced through the implementation of more efficient lighting, then the reduction in consumption due to daylighting is decreased, as a whole, on the building level.

Between each of the modelled cities, the trend in electrical energy consumption for Vancouver is found to differ from the other

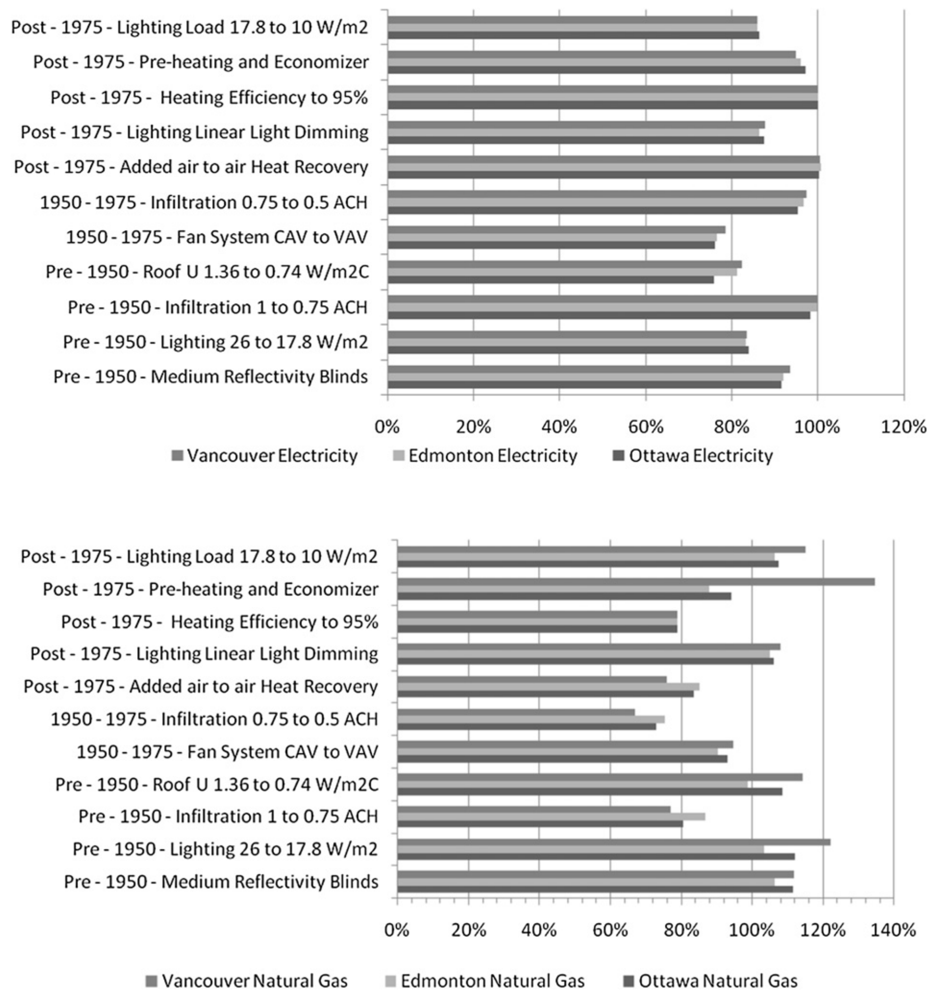
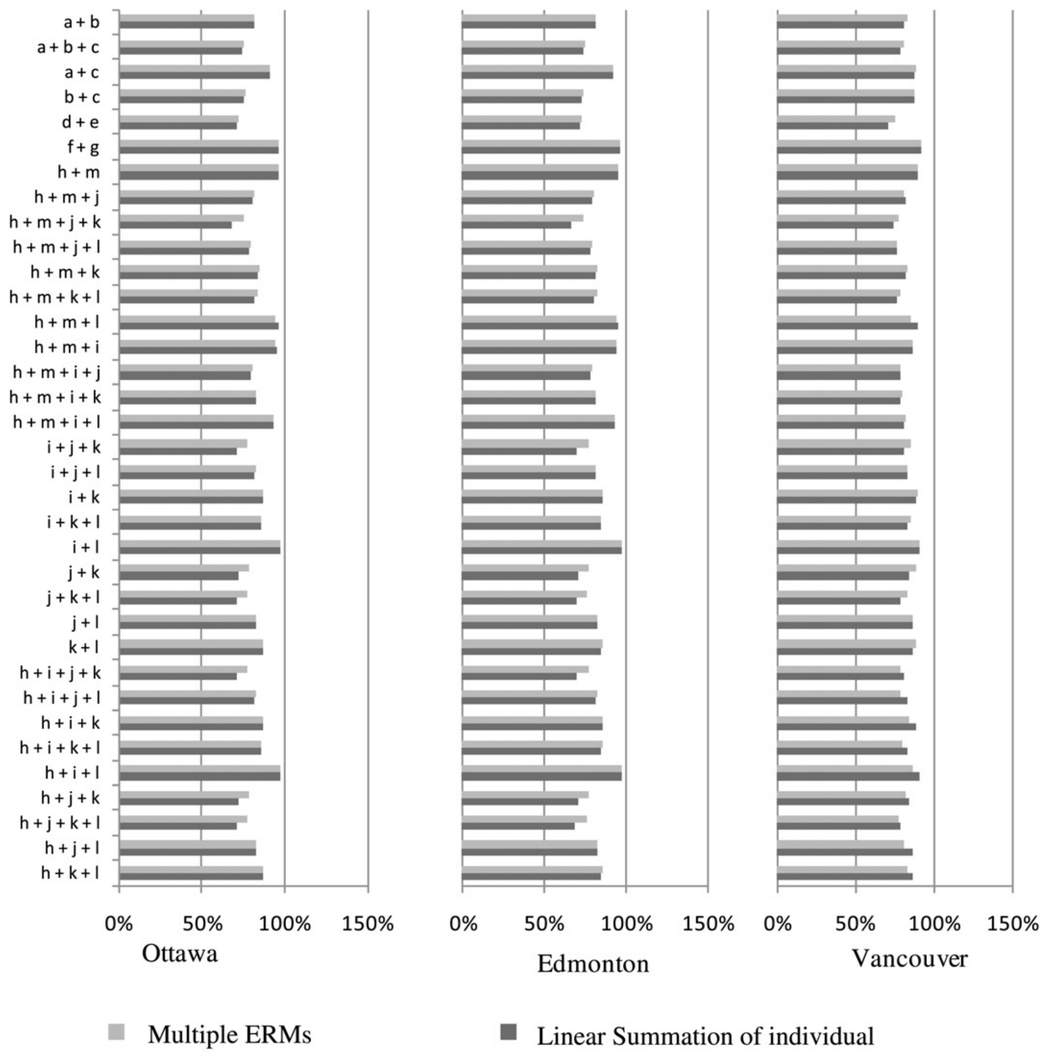


