ASSESSING POTENTIAL ENERGY RETROFITS OF MULTI -UNIT RESIDENTIAL BUILDINGS IN THE GREATER TORONTO AREA

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ABSTRACT

There are thousands of multi-unit residential buildings (MURBs) in Toronto and Southern Ontario. In the City of Toronto, these buildings provide over half of the dwelling units and are responsible for an estimated 17% of the total annual greenhouse gas (GHG) emissions associated with natural gas and electricity consumption. To reduce the impact of this existing building stock, energy retrofits must be undertaken. To maximize the effectiveness of expenditures directed to energy retrofits, the poorest performing buildings should be identified and targeted first. Further, the specific retrofit measures considered should maximize the energy use reduction potential in each building. This study assesses the potential for energy retrofits in the Toronto MURB stock in two ways. First, the energy use of the MURB stock is assessed to determine the building characteristics which contribute to the highest energy intensity. Then, a detailed analysis of four buildings is conducted using calibrated energy models to test the impact of various retrofit measures on energy use. Fenestration ratio was building characteristic most highly correlated ($R^2 = 0.69$ for double-glazed windows) to building energy intensity across the MURB sample, but this building characteristic is not easily altered by a retrofit. The energy modeling exercise indicated that improved air-tightness, envelope thermal resistance and boiler efficiency were the retrofit measures that resulted in the greatest reduction in building energy intensity. Using the results of the energy modeling, it was estimated that modest improvements to the energy efficiency Toronto MURBs could help the city achieve 2% GHG savings below 1990 levels of the required 30% savings to be achieved by 2020.

INTRODUCTION

Multi-unit residential buildings (MURBs) comprise 55% of the dwelling units in the City of Toronto (Touchie et al., 2013). It has been estimated that Toronto MURBs emit over 2.6M tonnes of eCO_2 annually due to the combined electricity and natural gas consumption of these buildings (Touchie et al., 2013) accounting for more than 17% of the total annual greenhouse gas (GHG) emissions associated with natural gas and electricity consumption in the City in 2004 (ICF International, 2007). Thus, MURBs contribute significantly to the environmental impact of residential building energy use in the City of Toronto.

Toronto has ambitious GHG emission reduction targets of 30%, below 1990 levels, by 2020 (City of Toronto, 2007). While energy-efficiency standards for new construction will help reduce overall energy consumption for new buildings, building stock turnover is only a few percent annually. Therefore, to significantly reduce the energy use intensity (EUI) of this sector, existing buildings must be retrofit. To maximize the impact of energy retrofits at the municipal level, buildings with the highest energy use intensities should be prioritized.

To efficiently target energy intensive buildings, researchers have sought correlations between energy intensity and building characteristics. In previous studies, all of which included less than 100 buildings, one study showed no significant correlations (Hart, 2005) while other studies found correlations (some without a specified strength) between energy intensity and building height, gross floor area, vintage ownership type, aspect ratio and common area size (Elmahdy, 1982; Enermodal Engineering Limited, 2000; Liu, 2007; Finch et al., 2010; Danielski, 2012; Choi, 2012). The correlations indicated the following: buildings heated with natural gas exhibited higher average energy intensities than those heated electrically (Liu, 2007), buildings constructed after the 1990s used more energy than older buildings due to increased ventilation rates and glazing ratios (Finch et al., 2010), and more compact buildings used less energy (Danielski, 2012).

The study presented here is comprised of two parts. First, an assessment of the energy consumption of Toronto MURBs was conducted in an effort to identify what building characteristics were associated with energy inefficiency. In an effort to establish stronger correlations than previous studies, a sample of over 100 buildings was gathered. Where possible, data about the building envelope and mechanical systems were also collected. Next, four sample buildings from different vintages were selected for further analysis. Calibrated energy models were then developed for each building and used to test a range of retrofit measures to determine which could have the greatest impact on energy use. Findings from the correlation analysis could be supported by the energy retrofit modeling. In other words, the building characteristics most highly correlated with building energy use should also yield significant energy savings when improved through retrofit.

