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Investigating the potential impact of a compartmentalization and ventilation system retrofit strategy on energy use in high-rise residential buildings

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ABSTRACT

A proposed retrofit strategy for high-rise residential buildings involving compartmentalization of apartment units and decentralised in-suite ventilation with heat recovery was studied in order to determine the impact on overall space heating energy for the building and the associated greenhouse gas (GHG) emissions. Field data from a case study building in Vancouver, Canada is used to create a calibrated energy model of the building using EnergyPlus simulation software, which was then used to simulate the proposed retrofit and estimate its impact on energy use. The simulation shows annual space heating energy decreasing by 49% with the associated GHG emissions decreasing by 70%. These results are compared to the measured impact of an enclosure retrofit which had been previously implemented on the building. The enclosure retrofit had a 55% decrease in measured impact on reducing the overall heat loss – slightly greater than that of the proposed retrofit – however the associated GHG emissions only decreased by 25% since only electric heating energy was impacted in this case, the source of which is a hydro-electricity dominated grid. With both retrofits (enclosure plus compartmentalization and in-suite ventilation with heat recovery) done together, a 78% reduction in total space heating energy and an 83% reduction in associated GHG emissions are realised. Another major benefit of the proposed retrofit would be improved indoor air quality for the building's occupants due to a significant improvement in mechanical ventilation distribution effectiveness. Because building enclosure air-tightness improvements can negatively impact air distribution in buildings with pressurized corridor ventilation systems, the proposed retrofit should be applied in combination with, or before, an enclosure retrofit. Thermal resilience should also improve, with longer passive surviveability durations from a reduction in uncontrolled air leakage induced by stack effect.

1. Introduction

1.1. Background and problem

High-rise multi-unit residential buildings (MURBs) in North America are predominantly designed with a pressurised corridor ventilation strategy [16]. This ventilation strategy employs a central supply fan, usually located on the building's rooftop, to supply the ventilation air for the entire building through ductwork to the corridor of each floor. The design intent of this system is for the ventilation air in the corridor, which is positively pressurised relative to the suites, to flow into the suites through the undercuts of their entrance doors and back outside through kitchen and bathroom exhaust ducts. Because these exhaust fans are only operated intermittently, whereas the central ventilation system is a constant flow rate, the air will tend to exit the suites through other cracks and openings in the building enclosure. Since there is typically no central return air there is no opportunity for heat recovery. The effectiveness of this ventilation strategy relies on a positive pressure differential from the corridor to adjacent suites, and from the suites to the outdoors in order to maintain the desired airflows. In reality, the air pressure distribution in the building is continually disturbed by factors such as stack effect, elevator operation, window operation, and wind pressures on the exterior of the building. The result is that the fresh air delivery rate to individual suites is highly variable and unpredictable under these constantly changing conditions, even during normal building operation, negatively impacting indoor environmental quality [11].

Stack effect refers to the natural tendency for air to rise or fall within a building due to the density difference between the

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indoor and outdoor air during heating and cooling seasons. This phenomenon produces a pressure gradient across a building enclosure from bottom to top. Similarly, wind creates a dynamic pressure differential around the building which, together with stack effect pressures, drives air leakage through the enclosure. Wind speeds increase exponentially with height, and the resulting pressure on the building increases exponentially with wind speed. This leads to wind pressures on the enclosure that can vary drastically from the lower to the upper floors, and from the windward to the leeward side of the building. The dynamic pressure fields around the building due to wind and stack effect can overpower the mechanical ventilation system, altering or even reversing airflow to the suites. Operable windows and balcony doors in high-rise residential buildings add an additional challenge to effective mechanical ventilation by corridor pressurization. Because pressurised air will flow along the path of least resistance, air in the corridor will tend to flow toward any suite with an open window or door (ignoring for the moment wind and stack effects), reducing ventilation rates to the surrounding suites of the same floor. Openings in the enclosure will also tend to further increase airflows induced by stack effect.

Energy efficiency retrofits of high-rise MURBs generally focus on increasing the insulation and air-tightness of the enclosure to improve overall thermal performance, however this can amplify the deficiencies of pressurised corridor ventilation systems [2]. One study examining the effect of enclosure retrofits on six MURBs in Canada showed that the average air leakage rates through the exterior enclosure were reduced by 31% [7]. If the enclosure is made more air tight without a change in the ventilation strategy the desired decrease in airflow through the enclosure also results in a corresponding and undesirable decrease in ventilation air reaching the suites from the corridor. Although air leakage can be a significant source of energy loss, enclosure air-tightness improvements without ventilation strategy changes will only redirect more ventilation air out through unintended pathways such as elevator shafts unless all leakage paths are effectively eliminated; air sealing of the walls and windows alone has the potential to further degrade ventilation distribution effectiveness.

1.2. Objective

The objective of this study is to examine and compare the impact on space heating energy and associated GHG emissions of the following three retrofit strategies for existing high-rise residential buildings with pressurised corridor ventilation systems:

- A complete enclosure retrofit with exterior insulation, triple-glazed windows, and increased overall enclosure assembly air-tightness.
- A suite compartmentalization retrofit with decentralised ventilation using suite-based heat recovery ventilators (HRVs).
- The above two retrofit strategies employed in combination.