Fig. 7. Effects of single ERM on electrical and natural gas consumption of building S.

Table 8
Percent of Base case energy consumption due to single ERM.

Building	Archetype	ERM	Percent of Base case energy consumption					
			Ottawa		Edmonton		Vancouver	
			Elec.	Gas.	Elec.	Gas.	Elec.	Gas.
LV	1950–1975	Infiltration rate 0.75–0.5 ach	99%	64%	100%	65%	89%	51%
LV	1950–1975	Convert HVAC: CAV to VAV	72%	108%	72%	104%	82%	122%
LV	Post-1975	Improve wall *U*-value 1.16–0.55	99%	90%	99%	90%	97%	86%
LV	Post-1975	Improve window *U*-value 3.4–1.8	99%	84%	99%	83%	94%	77%
LV	Pre-1950	Infiltration rate 1–0.75 ach	99%	71%	100%	72%	91%	62%
LC	1950–1975	Infiltration rate 0.75–0.5 ach	99%	68%	101%	68%	101%	54%
LC	1950–1975	Convert HVAC: CAV to VAV	69%	117%	68%	115%	72%	140%
LC	Post-1975	Improve window *U*-value 3.4–1.8	97%	69%	98%	68%	98%	59%
S	1950–1975	Infiltration rate 0.75–0.5 ach	95%	73%	97%	75%	97%	67%
S	1950–1975	Convert HVAC: CAV to VAV	76%	93%	77%	90%	78%	95%
S	Pre-1950	Infiltration rate 1–0.75 ach	98%	81%	100%	87%	100%	77%



a	*Pre 1950*	*Infiltration Rate 1 to 0.75 ACH*	*h*	*Post 1975*	*High Efficiency Boiler (95%)*
b	*Pre 1950*	*Lighting Load 26 to 17.8 W/m^2*	*i*	*Post 1975*	*Improve Wall U-Value 1.16 – 0.55*
c	*Pre 1950*	*Incorporate Window Blinds*	*j*	*Post 1975*	*Lighting Load 17.8 to 10 W/m^2*
d	*1950 - 1975*	*Convert HVAC: CAV to VAV*	*k*	*Post 1975*	*Daylighting*
e	*1950 - 1975*	*Infiltration Rate 0.75 – 0.5 ACH*	*l*	*Post 1975*	*Improve Window U-Value 3.4 – 1.8*
f	*1950 - 1975*	*High Efficiency Boiler (95%)*	*m*	*Post 1975*	*Preheat & Economizer*
g	*1950 - 1975*	*Preheat & Economizer*			