This paper begins with a discussion of the data collection and data processing procedures followed by presentation of the MURB energy use trends identified. Next, the subject buildings are described along with the energy modeling process. Finally, the retrofit measure impacts are presented and compared to the correlation analyses.

ENERGY CONSUMPTION DATA

To begin, data were assembled from three existing data sets to form the Meta-Analysis Data Set and were later supplemented with more detailed data to form the Refined Data Set. This section describes the characteristics of each data set and the data processing procedure used to allow a direct comparison between the buildings.

Data Collection

To build on the work of others, existing MURB energy-use data sets were sought. The "Meta-Analysis Data Set" combined the energy-use data and basic building characteristics from three sources namely: the Canada Mortgage and Housing Corporation's "High-rise Building Statistically Representative" (HiSTAR) Database and the Green Condo Champions Program and Tower Renewal Benchmarking Initiative, both run by the Toronto Atmospheric Fund. However, the Meta-Analysis energy-use data were incomplete and the building characteristic information did not include envelope or mechanical system details. Therefore, a "Refined Data Set" of 40 buildings with complete utility data and more detailed information such as envelope characteristics and mechanical system details was assembled to address the limitations of the Meta-Analysis Data Set.

The Refined Data Set included buildings from the Meta-Analysis Data Set supplemented by additional natural gas consumption data and nine new buildings including: two that were the focus of a study by Tzekova et al. (2011); three that were the subject of a community energy plan for the City of Toronto (Arup, 2010); and the remainder were obtained from energy audit reports conducted by engineering consulting firms for projects being carried out by the City of Toronto's Tower Renewal Office. More complete energy consumption data and information about building parameters such as fenestration-to-wall ratio, envelope thermal resistance and mechanical equipment efficiency were available for these buildings. Details of the data set characteristics are shown in Table 1.

Characteristics	**Meta-Analysis Data**	**Refined Data**
Number of buildings	108	40
% of mid- & high-rise Toronto MURB population	4.8%	1.9%
% of total Toronto MURB population	1.8%	0.7%
Vintage (year)	1941-2009	1960-2003
Height (storey)	4-46	5-28

TABLE 1: DATA SET CHARACTERISTICS

The heights and vintages of the buildings in both the Meta-Analysis Data Set and the Refined Data Set were compared to an estimate of the entire MURB population in Toronto to ensure the sample was representative of the population (Binkley et al., 2012; TOBuilt, 2012).

Data Processing

The energy data for each building was collected across different billing periods. Therefore, weather normalization was required to account for these variations and allow for a direct comparison between the buildings. A spreadsheet program was developed for all of the normalization processing and a description of the procedure used is provided in Touchie et al. (2013). The EUI of each building was then determined by dividing the total weather-normalized energy consumption by the gross floor area. The gross floor area represents the total area containing the residential suites, lobby, common areas, and any conditioned recreational areas. It typically did not include underground parking areas even though these spaces are at least partly conditioned in many buildings.

ENERGY CONSUMPTION TRENDS

With the processing complete, the building energy use data from the different sources could be directly compared. A discussion of the EUI of the data sets and a selection of the most significant correlations are presented here.

Energy Use Intensity

Figure 1 shows the weather-normalized EUI for each building in the data sets, with a median of 300ekWh/m^2. The worst performing buildings (grouped as the highest 10% of energy users) used more than three times the amount of energy consumed by the best performers (lowest 10% of energy users).

The high variability in EUI may reflect a variety of factors including differences in the way the buildings are operated, in the efficiency of the major mechanical and electrical systems, and in the materials and methods used to construct the building envelope. The authors of a similar study of building energy use intensity in New York (City of New York, 2012) suggested that the buildings with the highest energy intensities could achieve significant reductions in energy use through low-cost means such as adjusting controls, sensors and schedules of mechanical equipment. Further research on the worst performers in the Toronto MURB stock is needed to determine what proportion of building energy use can be influenced by these operational changes.