1.3. Previous research

Research on the ineffectiveness of the pressurised corridor ventilation strategy extends back to the 1990′s. Research by Canada Mortgage & Housing Corporation (CMHC) indicates that there are significant issues with this standard ventilation practice for high-rise residential buildings. CMHC concluded that “conventional corridor air supply and bathroom-kitchen exhaust systems do not, and cannot, ventilate individual apartments…[and] can compromise the integrity of fire and smoke control because they are dependent on a high level of interconnectivity between individual apartments and public areas” [6]. In addition, CMHC concluded that “corridor ventilation systems significantly add to the energy consumed in the building” [5]. Wray, Theaker, & Moffatt [20] also examined corridor ventilation systems, measuring airflows in ten Canadian high-rise MURBs up to 32 storeys in height built in the early 1990′s. Results showed significant differences in the supply air design specifications, ranging from 25 L/s to 109 L/s per suite. These rates translate to 50–350% oversizing as per ASHRAE Standard 62.1 guidelines. Actual supply airflow rates at the corridor however were measured at only 34–81% of the design flows [8]. It would seem that the mechanical ventilation systems in these MURBs had been designed without sufficient information about final construction conditions to ensure their effectiveness, and had no practical requirement to perform as designed once in operation. One study revealed that most suites in a high-rise MURB with a corridor pressurization system were significantly over-ventilated or under-ventilated from floor to floor, and that the ventilation system was unable to overcome stack effect pressures at times [17]. Another study in British Columbia of 39 mid- and high-rise MURBs also identified the pressurised corridor systems as being problematic in terms of energy efficiency and ventilation distribution effectiveness, and that independent suite-based ventilation and space heating systems should be considered, in conjunction with suite compartmentalization to mitigate pressure differentials across the enclosure due to stack effect [15].

Despite the significant body of research indicating that the corridor pressurization ventilation strategy is ineffective there is currently little published research on the energy implications of the proposed strategy as a retrofit.

In 2003, CMHC developed recommendations for effective and efficient ventilation strategies for individual suites in high-rise MURBs, hypothesizing that a suite compartmentalization strategy with balanced dedicated in-suite ventilation would be the least impacted by stack effect, and had the potential to achieve good ventilation performance in combination with airtight suites.

A study of eight high-rise MURBs in Toronto built in the early 2000′s concluded that the provision of airtight interior and exterior partitions around suites and the installation of in-suite ventilation systems with heat recovery would improve the overall performance of this class of building (CMHC, 2005).

1.4. Case study building

A 13-storey, 37-unit, 5176 m^2 (GFA) MURB constructed in 1983 in Vancouver, British Columbia, Canada, underwent an enclosure retrofit in 2012 to address water ingress issues and improve its durability, air-tightness, and thermal performance. Various performance characteristics of the building had been measured before and after the retrofit including data on the air-tightness level of the enclosure and some of its interior partitions [19]. Data was also available on mechanical ventilation rates at various distribution nodes, as well as partially sub-metered natural gas and electricity consumption. The building employs a corridor pressurization ventilation strategy with a natural gas-fired rooftop unit and supplemental heating provided by electric resistance baseboard convection heaters in each suite.

1.5. Retrofit proposal

Expanding on the previous research by CMHC, this study attempts to predict the resulting performance of a compartmentalization retrofit of the case study building’s suites by isolating them from the corridors, and installing dedicated, balanced, suite-based heat recovery ventilators (HRVs). The interior separation between the suite and corridor was measured to be the leakiest of the six suite partition surfaces (walls, floor and ceiling) by an order of magnitude due to the entrance door undercuts [17]. Air sealing the suite entrance doors therefore offers the greatest potential impact

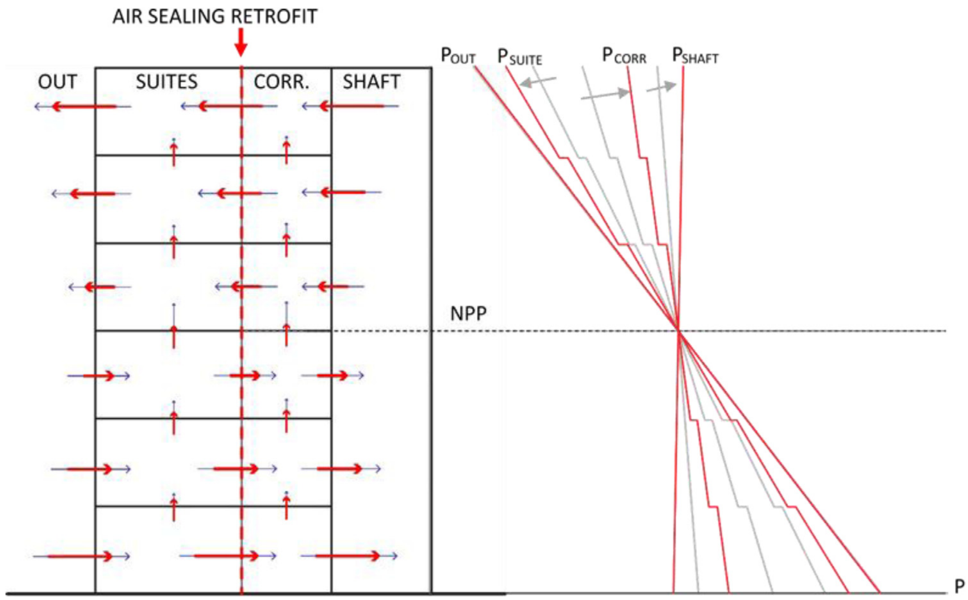

Fig. 1. Schematic illustrating the impact on pressure distribution and stack-induced airflows of the air-sealing retrofit.

toward compartmentalizing the suites and was the approach simulated in this investigation. By isolating the suites from the corridors through air-sealing, uncontrolled airflow between the suites and the outdoors would be reduced. These measures would shift stack-induced pressure differentials from across the exterior enclosure to the corridor-to-suite boundary. Suite ambient pressures could then equalize with outside atmospheric pressure, thereby reducing airflow through the enclosure. The central ventilation system flow rate could then be reduced significantly to the level required to serve only the common corridors, resulting in a corresponding decrease in natural gas consumption used to condition the outside air. Fresh air would be provided to each suite through a dedicated HRV. The HRV's balanced intake and exhaust flows help to avoid pressurization or depressurization of the suite, and reduce uncontrolled air leakage. A decentralised ventilation system also enables demand-control, so individual suites are not ventilated unnecessarily while unoccupied.

