Energy Consumption and Conservation in Mid- and High-Rise Residential Buildings in British Columbia

FINAL REPORT

FEBRUARY 2012

RDH | Building Engineering Ltd.

Client Report for:

CMHC SCHL

British Columbia

Homeowner Protection Office
Branch of BC Housing

City of Vancouver

BC hydro powersmart

FORTIS BC

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Acknowledgements

The potential for this research study was identified during the course of assisting owner groups deal with the need to rehabilitate their buildings. The rehabilitation projects described in this study were a considerable burden and unwanted expense. There was a desire to at least learn from this unique opportunity for the future benefit of building owners and the building community.

This project was sponsored by Canada Mortgage and Housing Corporation (CMHC), the Homeowner Protection Office, a branch of BC Housing, the City of Vancouver, BC Hydro, Terasen Gas (now FortisBC), and RDH Building Engineering Ltd. as study partners.

Warren Knowles directed and administered the project for RDH. Graham Finch was responsible for much of the analysis and detailed work including oversight of the thermal analysis and energy simulation. Eric Burnett provided ongoing invaluable insight and guidance throughout the study, as well as completed the literature survey and wrote the Comparative Study of Six Buildings-a Top down Analysis. Brittany Hanam assisted with the energy modeling of buildings and worked on extending the design methodology. Curt Hepting of Enersys Analytics Inc. gave valuable assistance with the energy model calibration and simulation of the buildings. Lorne Ricketts assisted with much of the work associated with the thermal modeling. Other people deserving recognition for their assistance at RDH include Natalie Williams Portal, David Sommer, and Clarissa Binkley. Warren Knowles, Graham Finch and Eric Burnett were responsible for the editing of the various reports and documents. In addition, the authors wish to recognize the owners of the study buildings for their support of this research, who in many instances, have had to endure major repairs to their buildings. In particular, we would like to acknowledge a past treasurer of one of the study buildings for his efforts at representing the interests of the owners in this endeavour.

RDH would like to express their thanks for the active support and participation of all of the study partners and a special acknowledgment to the Homeowner Protection Office, a Branch of BC Housing for overseeing the project on behalf of the industry consortium. We hope that the findings from this study will contribute to improved and more sustainable building practices in the future.

Disclaimer

Reasonable care has been taken to confirm the accuracy of the information contained herein. However, the authors and funding partners assume no liability for any damage, injury, expense or loss that may result from the use of this report, particularly, the extrapolation of the results to specific situations or buildings.

The views expressed herein do not necessarily represent those of any individual contributor, Canada Mortgage and Housing Corporation, the Homeowner Protection Office, a branch of BC Housing, City of Vancouver, BC Hydro, FortisBC, and RDH Building Engineering Ltd. Building science, and construction practices change and improve over time and it is advisable to regularly consult up to date technical publications on building science, products and practices rather than relying on this report. Always review and comply with the specific requirements of the applicable building codes for each construction project.

This report contains terminology used by those familiar with building enclosures and energy consumption of buildings. A glossary and definitions are provided at the end of this report containing common industry terminology used throughout.

EXECUTIVE SUMMARY

Many multi-unit residential buildings (MURBs) in British Columbia and other parts of North America have or are undergoing comprehensive building enclosure rehabilitation largely to remedy moisture-related problems. For reasons primarily related to short-term cost, little attention has been directed at energy conservation strategies and/or, greenhouse gas emissions. Nevertheless rehabilitation of the building enclosure does present a unique opportunity to examine and assess the actual energy-related performance of the in-service building, and to determine the energy impact of the building enclosure improvements.

This research study was undertaken to assess the impacts of building enclosure rehabilitations on the energy consumption of mid- to high-rise (5 to 33 storey) multi-unit residential buildings. The principal objectives of this study are to review and assess the actual energy consumption of in-service mid- to high-rise residential buildings, and the impacts of building enclosure rehabilitation related improvements on the overall energy consumption of these buildings. These findings are used to determine better building enclosure design strategies to reduce energy consumption and associated greenhouse gas emissions, while considering the other building functions for both new and existing buildings. The funding partners of this study include Canada Mortgage and Housing Corporation (CMHC), the Homeowner Protection Office (HPO), a branch of BC Housing, City of Vancouver, Terasen Gas, BC Hydro, FortisBC, and RDH Building Engineering Ltd. (RDH). Additional support in development and calibration of the energy simulations was provided by Enersys Analytics Inc.