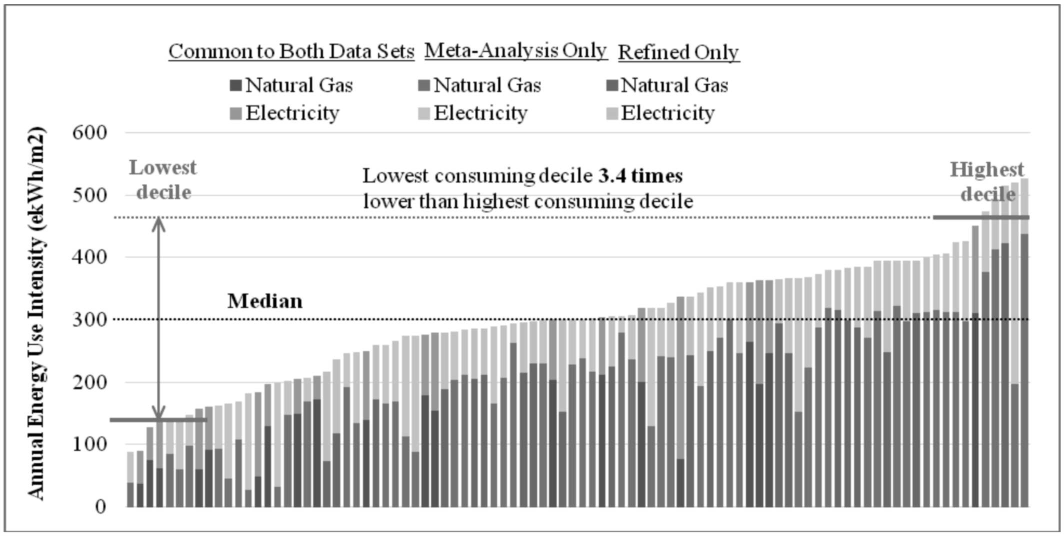

FIGURE 1: TOTAL ANNUAL WEATHER-NORMALIZED ENERGY USE INTENSITY OF THE SAMPLED BUILDINGS

Table 2 summarizes the weather-normalized minimum, maximum and average total annual EUI as well as the associated GHG emission intensity and the average energy source mix of each data set.

	Energy use intensity (ekWh/m^2)			GHG Emission Intensity(ekgCO_2/m^2)			Energy Source Mix	
Data set	Min	Max	Avg	Min	Max	Avg	Electricity	Natural Gas
Meta-Analysis	88	520	295	12.8	90.4	46.6	38%	62%
Refined	91	514	292	12.7	87.2	46.1	33%	67%
GHG emission intensity calculations are based on the following factors: 1.879kg/m^3 of natural gas and 0.11kg/kWh of electricity for the City of Toronto (Toronto Atmospheric Fund, 2013).								

TABLE 2: SUMMARY OF BUILDING ENERGY USE AND GHG EMISSION STATISTICS FROM THE DATA SETS

For reference, the published energy mix of apartment buildings in Ontario is 34% electricity and 66% natural gas (Natural Resources Canada, 2008). The GHG emission intensity figures together with average building size and number of MURBs are consistent with another published estimate which reported that Toronto MURBs erected between 1945 and 1984 were responsible for between 2.0M and 2.2M tonnes of eCO_2 (Stewart and Thorne, 2010). Generally, the results of this analysis are in line with existing studies when weather-normalization procedures are considered (Hart, 2005; Enermodal Engineering Limited, 2000; Elmahdy, 1982; Liu, 2007).

Building Energy Use Trends

With the weather-normalized EUI established for each building, correlations with various building characteristics were sought. A selection of the most significant correlations from each data set is presented here.

As architectural typologies are typically associated with a particular time period, the correlation between building energy use and date of construction was examined for the Meta-Analysis Data Set, as shown in Figure 2.