Fig. 1 depicts the proposed compartmentalization strategy schematically with the building airflows represented on the left and the corresponding pressure gradients on the right. Air sealing measures are shown as a dashed vertical red line along the suite-to-corridor boundary (indicated). The red arrows represent the corresponding change in magnitude of the stack-induced airflows in the building (during heating season), with the underlying grey arrows representing the airflows prior to compartmentalization. The pressure distribution lines show how the post-retrofit suite interior pressures will move toward equalization with outdoor ambient air pressure, reducing airflows through the enclosure.

2. Method

The proposed retrofit strategy was analysed through computer simulation using a calibrated energy model of the case study building using EnergyPlus^{TM} v.8.4.0. A model of the building in its current overclad condition was first constructed and calibrated to the available energy use data using actual weather data from the site. A second base model was then created for the building in its original as-built condition and calibrated to utility and weather data from that time in order to isolate and quantify the impact of the enclosure retrofit. The performance was then weather-normalized for comparison by running both model simulations with a CWEC typical meteorological year weather file. The proposed retrofit was then applied to each of the two calibrated base models to predict its impact on building performance as a stand-alone measure, and in combination with an enclosure retrofit.

The following sections describe the analysis of the available metered energy use and on-site weather data, as well as the energy modelling and calibration procedures. The methodology has been greatly condensed for brevity, however a more detailed description of the procedure and results can be found in "Impact Of A Compartmentalization And Ventilation System Retrofit Strategy On Energy Use In High-Rise Residential Buildings" [4].

2.1. Energy end use analysis

Table 1 summarizes the utility and weather data which was available for calibrating the two base models (pre- and post- enclosure retrofit). Further energy model input data used during calibration can be found in Table 3.

Natural gas and suite-level electricity use for each of the models was disaggregated into their heating and weather-independent components for further refinement of the model calibrations. The post-retrofit data was analysed first because the natural gas use was sub-metered by each of the end uses providing a direct measurement of the gas heating energy. A correlation of electricity use and heating degree days through linear regression yielded a high approximation of the electrical base load with the resulting y-intercept (an approximation of the weather-independent base load) being just over 1.93 kWh/m^2/mo., which was greater than the minimum monthly electricity usage of 1.83 kWh/m^2, occurring in July. The best fit line with the smallest coefficient of determination r^2 using linear regression was for a 15 °C balance point temperature, which is much lower than would be anticipated for a building maintained at 23 °C with only moderate internal gains. Base load electricity consumption was instead estimated by assuming the usage from July – when the outdoor temperature was above the indoor set point temperature – included no heating energy (the building has no air conditioning, either central or window units).

2.2. Base model setup & calibration – enclosure retrofit (ENCL)

An initial energy model of the case study building was generated based on its current condition. This model included the enclosure retrofit completed on the building in 2012 and will be

Table 1
Utility and weather data used for base building model calibration.

Energy data	Pre-Retrofit (2007–2011)	Post-Retrofit (2013)
Natural gas	Monthly utility bills (1 m)	Sub-metered monthly (domestic hot water (DHW), makeup air unit (MAU), fireplaces)
Electricity	Monthly utility bills (2 meters common + aggregated suites)	Monthly utility bills (2 meters common + aggregated suites)
Weather data	Environment Canada	On-site weather station

Table 2
ENCL model results by fuel type and end use for calibration acceptability statistical indices.

	NMBE (±5%)	CV(RMSE) (±15%)
Overall natural gas	0.7%	6.8%
Natural Gas for DHW	0.3%	5.6%
Natural Gas for MAU	1.6%	14.9%
Natural Gas for fireplaces	1.4%	3.3%
Overall electricity	0.3%	8.9%
Common area electricity	0.7%	4.5%
Suite-level heating electricity	0.5%	4.3%
Suite-level total electricity	−1.6%	13.8%

referred to as the Enclosure Retrofit (denoted by ENCL and represented by the icon next to this section heading for the purpose of clarity in later comparative figures). All known physical and operational characteristics of the building, both observed and measured, were incorporated into the model, as shown in Table 3. A custom 2013 weather file was created using data from a weather station located on the roof of the case study building which had recorded the hourly ambient data required for energy simulations including dry bulb temperature, relative humidity, barometric pressure, wind speed and direction, and total solar radiation. This custom weather file was used in the simulations during the calibration process of the ENCL model against the 2013 utility data. The model was calibrated to the available utility data by adjusting parameters according to a hierarchy of data source reliability, as described by Rafter, Keane, & O'Donnell [14]. Calibration followed the Whole Building Calibrated Simulation Performance Path of ASHRAE Guideline 14 [1] using the statistical comparison technique, which outlines two statistical acceptability indices for energy model calibration – the normalised mean bias error (NMBE) and the coefficient of variation/root mean squared error (CV(RMSE)) – with limits of +/- 5% and ±15%, respectively. Table 2 shows the performance results of the ENCL model by fuel type and end use.