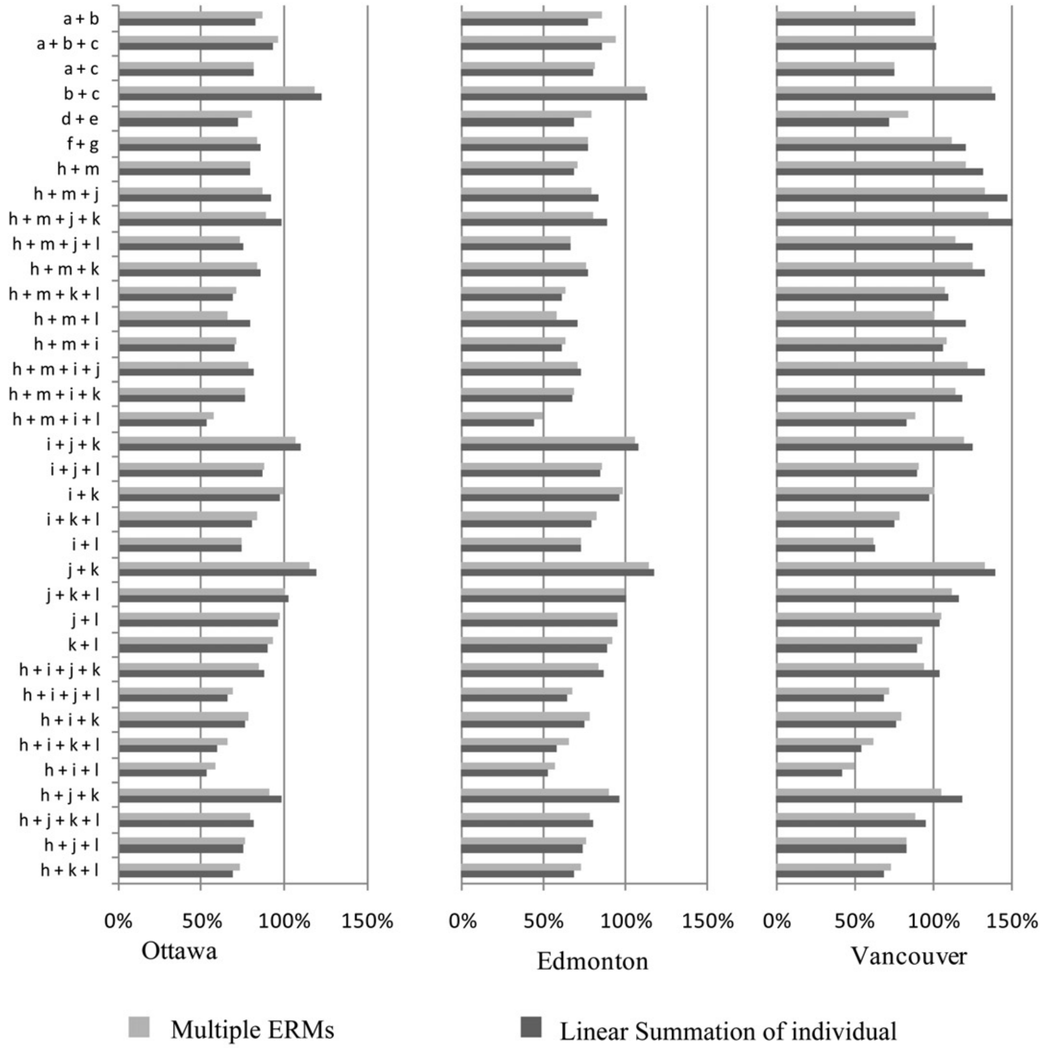
Fig. 8. Effects of single vs. multiple ERMs on electrical consumption of building LV.

two cities when it comes to set that includes lighting load and daylighting as retrofit measures. For Vancouver, the modelled reduction in electrical consumption is greater than the linear addition of the individual simulations. These sets always included a high efficiency boiler in the combination. Overall, the results indicate that while variations in climate affect the overall value of the reduction or increase in consumption due to measures, there is no significant change in the electrical consumption as measure sets are applied in these differing climates.

For the natural gas consumption for building LV, shown in Fig. 9, a similar trend is observed. Overall, the reduction in the modelled energy consumption is less than that of the linear additions. The largest differences occur for a simulated measure set that includes reductions to the infiltration rate and lighting load with increased boiler efficiency. The observed changes in natural gas consumption were highly influenced by the climate. In contrast, the changes in electrical consumption did not fluctuate between the cities modelled.

When examining the results of the simulations that involved changes to the lighting systems in combination with upgrades to the HVAC systems, it was observed that increases in energy consumption occurred primarily when Vancouver climate data was used. To aid in understanding this result each of the individual upgrades was examined separately.

Improving the lighting load from T12 to T8, or low to high efficiency lamps, resulted in a reduction in energy consumption of 90–80% of the original electrical consumption and an increase in natural gas consumption by 10–25%. Focusing on a heating efficiency upgrade alone it was observed that the reductions in natural gas averaged 80% of original levels and imposed no effect on the electrical consumption. When lighting upgrades are combined with heating efficiency improvements the benefits gained from the