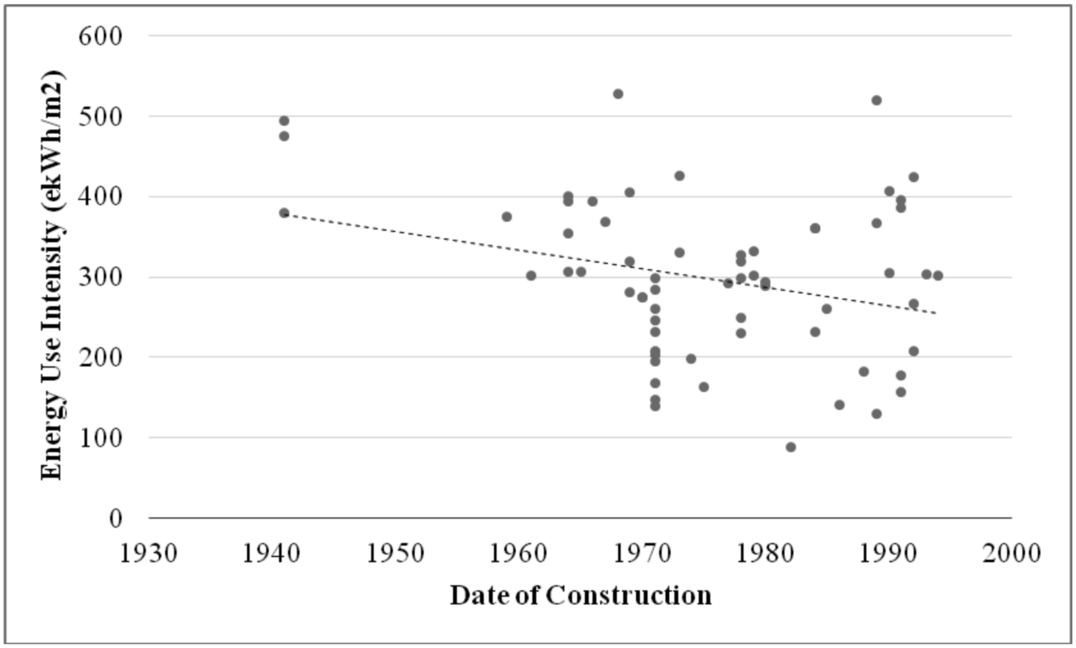

FIGURE 2: INFLUENCE OF BUILDING VINTAGE ON ENERGY USE INTENSITY

While there is slight downward trend, there is no significant correlation between building age and EUI despite more recent codes requiring higher levels of insulation and airtightness. The higher EUIs of the oldest buildings in the data set could be due to the age of the mechanical systems and the condition of the building envelope. However, the higher EUIs in the newer buildings may be due to the effects of better thermal insulation and air-tightness measures being offset by higher fenestration ratios. The intent of new codes and standards such as the Toronto Green Standard and 2012 Ontario Building Code requirements is to address this issue through establishment of a maximum prescribed fenestration ratio.

Within the Refined Data Set, variables relating to the mechanical and electrical system, the building envelope, and the occupancy characteristics were examined to determine their influence on EUI. These individual variables were tested against various measures of energy use such as total, base or variable consumption, to determine where correlations existed. A selection of the correlations is presented here.

Since the majority of heat loss and solar heat gain through the building envelope is through the glazing, it was expected that the larger the fenestration ratio, the greater the resulting heating and cooling loads. This is shown by the correlation in Figure 3 using the buildings for which these data were available. The relationship, with respect to variable natural gas consumption, appears to be stronger in buildings with double-glazed windows than in buildings with single-glazed windows as shown by the higher coefficient of determination for the double-glazed windows.