2.3. Base model setup & calibration – original building (ORIG)

Next, the original as-built condition of the building, referred to as the Original Building (and denoted ORIG), was modelled in order to compare the impact of each of the retrofits to a more typical base case. In particular, this model was created to determine if the proposed compartmentalization and in-suite ventilation system (C+ISV) retrofit strategy could have been an appropriate measure to apply prior to, or independently of, improvements to the thermal performance of the enclosure. Changes were made to the previous calibrated ENCL base model to account for the original enclosure construction as well as other measured performance characteristics of the original building in order to create the ORIG base model, and the simulation run with the actual meteorological year weather file matching the measured utility data prior to the enclosure retrofit. For the calibrated ORIG model, total natural gas use achieved a −0.3% NMBE and a 2.0% CV(RMSE), and overall electricity achieved a −1.3% NMBE and a 2.7% CV(RMSE). Following calibration, the fireplaces were removed from the models and simulations re-run using a typical meteorological year (CWEC) weather file in order to create the two baseline models, and before proceeding with the retrofit models.

2.4. Base model input summary

Table 3 lists select building characteristics for the creation of the ORIG and ENCL models.

2.5. Retrofit model – suite compartmentalization with in-suite ventilation (C+ISV)

The Suite Compartmentalization with In-Suite Ventilation retrofit model (denoted C+ISV), was created by modifying the ORIG model. The compartmentalization retrofit was simulated by eliminating the mechanical ventilation airflow to the suites from the corridors, adding balanced HRVs to each suite, and eliminating bathroom exhaust fans. Continuous supply and exhaust rates were set to 55 L/s to meet ASHRAE Standard 62.1-2016 area and occupancy requirements (44 L/s) and to account for a zone air distribution effectiveness factor of 0.8. To allow for ventilation demand control, a dynamic reset was incorporated to match the occupancy and area requirements of Section 6.2.7.1.2 in accordance with ASHRAE Standard 62.1 guidelines. The total make-up air unit (MAU) supply air rate was then reduced to 0.3 L/s/m^2 (188 L/s total), in accordance with the ASHRAE guidelines for common corridors. With the suites compartmentalised from the corridors and the original leaky enclosure, the internal air pressure in the suites should tend to equalize with the ambient outdoor air pressure, thus decreasing the driving force for airflow through the building enclosure, assuming the interior partitions can be made more airtight than the exterior enclosure. As such, infiltration in the C+ISV model was adjusted by assuming the average pressure differential across the building enclosure would decrease from 4 Pa (used in the ORIG model) to 1 Pa. The resulting impact on infiltration rates and the associated heating energy was examined in isolation to assess the sensitivity of the simulated overall building performance to this assumption. The resulting estimated infiltration rate was calculated to be 0.29 L/s/m^2 using the same measured enclosure airflow resistance characteristics as ORIG ($C = 25.56$, $n = 0.58$). Transient increases in infiltration rates due to wind pressure (based on the measured wind velocities in the custom weather file) were then accounted for using the linear wind velocity coefficient of the Zone Infiltration function in the energy model. A coefficient of 0.224 was used based on the DOE-2 infiltration model [10].

2.6. Retrofit model – combined retrofit of both ENCL and C+ISV (COMB)

The final combined model (denoted COMB) included both the enclosure retrofit (ENCL) and the compartmentalised suites with in-suite ventilation (C+ISV). It was generated in the same way as was described for the C+ISV model, but using the ENCL model as the base. The reduced enclosure infiltration rate was determined as 0.12 L/s/m^2, using the same measured enclosure airflow resistance characteristics as ENCL ($C = 9.99$, $n = 0.63$).

2.7. Retrofit model input summary

Table 4 summarizes the new building and equipment characteristics used in the retrofit energy models. All other characteristics and schedules were otherwise maintained the same as the base models.

Table 3
Select building characteristics used as energy model inputs for calibration.

Select building characteristics	ORIG	ENCL	Source
Windows & balcony doors			
USI (thermal transmittance)	4.1 W/m^2-K	1.57 W/m^2-K	Data provided by RDH
SHGC (solar heat gain coefficient)	0.7	0.2	Data provided by RDH
VT (visible transmittance)	0.8	0.7	Data provided by RDH
Exterior enclosure			
Effective *R*-value: walls	RSI-1.67 m^2-K/W (R-9.5°F-ft^2-hr/Btu)	RSI-2.84 m^2-K/W (R-16.1°F-ft^2-hr/Btu)	Data provided by RDH
Effective *R*-value: roof	RSI-0.7 m^2-K/W (R-4.0°F-ft^2-hr/Btu)	RSI-3.5 m^2-K/W (R-19.9°F-ft^2-hr/Btu)	Data provided by RDH
Enclosure air flow coefficient C	25.6	9.99	Data provided by RDH
Enclosure air flow exponent n	0.58	0.63	Data provided by RDH
Enclosure air tightness	0.69 L/s/m^2 @4 Pa	0.29 L/s/m^2 @4 Pa	Data provided by RDH
Active Systems			
Baseboard heater capacity (−01 suites)	11.0 kW		Nameplate
Baseboard heater capacity (−02 suites)	7.0 kW		Nameplate
Baseboard heater capacity (−03 suites)	10.5 kW		Nameplate
Suite heating setpoint temperature	23 C		Data provided by RDH
Suite cooling setpoint temperature	(no cooling)		N/A
Fireplace heating capacity	8.8 kW		Nameplate
Fireplace radiant fraction	0.4		Data provided by RDH
Fireplace heat fraction lost	0.6		Data provided by RDH
MAU flow rate	1440 L/s (avg.)		Data provided by RDH
MAU motor	1.12 kW (1.5 hp)		Nameplate
MAU supply fan efficiency	60%		Data provided by RDH
MAU heating coil capacity	73.2 kW		Nameplate
MAU heating coil efficiency	80%		Data provided by RDH
MAU supply air temperature	20.7 C		Data provided by RDH
Bathroom fan exhaust rate	33 L/s		Nameplate
Bathroom exhaust fan power	60 W		Nameplate
Bathroom fan efficiency	60%		Estimated
Bathroom exhaust fan static pressure	50 Pa		Estimated
DHW boiler capacity	178.7 kW		Nameplate
DHW supply temperature	55 C		Estimated
DHW boiler efficiency	82%		Data provided by RDH
DHW consumption	2.75 L/m^2-day		Estimated
DHW pump rated power	250 W		Nameplate
Internal Gains			
Occupants	1.8 persons/suite (radiant fraction 0.3)		Known qty residents
Lighting	300 W/suite, 200 W/corridor (radiant/visible fractions 0.2/0.7)		Data provided by RDH
Appliances	350 W/suite (radiant/lost fractions 0.05/0.05)		Data provided by RDH