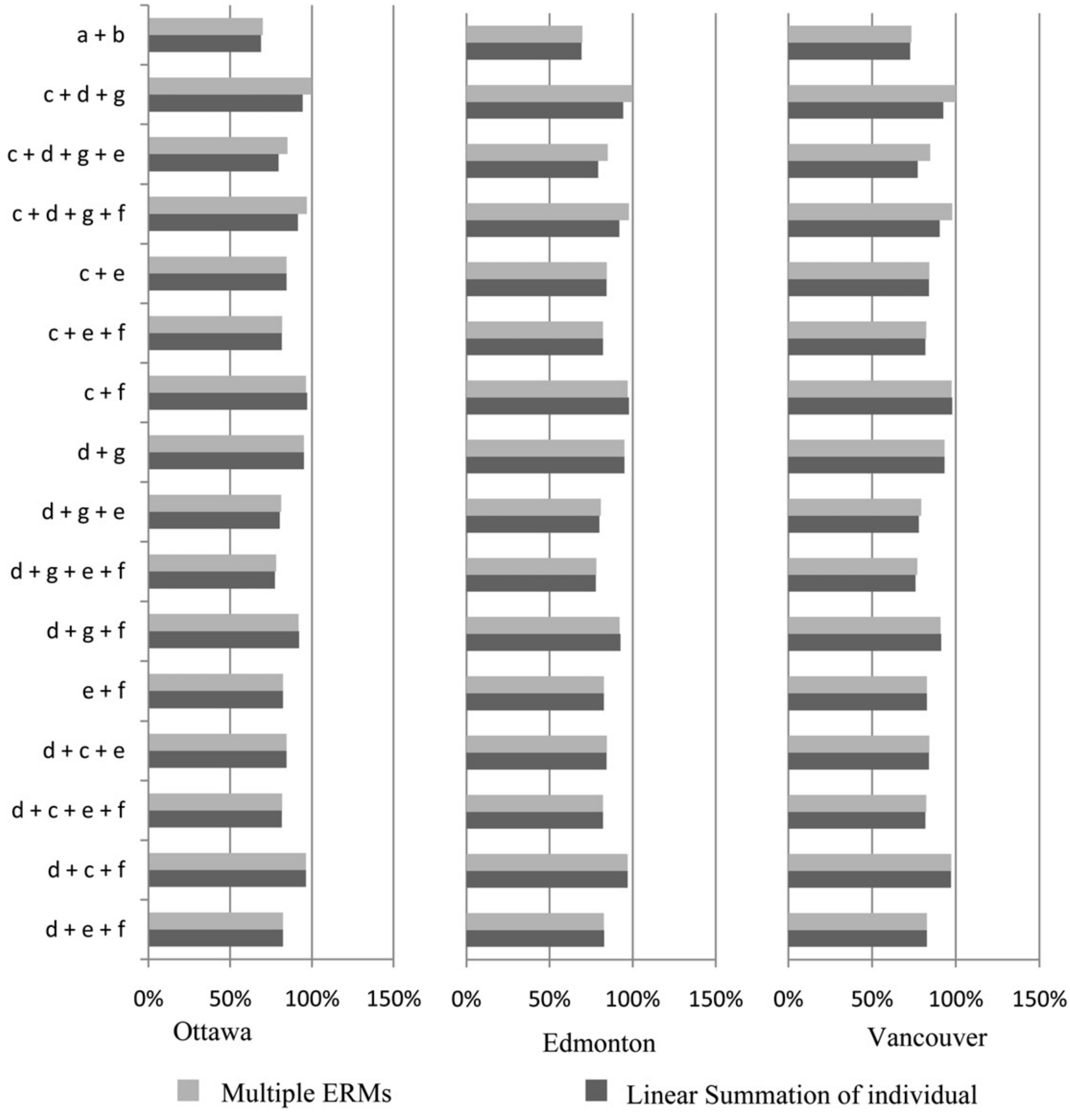
a	*Pre 1950*	*Infiltration Rate 1 to 0.75 ACH*	*h*	*Post 1975*	*High Efficiency Boiler (95%)*
b	*Pre 1950*	*Lighting Load 26 to 17.8 W/m^2*	*i*	*Post 1975*	*Improve Wall U-Value 1.16 – 0.55*
c	*Pre 1950*	*Incorporate Window Blinds*	*j*	*Post 1975*	*Lighting Load 17.8 to 10 W/m^2*
d	*1950 - 1975*	*Convert HVAC: CAV to VAV*	*k*	*Post 1975*	*Daylighting*
e	*1950 - 1975*	*Infiltration Rate 0.75 – 0.5 ACH*	*l*	*Post 1975*	*Improve Window U-Value 3.4 – 1.8*
f	*1950 - 1975*	*High Efficiency Boiler (95%)*	*m*	*Post 1975*	*Preheat & Economizer*
g	*1950 - 1975*	*Preheat & Economizer*			

Fig. 9. Effects of single vs. multiple ERMs on natural gas consumption of building LV.

higher efficiency heating system acts to neutralize the increases in natural gas energy resulting from the reduced heat gain from the more efficient lights.

Focusing on the addition of the air system upgrades of preheating and the addition of an economizer, the results fluctuate with the climate data used in the simulations. Temperature trends for the cities of Edmonton, Ottawa and Vancouver are presented in Figs. 3 and 4. For buildings modelled in the climates of Vancouver and Ottawa, an increase in energy consumption resulted, with Vancouver experiencing the greatest percentage increases with values ranging from 40% to 50% and Ottawa experiencing more subdued increases with a maximum of 7% as shown in Fig. 5. Edmonton, in contrast, experienced a slight decrease in energy consumption. To gain an understanding of why these changes in energy consumption are occurring, it is necessary to first examine the details associated with the implementation of the pre-heat and economizer retrofits.

The preheating system was modelled as electrically supplied heating coils operating at an off coil temperature of 10 °C. The economizer system was modelled to allow for 100% outside air when the outside dry bulb temperature is within the range of 24 °C and 11 °C. As the economizer is set to operate year round, the effects on energy consumption of its implementation in a Vancouver climate zone would respond with an increase in heating consumption. This result can be explained by the on average moderate temperature fluctuations within this climate region. The economizers are allowing a greater level of outside air into the buildings for more time throughout the winter and autumn months resulting in an increase in the heating required. When the economizer is applied in the climates experienced in Ottawa and Edmonton, the