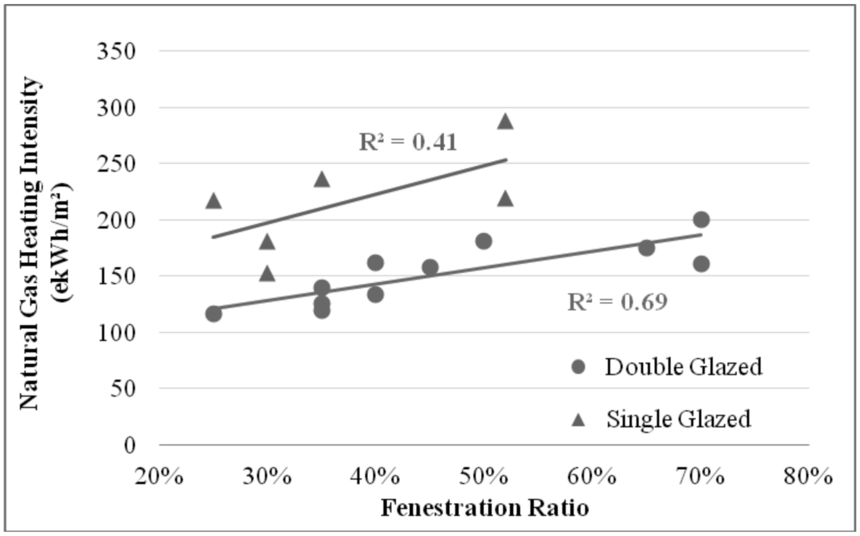

FIGURE 3: INFLUENCE OF FENESTRATION RATIO ON VARIABLE NATURAL GAS INTENSITY

It is possible that the coefficient of determination for buildings with single-glazed windows is lower than buildings with double-glazed windows because single-glazed windows are generally older and the glazing units are in worse condition. Thus, the air-tightness of the window assemblies may be the significant factor that governs heat loss for these buildings, as opposed to just the fenestration ratio. Generally, if buildings with single-glazed windows are assumed to be older than those with double-glazed windows, other envelope components may also contribute to air leakage which would, in turn, affect space heating energy use. However, this does not account for older buildings that have been retrofit with double-glazed windows. To explore the impact of glazing air tightness versus overall building envelope air tightness, more data are required. Also, no information about glazing films and coatings was available for analysis.

Similar to the correlation with space heating energy, a higher fenestration ratio also leads to greater air-conditioning loads (R^2 = 0.58 for electricity intensity versus fenestration ratio for buildings with double-glazed windows). This is to be expected because of the higher transmission of solar gains and conductive heat gains through glazing during the summer.

Window thermal conductance (U-value) is another factor contributing to heating and cooling loads. Higher U-values mean that more heat transfer occurs and thus heating and cooling loads will presumably be higher. This was confirmed for both heating and cooling as shown by the positive correlation between U-value and heating energy use (R^2 = 0.46) and, for buildings with air conditioning (A/C), cooling energy use (R^2=0.46). The stronger correlation between heating energy and fenestration ratio for buildings with double-glazed windows, compared with the U-value correlation, suggests that glazing area may have a greater effect on heating EUI than window thermal conductance.

Another factor affecting building heating loads is the efficiency of the heating system. It was expected that the more efficient the heating system, the lower the resulting variable natural gas intensity. However, the correlation between variable natural gas intensity and boiler efficiency was relatively weak (R^2 = 0.08). This may be due to the fact that the boiler efficiencies provided in the audit reports might not reflect the actual efficiency of the heating system since they are either rated or estimated. The rated efficiency is intended to be an indication of the efficiency of the boiler when it was new; however, it is possible that this efficiency was never achieved. Also, as the boiler ages, efficiency declines. The rate of decline depends on maintenance practices, the boiler use patterns, the type of boiler, and the overall system efficiency. Therefore, while the approximate relationship is correct, the correlation could be stronger with data that better reflects the actual performance of the heating system.

The correlation between EUI and ownership type (rented, subsidized rental, condominium and co-op) was also explored. On a gross floor area basis, condominiums have the lowest average EUI, but on a per suite basis, they have the highest EUI. The higher condominium EUI on a per suite basis can be attributed to generally higher incomes and therefore more household appliances and electronics as well as greater common area loads such as pools and gyms. The EUIs of the subsidized rental buildings on a per suite basis were lower compared to the other ownership types. This can perhaps be explained by restricted operating budgets and limited common areas, typical for this ownership type.

The correlations between energy use components and single building characteristics were lower than expected. Given the systems-based interaction between building components, the authors believed that considering a group of explanatory variables, instead of one variable at a time, may better explain the range of EUIs across the building stock. Therefore, a multi-variable regression analysis was conducted to determine the influence of a combination of variables. The coefficients of determination remained low in the multi-variable linear regression models conducted for the various components of EUI so the results have not been presented here.