Table 4
Retrofit model input summary.

Retrofit building and equipment characteristics	C+ISV & COMB
Infiltration (normalised to wall area) [L/s/m^2 @1 Pa]	0.12
MAU flow rate [L/s]	188
HRV flow rate [L/s]	55
HRV efficiency	75%
HRV fan power [W]	70

3. Results

The following is a comparison of the performance for the progression of the three possible retrofit conditions from the building's original construction (ORIG); i) enclosure retrofit (ENCL), ii) compartmentalization with in-suite ventilation (C+ISV), and iii) both together (COMB).

3.1. Space heating energy

Fig. 2 shows the annual space heating energy reductions for both natural gas and electricity for each of the retrofit progressions as determined through simulation.

For the enclosure retrofit (ENCL), results show a total space heating energy reduction of 55%, or 119 eke/m^2, with no change in the MAU energy consumption, but a 70% (119.3 kWh/m^2) reduction in the electric baseboard heater energy use. This simulated performance improvement is comparable to the actual metered energy data on which these two models were calibrated, which showed a 66% reduction in electric space heating energy after the enclosure retrofit.

The proposed C+ISV retrofit results indicate an overall space heating energy reduction of 49%, or 104.7 eke/m^2. However, unlike the ENCL model, this savings is dominated by a natural gas consumption decrease of 87% (38.0 eke/m^2) from the reduction in central ventilation air delivery by the MAU. Even with the introduction of heat recovery in the C+ISV retrofit, the new ventilation system induced an increased heating load due to the increased ventilation rate within the suites, as a result of the improved ventilation delivery effectiveness. Despite this, the in-suite electric heating energy provided by the baseboard resistance heaters decreased overall by 39% (66.7 kWh/m^2) due to the reduced heating load from the reduction of infiltration.

Both retrofit measures applied together – the proposed retrofit combined with the enclosure retrofit – are predictably the most impactful, with an overall space heating energy reduction of 78%, or 167.8 eke/m^2. Natural gas savings are again estimated to be 87% (38.0 eke/m^2) from the reduced MAU airflow rate, and electrical heating energy decreased by 76% (129.8 kWh/m^2).

3.2. GHG emissions

Fig. 3 shows the resulting annual GHG emissions from heating energy by fuel type for both natural gas and electricity for each of the three retrofit progressions.

Carbon equivalent emissions are calculated by multiplying the emissions factor for a GHG by the measure of consumption to produce the corresponding emissions for that GHG and then

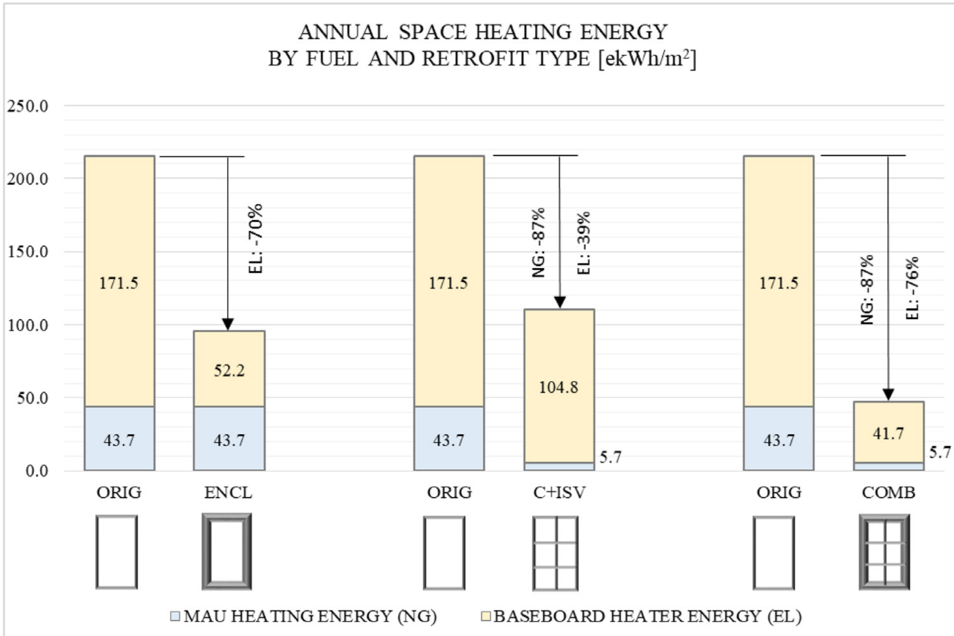

Fig. 2. Simulated annual space heating energy by fuel and retrofit type.