Detailed energy consumption data was provided by the local gas and electric utility suppliers for a sample set of private-sector condominiums constructed over the past 40 years. Consumption data from 39 non-combustible construction MURBs located in the Lower Mainland of BC, and Victoria, BC were analyzed to assess the current levels of energy consumption. The contribution of gas and electricity to overall energy consumption and, specifically, space heat are examined in great detail. Total energy use intensity for the 39 study buildings was found to be in the range of 144 to 299 kWh/m^2/yr with an average of 213 kWh/m^2/yr for all years of data reviewed. On average, 37% of this energy was space conditioning energy (heating and ventilation), ranging from 24 to 52%. Although the majority of the buildings incorporated electric baseboards to provide the space heat to the suites and common areas, 69% of the space heat energy was provided by gas burning equipment. Gas for heating or tempering of ventilation air and gas fireplace operation makes up the majority of this total. These findings highlight a significant disconnect between building energy consumption and direct billing to occupants for their share of total energy usage, and the need for individual suite metering (particularly for gas fireplaces and hot water usage).

Space heating and overall energy consumption has not decreased in newer MURBs and actually appears to have increased slightly. Newer MURBs (constructed from the 1990s to present) use more energy on average than the older buildings (constructed in the 1970s and 1980s) based on the analysis of the study buildings. In addition, the overall effective thermal performance of MURBs has not improved, and the amount of space heating associated with ventilation has increased. The use of gas fireplaces in newer buildings has also displaced electrical space heat.

Once the baseline energy consumption for both pre- and post- rehabilitation was established, the impact of the enclosure upgrades and building enclosure attributes was assessed on 13 sample buildings representative of the larger building set. 11 of these buildings underwent a full building enclosure rehabilitation (pre-post buildings) and two of these buildings are representative of typical high-rise MURB construction over the past decade. Although the rehabilitation work was undertaken to cost effectively address moisture ingress related problems and associated damage rather than reduce energy consumption, a reduction in energy consumption was typically realized. Average pre-rehabilitation normalized energy use intensity for the 11 buildings is 203 kWh/m^2/yr and

post-rehabilitation is 188 kWh/m^2/yr, for a total energy savings of 8% and space heat savings of 14%. For these 11 buildings, typical whole building energy savings ranged from 1% to 19% and space heat savings ranged from 9% to 22% depending on the total electric and gas heat and overall energy mix within the building. Overall greenhouse gas emissions were reduced on average by 9%, or 22.6 tCO_2 equivalent. Based on the study findings, there is the potential to significantly improve the energy consumption characteristics as part of future building rehabilitation or renewal programs.

Detailed whole building energy models were assembled of the sample buildings to determine the building enclosure characteristics, including area quantities and overall effective R-values. Heat transfer simulation of the 11 building enclosure components found that the overall effective building R-values are less than R-3.0 ft^2·h·°F/Btu for typical MURBs representative of architectural styles from the 1970s to the present. For the 11 pre-post buildings, the overall R-values were improved from an average of R-2.4 pre-rehabilitation to R-3.4 post-rehabilitation (an improvement of 44%). The calculated enclosure R-values were used as inputs in comparing energy modeled results to actual performance characteristics. This information, along with air leakage testing data, was used to estimate air leakage rates of these buildings in-service during the time periods assessed. This assessment of actual building enclosure performance then allowed the analysis of potential effects of changes to other building systems with the use of the models.

Several opportunities exist to significantly improve the performance of mid- and high-rise residential MURBs. These opportunities include improving glazing and wall assemblies, in conjunction with better control of air flow including make-up air ventilation strategies and control of air leakage.

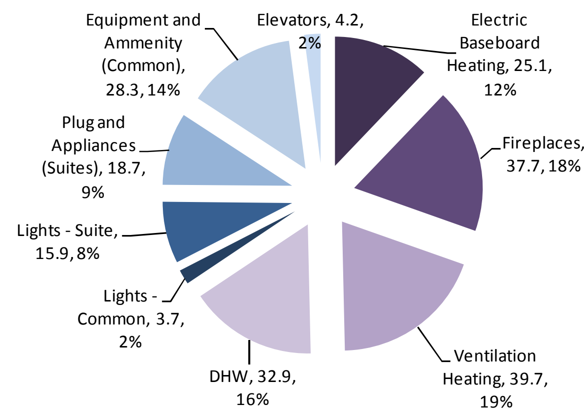


Fig. 1.1 Distribution of annual energy consumption in simulated typical building, kWh/m^2/year and percentage.