EVALUATING RETROFIT MEASURES WITH ENERGY MODELING

This section describes the energy modeling of possible retrofit measures for four buildings that were selected for more detailed study. The intent of this analysis was to support the correlation findings as well as examine the impact of other building characteristics for which data were not available. A discussion of how the calibrated base case energy models were developed for the four buildings is presented. Then, using these base case models, various retrofit measures are evaluated based on their energy performance. This section concludes with a summary of the retrofit measures with the greatest potential impact on EUI.

Subject Building Selection

Of the four buildings selected, two were from the 1970's, as this vintage represents the largest proportion of buildings in the population. One building was included from the 1960's as this was the second largest group in both the sample and the population. The final building included in the detailed building energy modeling was from the 1980's. A summary of the basic building characteristics determined from drawings, audit reports and other sources is provided in Table 3. All of the buildings have exposed slab edges.

Name	1960	1970a	1970b	1980
Year built	1967/1969	1971	1977	1984
Size	17 above ground (A/G) floors 192 units	22 A/G floors 122 units	25 A/G floors 193 units	4 A/G floors 71 units
Envelope	Concrete masonry unit (CMU) with 25mm exterior insulation, masonry façade; single-glazed (SG) windows; R_{wall}=1.1m^{2}K/W; U_{window}=5.7W/m^{2}K	CMU with 50mm EPS interior insulation, masonry façade; double-glazed (DG) windows; R_{wall}=1.9m^{2}K/W; U_{window}=2.1W/m^{2}K	Steel stud wall with 50mm of insulation, metal cladding; SG windows; R_{wall}=1.3m^{2}K/W; U_{window}=5.7W/m^{2}K	Steel stud wall with brick veneer, no insulation indicated (assumed same level as 1970b); DG windows; R_{wall}=1.8m^{2}K/W; U_{window}=2.1W/m^{2}K
Heating	Hydronic Baseboard Radiators (2x3.5MBTU)	Hydronic Baseboard Radiators (1&1.5MBTU, η= 85%)	Vertical Fan Coil Units (2x3MBTU, η= 70%)	Hydronic and Electric Baseboard Radiators
Cooling	No central system, data indicate some window A/C	No central system, data indicate some A/C	Vertical Fan Coil Units	No central system, data indicate some A/C
Pressurized Corridor Ventilation	Unconditioned make-up air (MAU)	Conditioned MAU	Conditioned MAU	Unconditioned MAU
Energy Use Intensity	391 ekWh/m^2	264 ekWh/m^2	207 ekWh/m^2	336 ekWh/m^2

TABLE 3: CHARACTERISTICS OF THE FOUR SUBJECT BUILDINGS

Energy Model Generation

The Quick Energy Simulation Tool (eQUEST), developed by the U.S. Department of Energy (DOE), was used to model the energy performance of the MURBs in this study. A base case model for each building was constructed in eQUEST with all available data from the building audit reports and floor plans. The models were then calibrated by comparing the model output to the utility-bill data which was weather normalized to the Canadian Weather for Energy Calculations (CWEC) standard weather year used by the software program.

The procedure for calibrating the model-generated base natural gas use with the actual base natural gas use began with adjusting the magnitude of the modeled domestic hot water (DHW) load per person so that the modeled value output agreed with the average of the actual July and August natural gas load. The model DHW consumption for each building was compared with other sources to ensure that it was reasonable.

The variable or space heating natural gas consumption model output was then matched with the actual variable natural gas consumption throughout the year. Where boiler size and efficiency were provided, the perimeter air-tightness value was adjusted to match the modeled natural gas profile to the actual profile.

When only the boiler size was provided, both the efficiency and perimeter air-tightness were adjusted to fit the model. Where no boiler information was available, the boilers were auto-sized and then the efficiency and perimeter air-tightness were adjusted. The resulting perimeter air-tightness values from each building were compared with experimental studies (Hanam, Finch, & Hepting, n.d.) to ensure the resulting value was within a reasonable range.

Default electrical and lighting loads from eQUEST were used for the most part except where explicit information was available that allowed for a truer representation of the specific building. For example, Building 1970a has undergone an in-suite lighting retrofit so the loads in this particular building were reduced to account for the transition from incandescent to compact fluorescent lighting.