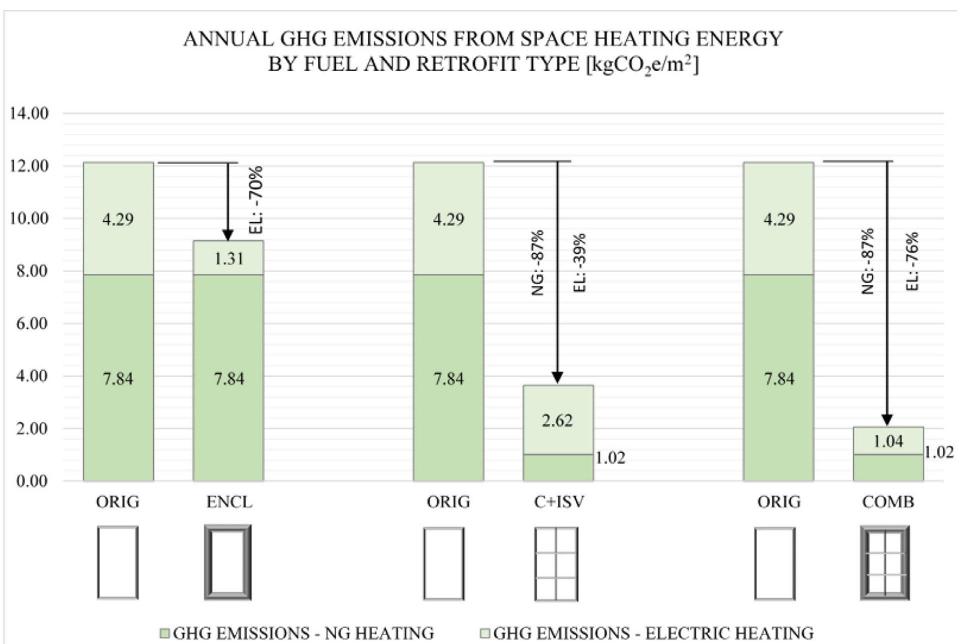

Fig. 3. Annual GHG emissions by fuel type for retrofit progressions .

multiplying those emissions by their global warming potential to produce the corresponding carbon dioxide equivalent (CO_2e) emissions, as outlined in "2016/17 B.C. Best Practices Methodology For Quantifying Greenhouse Gas Emissions" published by the province [3].

The proposed retrofit offers greater GHG emission reductions than the enclosure retrofit due to its significant reduction of natural gas consumption. Reductions in electricity usage result in a minimal impact because the GHG emissions factor for electricity in B.C. is only 25 gCO_2e/kWh due to the abundance of hydroelectricity. By comparison, the 2013 Canadian national average was 150 gCO_2e/kWh [9]. For the ENCL retrofit, results show an overall GHG emissions reduction associated with space heating energy of 25% driven completely by a 70% reduction in emissions from electricity use by the electric baseboard heaters. The proposed C+ISV retrofit results indicate a greater overall reduction in GHG emissions associated with space heating energy of 70% driven by an 87% reduction in emissions from natural gas combustion by the MAU, and 39% reduction in the emissions from electric heating. Both retrofit measures when applied together result in an overall 83% reduction in GHG emissions associated with space heating energy.

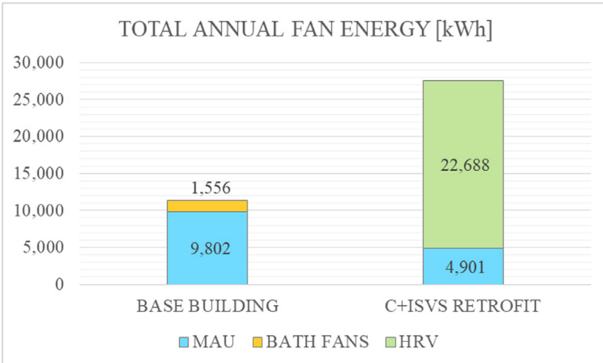

Fig. 4. Total fan energy per year, base vs. retrofit buildings.

3.3. Fan energy

Fig. 4 shows the increase in fan energy for the retrofit case, compared to the base building. There is a 50% decrease in the MAU fan energy for the retrofit over the base case, however the addition of HRV fan energy in the retrofit results in an overall fan power nearly two and a half times greater than the base case. The approximately 16,000 kWh increase in fan energy translates to an increase of about 3.14 kWh/m^2 which is far outweighed by the 66.7 kWh/m^2 reduction seen by just the electric baseboard heaters due to the introduction of heat recovery by the in-suite ventilation system.

4. Discussion

4.1. Energy and GHG results

Each of the retrofit measures examined offer both energy and GHG reductions through the resulting decrease in space heating energy demand as compared with the original building construction. Increasing the thermal performance and air-tightness of the building enclosure through a complete enclosure retrofit reduces the air infiltration and conductive losses through the outside walls, resulting in a reduction in overall space heating energy. Since mechanical ventilation rates are not adjusted in this scenario the heating energy savings are realised solely by the electric baseboard heaters in each suite. Because British Columbia's electrical grid is largely supplied by renewable energy resources the reduction in electricity use for heating has very little impact on the building's overall GHG emissions in the ENCL scenario.