Much higher thermally performing windows and reasonable glazing ratios (i.e. less than 40% window area) are necessary. In terms of targets, glazing assemblies with R-values in the range of R-4 to R-6 (double to triple glazing within non-conductive frames, i.e. Energy Star Zone C & D windows) should be considered for use in mid- and high-rise buildings. Overall effective wall assembly R-values (accounting for all thermal bridging) according to ASHRAE 90.1 and 189.1 standards are the suggested minimums (i.e. R-15.6 to R-18.2). Current practice is on average less than R-5 for exterior walls. More effective use of the same level of currently provided insulation (i.e. by the reduction of thermal bridging at cladding supports, and thermal breaks within balcony and projecting slabs etc.). Roofs and decks should also be insulated effectively to minimum ASHRAE 90.1/189.1 levels; however, the impact of roof R-values on the overall thermal performance of a MURB is small due the relatively small area of a roof on a tall building compared to the exterior walls.

Better control of air flow within, and through buildings is a key factor in reducing energy consumption in this building type. Optimal airtightness levels for both the building enclosure and the whole building under in-service conditions should be determined. While enclosure airtightness is important, window operation and occupant behaviour can significantly affect building airtightness characteristics by orders of magnitude higher (worse) compared to the performance characteristics of the enclosure assemblies. This highlights the need for in-suite and space heating and ventilation systems where occupants are directly responsible for their energy consumption without impact to the remainder of the building.

The study findings identify the need to move away from the traditional pressurized corridor approach of MURB ventilation and de-couple ventilation from space heating. Separate in-suite ventilation and space heat systems should be considered. The energy simulations for a typical building showed significant benefits with the use of heat-recovery ventilators (either in-suite or ducted central systems). Direct ventilation systems with heat recovery can improve occupant comfort, even in temperate climates such as Vancouver. As part of the improvements to ventilation strategies, there is a need for suite compartmentalization to control stack and mechanical pressures across the building enclosure and across the ducts of in-suite systems.

The simulations identified remarkable opportunities to reduce energy consumption characteristics using existing technologies when integrated building improvements are adopted that include improvements to the thermal performance of the building enclosure (walls, roofs and windows), airtightness, space heating system, and ventilation strategies. Reductions in space-conditioning (space heating and ventilation) loads from greater than 100 kWh/m^2/yr to less than 10 kWh/m^2/yr were obtained using the calibrated typical building model by implementing these combined energy efficiency measures.

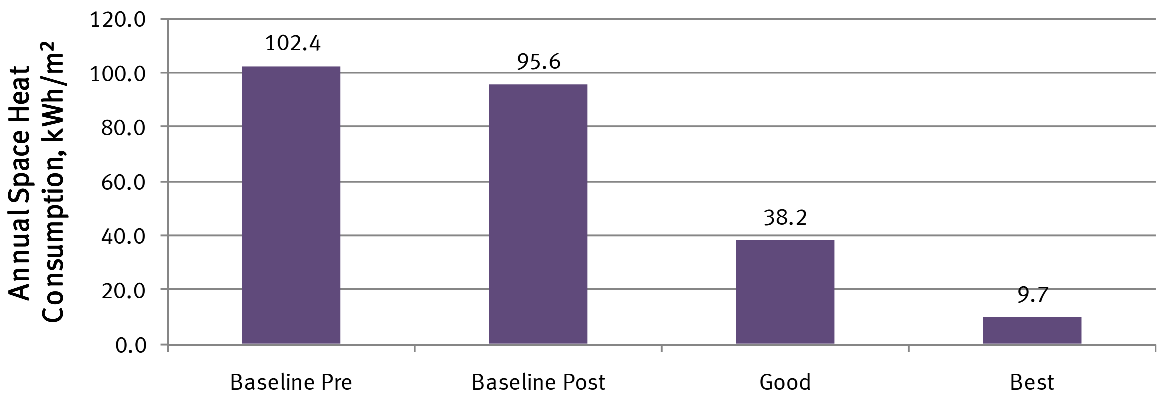


Fig. 1.2 Annual simulated energy consumption of improved buildings, kWh/m^2/year.