RETROFIT MODELING

The retrofits modeled were grouped into three categories: improvements or changes in operation of the HVAC system, envelope improvements and reductions in electrical loads. The specific retrofit measures were determined by reviewing published reports on MURB retrofits, [including (ARUP, 2010), (Genge & Rousseau, 1996), (Canada Mortgage and Housing Corporation)] and the options within eQUEST. Where particular values had to be selected such as air leakage rates and boiler efficiency, the literature was used to determine appropriate values for model input. Table 4 shows a list of all of the retrofit measures which were tested individually.

Building Element Retrofit	Base Case	Retrofit Range
Corridor supply air temperature	Heating 20°C, Cooling 26°C	Heating 18°C, Cooling 28°C Heating 15°C, Cooling 30°C
Boiler efficiency	60-85%	65%-95% in 5% increments
Fan type	Constant	Variable Speed
Fan efficiency	Standard or High	Premium
Pump efficiency	Standard or High	Premium
Air-tightness of envelope	0.65-2 L/s·m^2	0.25,0.40, 0.75, 1.0, 1.5 L/s·m^2
Windows	Single-glazed clear, Double-glazed low-e	Double-glazed low-e Triple-glazed low-e
Exterior insulation	25-50mm polystyrene	50-75mm polystyrene
Roof insulation	25-75mm polystyrene	50-100mm polystyrene
Common area lighting	T12 (40W)	T8 (32W)
Suite lighting and plug loads	Mostly default loads	Reduce by 10-30%

TABLE 4: RETROFIT MEASURES MODELED FOR THE SUBJECT BUILDINGS

Table 5 summarizes the three energy retrofit measures for each building which have the greatest potential effect on reducing modeled energy consumption. The percentage reduction is relative to the base case energy consumption for each retrofit measure assessed individually, without cumulative effect. These three measures have been presented and ranked in order of significance and colour-coded according to the type of measure: improved air tightness, improved thermal resistance or improved boiler efficiency. Improvements in air-tightness have been limited to a maximum of 0.5L/s·m^2 and retrofits for single-glazed windows have been limited to double-glazed windows.

Rank		Building			
		1960	1970a	1970b	1980
1	Measure	Improved air-tightness (2.0 to 0.5L/s·m^2)	Boiler Refurbishment or Replacement (85% to 95%)	Window Replacement (SG to DG)	Improved air-tightness (1.5 to 0.5L/s·m^2)
	Electricity	4%	0%	5%	6%
	Natural Gas	25%	6%	28%	18%
	Total Energy	21%	4%	21%	15%
2	Measure	Boiler Replacement (60% to 95%)	Addition of Roof Insulation (40 to 100mm)	Boiler Replacement (70% to 95%)	Boiler Replacement (75% to 95%)
	Electricity	0%	0%	0%	0%
	Natural Gas	23%	6%	20%	14%
	Total Energy	18%	4%	14%	10%
3	Measure	Addition of Exterior Wall Insulation (25 to 75mm)	Improved air-tightness (0.675 to 0.5L/s·m^2)	Improved air-tightness (0.65 to 0.5L/s·m^2)	Addition of Roof Insulation (50 to 100mm)
	Electricity	2%	0%	0%	2%
	Natural Gas	9%	6%	4%	5%
	Total Energy	8%	4%	3%	4%

TABLE 5: SUMMARY OF ANNUAL ENERGY REDUCTIONS BY SUBJECT BUILDING AND RETROFIT MEASURE

Increases in boiler efficiency and envelope airtightness and thermal resistance were among the most significant contributors to reduced energy consumption. Though the incremental impact of each retrofit type can be shown through this modeling, the synergies and secondary effects of some measures have not been accounted for here. For example, when windows are replaced, air leakage rates often decline because the installed window assembly is more airtight than the previous window. These synergies could be verified in the future by calibrating an energy model to a monitored building undergoing phased energy retrofits in order to determine the true impact of each retrofit. For the purposes of this analysis, all measures have been assessed independently.