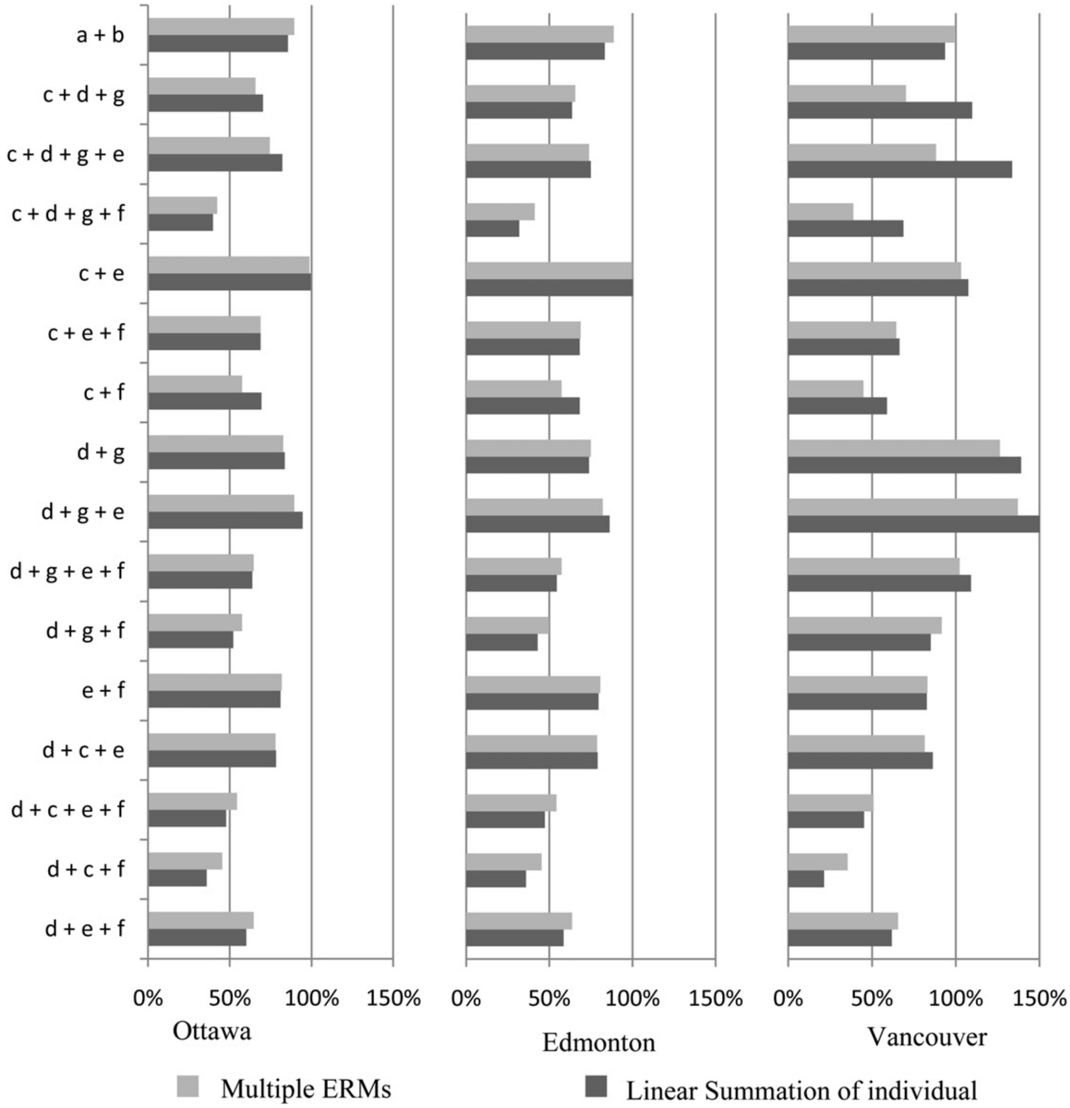
a	*1950 - 1975*	*Convert HVAC: CAV to VAV*
b	*1950 - 1975*	*Infiltration Rate 0.75 – 0.5 ACH*
c	*Post 1975*	*Add Heat Recovery*
d	*Post 1975*	*High Efficiency Boiler (95%)*
e	*Post 1975*	*Lighting Load 17.8 to 10 W/m^2*
f	*Post 1975*	*Improve Window U-Value 3.4 – 1.8*
g	*Post 1975*	*Preheat & Economizer*

Fig. 10. Effects of single vs. multiple ERMs on electrical consumption of building LC.

resultant effect on heating consumption is not as significant as Vancouver due to the lesser number of hours with temperatures between 24 °C and 11 °C in these zones. The measure was equally implemented for the three climate zones for comparison purposes. However, if economizers in buildings located in Vancouver are either cut out during the winter months or were modelled to allow for 100% outside air when the outside dry bulb temperature is within the range of 26 °C and 18 °C, energy reductions will appear.

4.2. Building LC

The primary structural differences between building LV and LC are the window to wall ratio and the type of building envelope material used. As such, it is expected that similar trends in consumption reduction would occur between these two buildings. For each of the combinations of retrofits modelled the reduction in electrical consumption was less than the linear additions as shown in Fig. 10. The greatest differences occurred when heat recovery and heating efficiency/economizer/preheat measures were applied in combination with a lighting system upgrade. Heat recovery systems use the heat remaining in the exhaust air to warm incoming fresh air. However, this retrofit has no direct impact on electrical energy consumption. The measures of this set that affect electrical consumption are the economizer and the lighting system upgrades. Individually each of these measures reduces electrical energy consumption by 5% and 15%, respectively, for all climate



a	*1950 - 1975*	*Convert HVAC: CAV to VAV*
b	*1950 - 1975*	*Infiltration Rate 0.75 – 0.5 ACH*
c	*Post 1975*	*Add Heat Recovery*
d	*Post 1975*	*High Efficiency Boiler (95%)*
e	*Post 1975*	*Lighting Load 17.8 to 10 W/m^2*
f	*Post 1975*	*Improve Window U-Value 3.4 – 1.8*
g	*Post 1975*	*Preheat & Economizer*

Fig. 11. Effects of single vs. multiple ERMs on natural gas consumption of building LC.