To design more energy efficient MURBs, a holistic approach that better considers occupant behaviour and all building systems is required; an approach based on actual building performance data using a feed-back loop. Whole building energy labelling for MURBs, real-time in-suite energy meters, and the reporting of actual energy use data as well as other building operation and performance characteristics should be made available to all parties in order to effectively build on past improvements. An increased demand for more efficient, durable buildings will result from this better understanding of actual building performance.

RÉSUMÉ

Plusieurs collectifs d'habitation en Colombie-Britannique et en d'autres régions de l'Amérique du Nord ont subi ou subissent une remise en état complète de l'enveloppe du bâtiment, principalement pour corriger des problèmes liés à l'humidité. Pour des motifs qui tiennent surtout au coût à court terme, on ne s'est guère préoccupé des stratégies de conservation de l'énergie ni des émissions de gaz à effet de serre. Néanmoins, la remise en état de l'enveloppe du bâtiment fournit une occasion unique d'examiner et d'évaluer le rendement énergétique réel d'un bâtiment en service et de déterminer les répercussions des améliorations de l'enveloppe du bâtiment sur la consommation d'énergie.

La recherche visait à évaluer les répercussions de la remise en état de l'enveloppe du bâtiment sur la consommation d'énergie de collectifs d'habitation de moyenne hauteur et de tours d'habitation (5 à 33 étages). Les principaux objectifs de l'étude sont d'examiner et d'évaluer la consommation énergétique des collectifs de moyenne hauteur et de tours d'habitation actuellement en service et les répercussions des améliorations liées à la remise en état de l'enveloppe du bâtiment sur la consommation d'énergie globale de ces bâtiments. Ces conclusions servent à déterminer les meilleures stratégies de conception de l'enveloppe des bâtiments en vue de réduire la consommation énergétique et les émissions de gaz à effet de serre qui y sont associées, tout en prenant en compte les autres fonctions du bâtiment, tant dans le cas des bâtiments neufs que dans celui des bâtiments existants. L'étude a été financée par la Société canadienne d'hypothèques et de logement (SCHL), le Homeowner Protection Office, Logement Colombie Britannique, la Ville de Vancouver, Terasen Gas, BC Hydro, Fortis BC et RDH Building Engineering Ltd. (RDH). Enersys Analytics Inc. A également fourni un soutien pour l'élaboration et le calibrage des simulations énergétiques.

Les données détaillées sur la consommation d'énergie d'un échantillon de logements en copropriété du secteur privé construits au cours des 40 dernières années proviennent des fournisseurs locaux de gaz et d'électricité. Les données de consommation de référence de 39 collectifs et de tours d'habitation de construction incombustible situés dans le Lower Mainland et à Victoria (C.-B.) ont été analysées afin d'évaluer les niveaux actuels de consommation d'énergie dans des collectifs d'habitation de moyenne hauteur et de tours d'habitation. La contribution du gaz et de l'électricité à la consommation d'énergie globale et, particulièrement, au chauffage est examinée en détail. La consommation d'énergie globale des 39 bâtiments visés par l'étude s'établit entre 144 et 299 kWh/m^2/année, la moyenne étant de 213 kWh/m^2/année pour l'ensemble des années étudiées. En moyenne, 37 % de cette énergie servait au conditionnement des locaux (chauffage et ventilation), le pourcentage variant entre 24 % et 52 %. Même si la majorité des bâtiments utilisaient des plinthes électriques pour le chauffage des logements et des aires communes, 69 % de l'énergie pour le chauffage provenaient d'appareils au gaz. Le gaz utilisé pour chauffer ou tempérer l'air de ventilation et faire fonctionner les foyers au gaz constitue la majorité de ce total. Ces conclusions font ressortir un écart important entre la consommation d'énergie du bâtiment et la facturation directe aux occupants de leur part de l'énergie consommée et soulignent la nécessité de compteurs pour chaque logement (surtout pour les foyers au gaz et l'utilisation de l'eau chaude).

La consommation d'énergie pour le chauffage et la consommation globale n'ont pas diminué dans les collectifs d'habitation récents et semblent en fait avoir augmenté légèrement. Les collectifs d'habitation récents (conformes aux codes du bâtiment plus rigoureux en vigueur depuis les années 1990) consomment en moyenne plus d'énergie que les anciens bâtiments (construits dans les années 1970 et 1980) d'après l'analyse des bâtiments à l'étude. En outre, le rendement thermique global réel des collectifs d'habitation ne s'est pas amélioré, et la valeur correspondant au chauffage associée à la ventilation a augmenté. L'utilisation de foyers au gaz dans les immeubles récents a aussi remplacé le chauffage électrique.