In the proposed C+ISV retrofit scenario the energy savings are predominantly a result of the addition of heat recovery for mechanical ventilation. The use of in-suite HRVs allows for heat to be recovered from the exhaust air and used to temper the supply air stream. Since ventilation air is supplied directly to the suites the central ventilation rate from the MAU can be significantly reduced to just what is required for the corridors. Although the overall space heating energy savings are slightly less with the proposed retrofit than with the enclosure retrofit, the GHG emissions reductions are far greater. Since the MAU supply air is conditioned by the combustion of natural gas, the reduction in central ventilation in the proposed C+ISV retrofit scenario offers the greatest GHG emission reduction potential.

In 2013, 33% of all natural gas in the province of B.C. was consumed by residential buildings [18], 58% of which was used for space heating [12]. With apartment buildings alone accounting for 17% of all residential GHG emissions in the province [12], the proposed retrofit is an opportunity to reduce provincial GHG output and support B.C.'s Greenhouse Gas Reductions Target Act [13].

At the national level, residential buildings accounted for 15% of Canada's overall GHG emissions in 2013, with space heating making up 64% of the total residential sector output [12]. Although GHG emissions factors and typical fuel mixes vary by province, the benefits of the proposed retrofit would apply across the other provinces of Canada. The GHG emissions factor for electricity in B.C. is relatively low at 25 gCO_2e/kWh compared to the 2013 Canadian national average of 150 gCO_2e/kWh [9], so the benefits of the proposed retrofit should be more significant in most other provinces. The GHG reduction potential would also be amplified in the other provinces as their climates are generally much colder than B.C.'s, resulting in higher heating energy demand and greater stack effect pressures. The proposed retrofit is therefore an opportunity to contribute to municipal, provincial, and national GHG emissions reduction objectives across the country, and particularly in regions where the majority of grid electricity is produced from renewable sources.

4.2. Collateral benefits

Unrelated to energy or carbon savings but of equal importance is the potential for improved indoor air quality as a result of the proposed retrofit. Compartmentalization of the suites serves to mitigate the transfer of airborne contaminants among suites, and the addition of dedicated HRVs allows for fresh air to be provided to the suites at the full recommended design rate, which has been shown to be difficult to achieve in reality through corridor pressurization. The reduction in stack effect from suite compartmentalization also has the benefit of reducing the quantity of airborne pollutants which are drawn up from the below-grade parking levels to the lower occupied floors of the building. The overall effect should be improved air quality within the suites and a healthier indoor environment for the building's occupants.

In addition to improved indoor air quality, the proposed C+ISV retrofit allows for demand control of ventilation rates at the individual suite level. Ventilation can be reduced or turned off during unoccupied hours of the day and/or days of the year, reducing unnecessary heat loss and fan energy.

The mitigation of stack effect from a compartmentalization retrofit results in another positive benefit of improving the thermal resilience of high-rise MURBs in the event of power loss during both the heating or cooling seasons. During a power outage a typical high-rise will become quickly uninhabitable due to the resulting loss of space conditioning capacity and the rapid loss of conditioned air from the building due to stack effect. Mitigating stack effect through suite compartmentalization can help to reduce the uncontrolled flow of conditioned air out of the building allowing occupants to remain in place for a longer period before interior temperatures force evacuation. Other benefits include reduced sound transmission, improved odour control, and better smoke and fire control.

4.3. Energy modelling limitations

The results of any simulation aiming to forecast building performance are fundamentally dependent on the many assumptions. Care is taken to use the best available information possible, however, some parameters contain a fair amount of uncertainty by nature. Predictions of the weather and occupant behaviour for example are based on historical statistics, but both have significant variability in reality, as well as significant influence on actual building performance. In addition, the standard approach when converting air-tightness characteristics of a building measured at 75 Pa is to assume that the pressure difference across the enclosure during normal operation over the course of the year is a constant 4 Pa. This constant pressure difference is converted to a constant

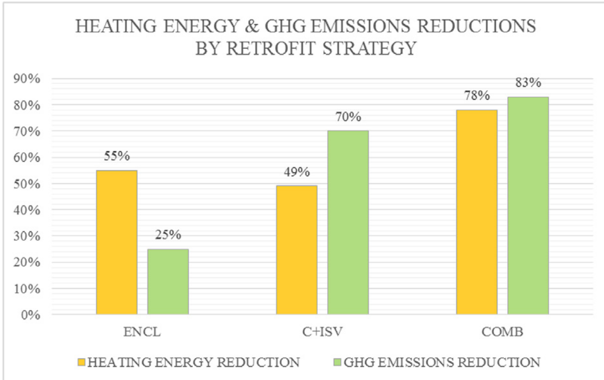

Fig. 5. Heating energy and GHG emissions reductions by retrofit strategy.

infiltration rate (using the crack flow equation or other linear conversion factor) which is then used as an input to the energy model. This approach is considered adequate for approximating annual average infiltration rates, and is appropriate for comparative modelling exercises where relative changes are being investigated against a reference model. The actual pressure difference across the building enclosure driving infiltration is of course constantly changing with time. And at any one time the pressure difference across the enclosure at any location is a function of height, orientation, HVAC system operation, occupant behaviour (window and exhaust fan operation, heating and cooling set points), outside temperature (and thus stack effect), wind speed and direction, elevator operation, etc. For a building well-sheltered from the wind, and without operable windows, an annual average infiltration rate may be sufficient to forecast the associated energy impact. for a more granular analysis a constant infiltration rate is unlikely to represent actual conditions at any moment in time or location within the building.