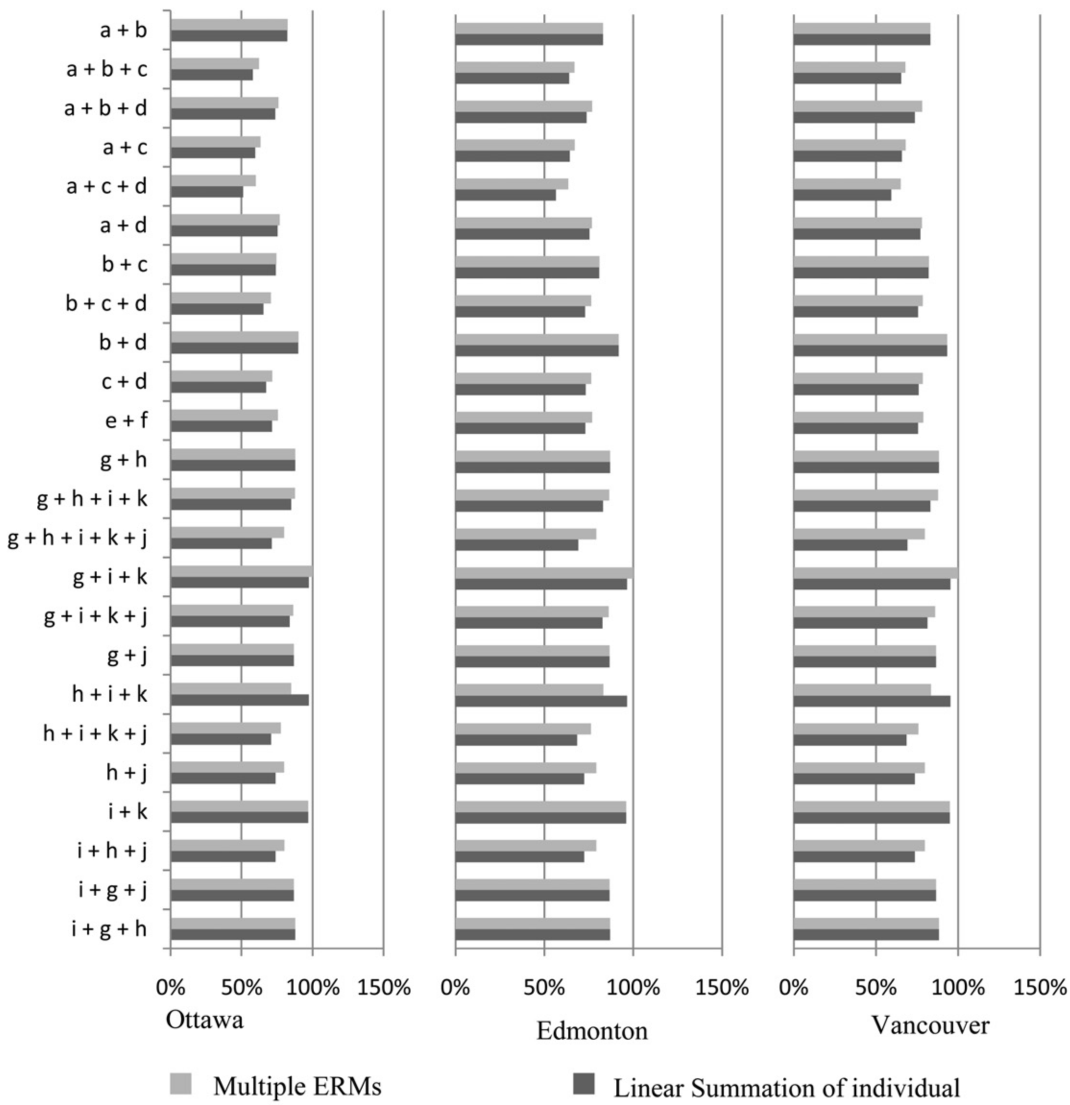
data. However, in the simulated set a 15% reduction occurs. Therefore, the benefits of combining both ERMs in a single building are not as great as the sum of the individual simulations.

For natural gas consumption, shown in Fig. 11, it is found that the climate has a significant effect on the reductions in secondary energy consumption that occur. For Ottawa and Edmonton, similar results were found, such that combinations involving HVAC and building envelope properties resulted in a synergistic improvement in energy reductions. However, after breaking down the ERMs into a boiler upgrade, preheating/economizer addition, heat recovery and envelope improvements, it can be seen that the heat recovery components of the retrofits are the catalyst in the synergistic effect.

Vancouver energy consumption results differed greatly from the other two cities particularly when the addition of a high efficiency boiler with an economizer and preheating system with a lighting load retrofit were incorporated. The net effect of these two retrofits resulted in an increase in energy consumption. This corresponds with the results obtained for building LV and help to reaffirm the assumption that the warmer climate experienced in the city of Vancouver has a significant effect on energy consumption reduction.

4.3. Building S

Building S, which possesses similar building properties as building LV including envelope materials and window/wall