Une fois déterminée la consommation énergétique de référence avant et après la remise en état, on a évalué l'effet des améliorations et des caractéristiques de l'enveloppe d'un échantillon de 13 bâtiments représentatifs de l'ensemble. Onze de ces bâtiments ont subi une remise en état complète de l'enveloppe (bâtiments avant-après) et deux autres sont représentatifs de la construction d'une tour d'habitation type au cours de la dernière décennie. Même si les travaux de remise en état visaient à régler de manière rentable les problèmes d'entrée d'humidité et les dommages connexes plutôt qu'à réduire la consommation d'énergie, il y a eu en général réduction de la consommation d'énergie. La consommation moyenne normalisée d'énergie avant les travaux pour les 11 bâtiments était de 203 kWh/m^2/année, tandis qu'elle est de 188 kWh/m^2/année après les travaux, soit une économie totale d'énergie de 8 % et une économie de 14 % pour le chauffage. Pour ces 11 bâtiments, l'économie globale d'énergie s'échelonne entre 1 % et 19 %, tandis que l'économie pour le chauffage varie entre 9 % et 22 %, selon la répartition du chauffage électrique et au gaz et de la consommation globale d'énergie dans le bâtiment. Dans l'ensemble, les émissions de gaz à effet de serre ont été réduites de 9 %, soit l'équivalent de 22,6 tCO_2. Selon les conclusions de l'étude, il est possible d'améliorer considérablement les caractéristiques de la consommation énergétique dans le cadre des programmes futurs de remise en état ou de rénovation des bâtiments.

Des modèles énergétiques détaillés de l'ensemble de chacun des bâtiments de l'échantillon ont été assemblés pour déterminer les caractéristiques de l'enveloppe du bâtiment, y compris les quantités des surfaces et les valeurs R réelles globales. La simulation du transfert thermique des composantes de l'enveloppe du bâtiment a révélé que les valeurs R réelles globales des immeubles sont inférieures à R-3,0 pi^2·h·°F/Btu pour les collectifs d'habitation types représentatifs des styles architecturaux depuis les années 1970 jusqu'à maintenant. Dans les cas des 11 bâtiments avant-après, les valeurs réelles globales sont passées en moyenne de R-2,4 à R-3,4 après les travaux (soit une amélioration de 44 %). Les valeurs R calculées de l'enveloppe sont utilisées comme données entrées pour comparer les résultats modélisés aux caractéristiques réelles de rendement. Cette information, ajoutée aux données des tests de fuite d'air, sert à mieux déterminer les taux réels de fuite d'air de ces bâtiments en service pendant les périodes étudiées. Cette évaluation du rendement réel de l'enveloppe du bâtiment permet ensuite d'analyser les effets éventuels des modifications des autres systèmes du bâtiment au moyen de ces modèles.

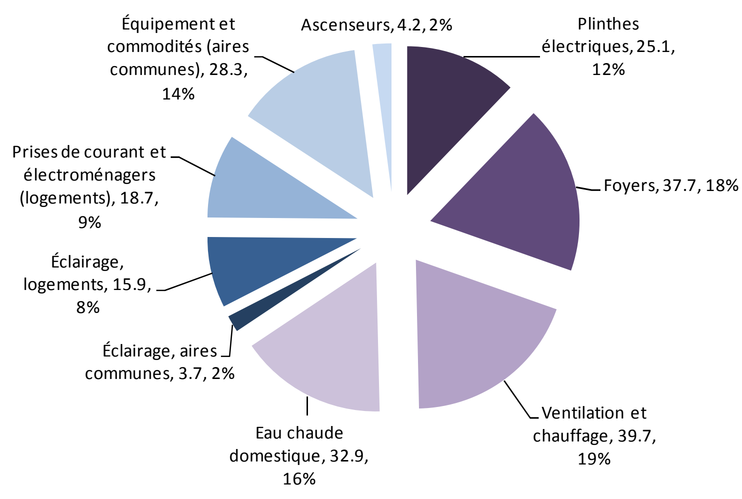


Fig. 1.3 Répartition de la consommation d'énergie annuelle dans un bâtiment type simulé typique, en kWh/m^2/année et en pourcentage.