5. Conclusions

Field data from a high-rise residential case study building in Vancouver was used to create a calibrated energy model using EnergyPlus in order to examine the potential impact on overall space heating energy and GHG emissions of a compartmentalization and in-suite ventilation (C+ISV) retrofit strategy. The impact of the proposed retrofit was examined for the building in its original 1983 as-built condition, and compared to the impact of the enclosure retrofit (ENCL) which had been carried out in 2012. Fig. 5 summarizes the heating energy and associated GHG emissions reductions of each retrofit strategy.

The ENCL retrofit, which mitigated conductive heat loss through the building enclosure, resulted in the greatest reduction in space heating energy, decreasing by 55% (617 MWh or 119 ekWh/m^2).

The C+ISV retrofit, which eliminated the majority of the natural gas combustion associated with conditioning ventilation air, resulted in the greatest GHG emissions savings with a reduction of 70% (43.9 tCO_2e, or 8.5 $kgCO_2e/m^2$).

The greatest savings are found with both retrofit measures applied together (COMB), resulting in a space heating energy reduction of 78% (869 MWh or 168 ekWh/m^2), and reduction in the associated GHG emissions of 83% (52.1 tCO_2e, or 10.1 $kgCO_2e/m^2$).

The impact of the proposed retrofit if applied on its own to a high-rise MURB with a leaky and thermally inefficient enclosure can reduce energy consumption by reducing infiltration due to wind and stack effect, and have a positive impact on mechanical ventilation distribution effectiveness which had been found to be poor at the case study building, consequently improving indoor air quality for the residents. Because building enclosure air-tightness improvements can negatively impact ventilation air distribution to suites in buildings with pressurised corridor ventilation systems, the proposed measures should be applied in combination with, or before, any enclosure retrofit.

The findings of this research support the general hypothesis that suite compartmentalization in a high-rise MURB will reduce energy losses due to uncontrolled airflows. The in-suite ventilation system necessary to supply air to the suites offers further energy savings through heat recovery, as well as enabling demand control to reduce energy while suites are unoccupied. A reduction in central ventilation rates is then made possible, and the associated natural gas reduction significantly lowers the building's GHG emissions.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.enbuild.2019.06.035.

References

[1] ANSI/ASHRAE, ASHRAE Guideline 14 - 2014 Measurement of Energy, Demand, and Water Savings, 8400, Ashrae, 2014.
[2] BC Housing, Heat Recovery Ventilation Guide for Multi-Unit Residential Buildings, 2015.
[3] British Columbia Ministry of Environment, 2016/17 B.C. Best practices methodology for quantifying greenhouse gas emissions, Build. Simul. (2016). http://doi.org/10.1007/s12273-013-0159-y.
[4] M. Carlsson, Impact of a Compartmentalization and Ventilation System Retrofit Strategy on Energy use in High-Rise Residential Buildings, 2017.
[5] CMHC, Corridor air ventilation system energy use in multi-unit residential buildings, J. Therm. Envel. Build. Sci. 24 (October) (2000) 168–172. http://doi.org/10.1106/RE0B-R090-YLEK-LV4.
[6] CMHC, Ventilation Systems for Multi-Unit Residential Buildings – Performance Requirements and Alternative Approaches, 2003.
[7] CMHC, Air Leakage Control in Multi-Unit Residential Buildings – Development of Testing and Measurement Strategies to Quantify Air Leakage in MURBs, 2013.
[8] Edwards, C. (1999). Modelling of Ventilation and Infiltration Energy Impacts in Mid and High-Rise Apartment Buildings.
[9] Environment Canada, National Inventory Report 1990–2013. Greenhouse Gas Sources and Sinks in Canada – Part 3, 1–85, 2015. http://doi.org/ISSN:1719-0487.
[10] K. Gowri, D. Winiarski, R. Jarnagin, Infiltration Modeling Guidelines for Commercial Building Energy Analysis, 2009.
[11] J. Montgomery, Air quality in multi-unit residential buildings, RDH Tech. Bull. (009) (2015).
[12] NRCan., Comprehensive Energy use Database, 2017 Retrieved from http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm.
[13] Province of British Columbia, Greenhouse Gas Reduction Targets Act, 2017 Retrieved from http://www.bclaws.ca/EPLibraries/bclaws_new/document/ID/freeside/00_07042_01.
[14] P. Raftery, M. Keane, J. O'Donnell, Calibrating whole building energy models: an evidence-based methodology, Energy Build. 43 (9) (2011) 2356–2364. http://doi.org/10.1016/j.enbuild.2011.05.020.
[15] RDH Building Engineering Ltd., Energy Consumption and Conservation in Mid- and High-Rise Residential Buildings in British Columbia, 2012.
[16] RDH Building Engineering Ltd., Air Leakage Control in Multi-Unit Residential Buildings, 2013.

[17] L. Ricketts, A Field Study of Airflow in a High-Rise Multi-Unit Residential Building, University of Waterloo, 2014.
[18] Statistics Canada, Report on Energy Supply and Demand in Canada – 2014 Preliminary (57-003-X), 2014 Retrieved from http://www5.statcan.gc.ca/olc-cel/olc.action?ObjId=57-003-X&ObjType=2&lang=en&Limit=1.
[19] R. Urquhart, R. Richman, G. Finch, The effect of an enclosure retrofit on air leakage rates for a multi-unit residential case-study building, Energy Build. 86 (2015) 35–44. http://doi.org/10.1016/j.enbuild.2014.09.079.
[20] C. Wray, I. Theaker, P. Moffatt, Field Testing to Characterise Suite Ventilation in Recently Constructed Mid and Residential Buildings, 1998.