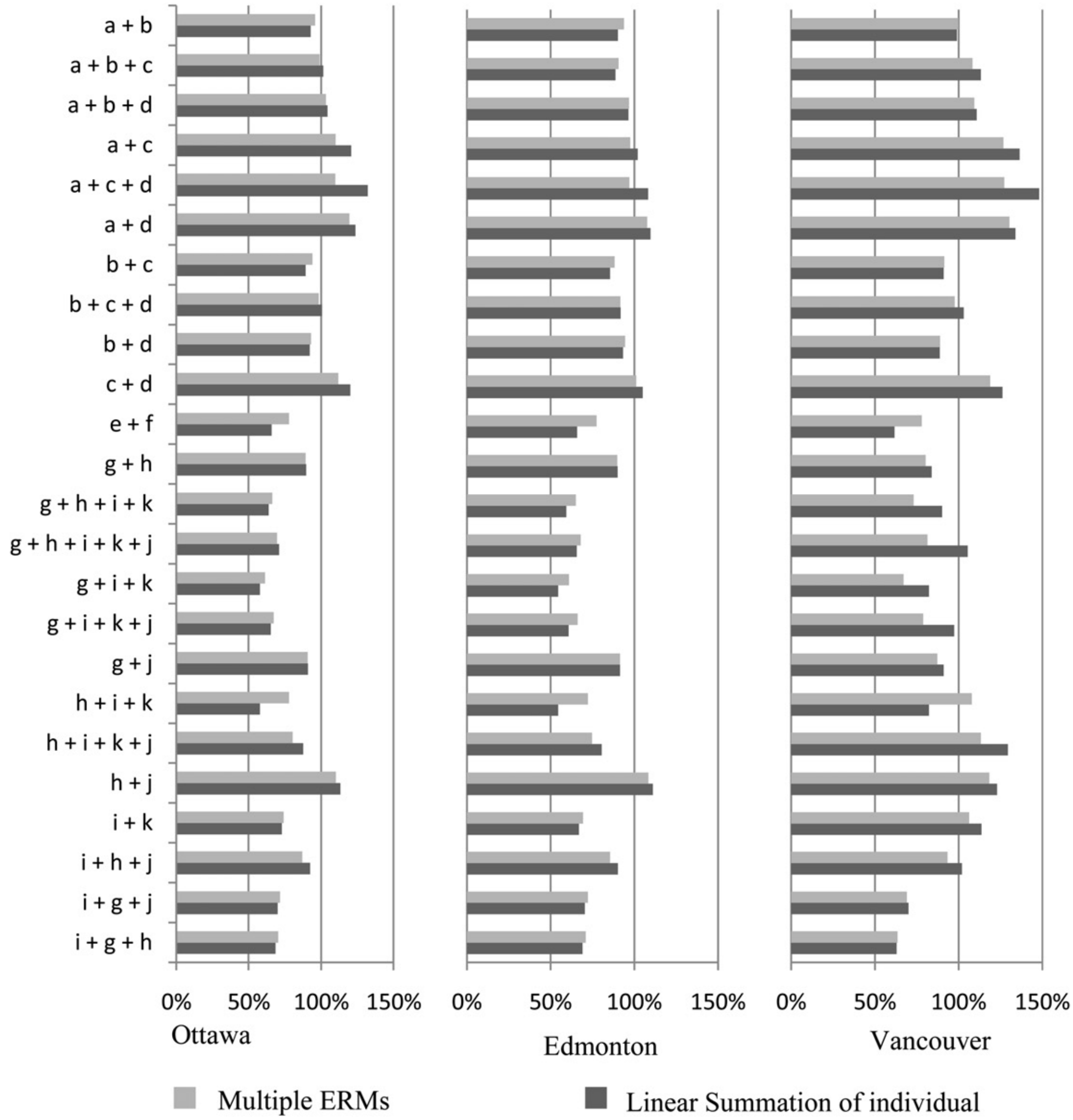


a	*Pre 1950*	*Lighting Load 26 to 17.8 W/m²*	*g*	*Post 1975*	*Add Heat Recovery*
b	*Pre 1950*	*Infiltration Rate 1 to 0.75 ACH*	*h*	*Post 1975*	*Daylighting*
c	*Pre 1950*	*Roof U-Value 1.36 to 0.74*	*i*	*Post 1975*	*High Efficiency Boiler (95%)*
d	*Pre 1950*	*Incorporate Window Blinds*	*j*	*Post 1975*	*Lighting Load 17.8 to 10 W/m²*
e	*1950 - 1975*	*Convert HVAC: CAV to VAV*	*k*	*Post 1975*	*Preheat & Economizer*
f	*1950 - 1975*	*Infiltration Rate 0.75 – 0.5 ACH*			

Fig. 12. Effects of single vs. multiple ERMs on electrical consumption of building S.

percentages, showed comparable reactions to multiple ERM implementations. In the modelling of the single ERM applications, window blind additions were found to be much more significant in reducing energy consumption then in the large building types. As such this ERM was included in the multiple set analyses. For each model that included a window blind addition, the resultant reduction in energy consumption was consistently lower in the simulated results than the sum of the ERMs. The combination of ERMs that had the most widely differing results, between the summation and simulation results in terms of electrical consumption as shown in Fig. 12, was the addition of a daylighting retrofit with an HVAC system upgrade. Comparing the linear addition of the two retrofit options with the combined simulation results, one obtains values of approximately 3% and 18% reduction in electrical consumption, respectively. Conversely, these two ERMs, when combined had varying degrees of effect on the natural gas consumption for each of the climate conditions as shown in Fig. 13. Edmonton and Ottawa experienced a reduction in natural gas consumption due to their colder winter temperatures where Vancouver responded with a slight increase. The incorporation of a daylighting retrofit reduces the internal heat gains to which a building is subjected. As a result, the cooling requirements are reduced while the heating demands are increased.

Other retrofits that had a significant difference between the combined and simulated energy consumption involved the implementation of lighting retrofits, heat recovery and boiler/



a	*Pre 1950*	*Lighting Load 26 to 17.8 W/m²*		*g*	*Post 1975*	*Add Heat Recovery*
b	*Pre 1950*	*Infiltration Rate 1 to 0.75 ACH*		*h*	*Post 1975*	*Daylighting*
c	*Pre 1950*	*Roof U-Value 1.36 to 0.74*		*i*	*Post 1975*	*High Efficiency Boiler (95%)*
d	*Pre 1950*	*Incorporate Window Blinds*		*j*	*Post 1975*	*Lighting Load 17.8 to 10 W/m²*
e	*1950 - 1975*	*Convert HVAC: CAV to VAV*		*k*	*Post 1975*	*Preheat & Economizer*
f	*1950 - 1975*	*Infiltration Rate 0.75 – 0.5 ACH*				

Fig. 13. Effects of single vs. multiple ERMs on natural gas consumption of building S.

Table 9
Percent of base case energy consumption due to linear (L.A.) and multiple (M) ERM applications.