Discussion of Results

This section presents a comparison between the correlation analysis and the results of the energy modeling exercise. In particular, the impact of air-tightness, glazing and heating system efficiency is discussed. The correlation analysis showed that fenestration ratio can have a strong influence on EUI. However, post-construction this characteristic is difficult to modify and is not considered here as a viable retrofit option.

While air-tightness data was not available for the correlations analysis, it was suspected that air leakage contributed to the difference in coefficient of determination between the single- and double-glazed window correlations. Air-tightness is important for all buildings, but particularly in high-rises because large differential air pressures can occur across the envelope due to stack effect. Buildings 1960 and 1980 saw the most significant reductions in energy use associated with the modeled pre- and post-retrofit air-tightness but even the modest increases in air-tightness for Buildings 1970a and 1970b made this measure an important strategy for energy savings in all of the buildings. A tighter envelope can be achieved in several ways. When replacing envelope components such as windows or over-cladding, a building often becomes more air-tight. As well, a tighter envelope can be achieved by applying air sealing products to existing components for a relatively inexpensive energy retrofit. A detailed on-site assessment, including blower-door testing, would be required to determine what air sealing measures are most appropriate for each particular building.

As shown by the correlation analysis, window U-value is also correlated with heating and cooling EUI. Two buildings included a modeled retrofit from single- to double-glazing: Buildings 1960 and 1970b. This measure resulted in a 21% energy use reduction for Building 1970b. Building 1960, on the other hand, had other energy savings opportunities such as the highest air-leakage rate and lowest boiler efficiency and wall insulation level of the sample buildings, making the impact of the window retrofit less significant.

While not part of the correlation analysis due to a lack of data, the addition of insulation to the roof or walls was in the top three significant retrofit measures for three of the four buildings. The opportunity to add exterior insulation can arise when an over-cladding retrofit for rain penetration or a roof replacement is being considered. Applying exterior insulation to the building envelope is often a less intrusive means of improving envelope thermal resistance compared with insulating from the interior in an existing building. Most of the energy savings associated with exterior insulation can be attributed to a reduction in natural gas space heating.

In the boiler efficiency correlation, the coefficient of determination was much lower than expected given the total amount of space heating energy used in each building. This may have occurred because the efficiencies provided were not indicative of actual system performance. The retrofit analysis confirmed this suspicion when the increases in boiler efficiency were among the top two most impactful retrofit measures for all four buildings. Due to the uncertainty surrounding actual heating system efficiency, it is important to determine the actual performance of the system before exploring retrofit options.

Finally, a brief analysis of the potential impact of retrofit measures on the city-wide GHG emissions reduction goals was conducted. If only the top ranked retrofit measure in each of the buildings above was implemented, the average reduction in GHG emission intensity would be 16% across the four buildings. Assuming that, with the appropriate economic and policy environment, all Toronto MURBs will undertake a retrofit measure with an impact equivalent to this average reduction, this modest decrease in GHG emission intensity reduction could achieve approximately 2% of the 30% required reduction below 1990 levels. This is not unrealistic considering some buildings will achieve deeper savings and some may not undergo any retrofit.

CONCLUSIONS

This study of MURB energy use intensity showed that energy consumption data is useful for identifying the worst performers in the sample but, due to the systems-based nature of building operation, energy modeling is needed to test the sensitivity of separate energy end-uses on overall building energy performance.

By examining correlations between EUI and building characteristics, it was concluded that window characteristics were most closely linked to building energy use based on the data collected. However, the strength of the correlation between boiler efficiency and variable natural gas intensity was much lower than expected. This was likely due to uncertainties in the actual heating system efficiencies. More generally, differences in building operation and maintenance likely contributed the wide range of EUIs and therefore, even with more complete building data, the correlations may be insufficient on which to base any policy recommendations.

The retrofits with the highest impact in terms of energy savings were reduced air leakage, improved envelope thermal resistance through added insulation and window replacement and improved boiler efficiency. The impact of these measures varied depending upon the particular building examined. However, with adequate building data, this energy modeling can be used to assess the potential individual and combined impacts of various retrofit measures.

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