Building	95% Boiler	Preheat + econ.	Heat rec.	T8 lights	Day- lighting	Wall U	Window U	Ottawa				Edmonton				Vancouver			
								Elec.		Gas.		Elec.		Gas.		Elec.		Gas.	
								L.A.	M.	L.A.	M.	L.A.	M.	L.A.	M.	L.A.	M.	L.A.	M.
LV	x				x		x	86%	87%	69%	73%	85%	86%	68%	73%	87%	83%	69%	73%
LV	x			x			x	83%	83%	75%	77%	83%	83%	74%	76%	86%	81%	83%	83%
LV	x			x	x		x	71%	77%	82%	80%	69%	77%	80%	79%	79%	78%	96%	89%
LV	x			x	x			72%	79%	98%	91%	71%	78%	97%	91%	84%	82%	119%	105%
LV	x					x	x	98%	98%	53%	58%	98%	98%	52%	58%	91%	87%	42%	49%
LV	x				x	x	x	85%	86%	60%	66%	85%	85%	59%	65%	84%	80%	54%	62%
LV	x				x	x		87%	86%	76%	79%	86%	86%	75%	78%	89%	84%	77%	80%
LV	x			x		x	x	82%	82%	66%	69%	82%	82%	64%	68%	83%	78%	69%	72%
LV	x			x	x	x		71%	78%	88%	84%	70%	77%	87%	83%	81%	79%	104%	95%

Table 9 (*continued*)

Building	95% Boiler	Preheat + econ.	Heat rec.	T8 lights	Day- lighting	Wall U	Window U	Ottawa				Edmonton				Vancouver			
								Elec.		Gas.		Elec.		Gas.		Elec.		Gas.	
								L.A.	M.	L.A.	M.	L.A.	M.	L.A.	M.	L.A.	M.	L.A.	M.
LV	x	x				x	x	93%	93%	53%	58%	94%	93%	45%	50%	81%	82%	83%	89%
LV	x	x				x		95%	95%	70%	71%	95%	95%	62%	63%	87%	87%	106%	109%
LV	x	x					x	96%	94%	79%	66%	96%	94%	71%	58%	90%	85%	121%	102%
LC	x			x			x	82%	82%	60%	65%	83%	83%	59%	64%	83%	83%	62%	65%
LC	x		x				x	96%	96%	36%	45%	97%	97%	36%	45%	97%	97%	21%	35%
LC	x		x	x			x	82%	82%	48%	54%	82%	82%	47%	54%	82%	82%	45%	51%
LC	x		x	x				84%	85%	78%	78%	84%	84%	79%	79%	84%	84%	86%	81%
LC	x	x					x	92%	92%	52%	58%	93%	92%	43%	50%	91%	91%	85%	92%
LC	x	x		x			x	77%	78%	64%	65%	78%	78%	55%	57%	76%	77%	109%	102%
LC	x		x				x	92%	97%	40%	42%	92%	98%	32%	41%	90%	98%	69%	39%
S	x		x		x			88%	88%	68%	70%	87%	87%	69%	71%	88%	88%	63%	63%
S	x	x			x			97%	85%	58%	78%	97%	83%	55%	72%	95%	84%	82%	108%
S	x	x	x	x	x			71%	80%	71%	70%	69%	79%	66%	68%	69%	80%	105%	81%
S	x		x	x				87%	87%	70%	72%	87%	87%	70%	72%	87%	87%	70%	69%
S	x			x	x			74%	80%	92%	87%	72%	79%	90%	86%	74%	80%	102%	93%

economizer/preheat upgrades. The impact on electrical consumption of the inclusion of both types of lighting retrofit measures resulted in changes that followed a similar pattern to building LV and building LC.

One retrofit set of interest is the combination of five retrofit opportunities that were applied to this building. These are the ERMs of heat recovery, daylighting, boiler efficiency economizer/preheat upgrade and lighting load reduction. The estimated combined reduction in electrical consumption for this ERM set is approximately 29–31% over all cities modelled. For natural gas the changes in consumption were 28%, 34% and −5% for Edmonton, Ottawa and Vancouver respectively. In comparison, the simulation of this retrofit set resulted in an actual reduction of 20% for electrical consumption for all cities and 30%, 32% and 19% reduction in natural gas for each of the respective cities. These results indicated that the electrical consumption reduction is grossly overestimated when simple linear addition is used to predict energy changes and that the natural gas adjustments are poorly predicted.

5. Conclusions

The selection of multiple measures to apply to a building retrofit is crucial to reduce energy consumption. It is dependent on climate, building type and occupancy as well as the technologies applied. More often than not, combining multiple ERMs is not as beneficial as the sum of individual ERM modelling. From the limited set of ERMs presented in this paper several preliminary conclusions can be made.

1. The implementation of a retrofit that reduces the lighting load within a building can have a significant negative impact on the effectiveness of a light dimming strategy when applied concurrently. Reductions in electrical consumption and increases in natural gas consumption are over predicted.
2. Differences between modelled sets and sum of individual ERMs are found to be much larger for the natural gas consumptions in comparison to the electrical consumptions for the majority of the cases studied.
3. For a post-1975 building type LV located in Vancouver only, the reduction in electrical consumption due to ERMs sets that include daylighting and/or reduction in lighting load and high efficiency boiler is found to be greater than the linear additions.
4. Combining air handling system upgrades with building envelope improvements can be more beneficial than estimated using individual ERMs.
5. Climate can impact the effectiveness of multiple ERMs as it was observed that buildings simulated using Vancouver climate data showed the least reductions in natural gas consumption.
6. By comparing the linear addition of multiple ERMs with simulated combination results, the trend found was that the majority of results were less than the sum of single ERM modelling.
7. In order to properly capture the complete energy consumption picture a simulation of all combined ERMs must be performed.

Acknowledgements

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