Il existe plusieurs possibilités d'améliorer considérablement le rendement des collectifs de moyenne hauteur et tours d'habitation, notamment améliorer le vitrage et les assemblages des murs en même temps qu'un meilleur contrôle de la circulation de l'air, y compris des stratégies de ventilation de l'air de compensation et le contrôle des fuites d'air.

Des fenêtres présentant un rendement thermique de beaucoup supérieur et des coefficients de vitrage raisonnables (c'est-à-dire moins de 40 %) sont nécessaires et constituent peut-être le plus important facteur pour un meilleur rendement global de l'enveloppe du bâtiment. Pour ce qui est des cibles, on devrait envisager d'utiliser dans les collectifs de moyenne hauteur et les tours d'habitation des vitrages présentant une valeur R de l'ordre de R-4 à R-6 (vitrage double ou triple avec des châssis non conducteurs, c'est-à-dire des fenêtres EnergyStar Zone C et D). Le minimum suggéré pour la valeur R réelle globale des murs (compte tenu de tous les ponts thermiques) est de l'ordre des normes ASHRAE 90.1 189.1 en vigueur (c'est-à-dire R-15,6 à R-18,2). Par rapport à la pratique actuelle qui est en moyenne inférieure à R-5 pour les murs extérieurs, ceci exige une utilisation plus efficace du niveau actuellement fourni d'isolation (c'est-à-dire par la réduction des ponts thermiques aux supports du bardage et l'utilisation de barrières thermiques dans les structures pour les balcons et les dalles en saillie, etc.) Les toits et terrasses devraient aussi être isolés efficacement pour atteindre le niveau minimum des normes ASHRAE 90.1/189.1; toutefois, l'effet des valeurs R du toit sur le rendement thermique global d'un collectif d'habitation est peu important en raison de la superficie relativement petite du toit d'une tour d'habitation par rapport aux murs extérieurs.

Un meilleur contrôle de la circulation d'air à l'intérieur des immeubles et à travers ceux-ci est un facteur clé pour réduire la consommation d'énergie dans les bâtiments de ce genre. Les niveaux optimal d'étanchéité à l'air pour l'enveloppe du bâtiment et aussi pour tout le bâtiment dans conditions de service doivent être déterminés. Malgré l'importance de l'étanchéité à l'air de l'enveloppe, le fonctionnement normal des fenêtres et le comportement des occupants peuvent donner lieu à des caractéristiques réelles d'étanchéité à l'air qui sont pires (plus élevées) de plusieurs ordres de grandeur que les caractéristiques de rendement des assemblages de l'enveloppe. C'est pourquoi il faut dans les logements des systèmes de chauffage et de ventilation tels que les occupants soient directement responsables de leur consommation énergétique, sans répercussions sur le reste de l'immeuble.

Les conclusions de l'étude indiquent clairement qu'il faut abandonner la méthode traditionnelle de pressurisation des corridors pour la ventilation des collectifs d'habitation et séparer la ventilation du chauffage. Il faudrait envisager, dans les logements, des systèmes distincts de chauffage et de ventilation intégrant la récupération de chaleur. Les simulations énergétiques calibrées pour un bâtiment type indiquent des avantages importants pour les ventilateurs récupérateurs de chaleur (soit dans les logements ou des systèmes centraux à conduites) au titre de la consommation d'énergie. Des systèmes de ventilation directe avec récupération de chaleur amélioreront aussi le confort des occupants, même dans des climats tempérés comme celui de Vancouver. Dans le cadre de ces améliorations des stratégies de ventilation, il faut compartimenter les logements pour contrôler le tirage et les pressions mécaniques à travers l'enveloppe du bâtiment et les conduites des systèmes dans chaque logement.

Les simulations ont permi d'identifier des occasions remarquables de réduire les caractéristiques de consommation d'énergie de ces bâtiments au moyen des technologies existantes si on adopte des améliorations intégrées comprenant des améliorations du rendement thermique de l'enveloppe du bâtiment (murs, toits et fenêtres), l'étanchéité à l'air, et des stratégies de ventilation dans les nouveaux collectifs d'habitation. Le modèle calibré du bâtiment type permet de faire passer les charges de conditionnement (chauffage et ventilation) de plus de 100 kWh/m^2/année à moins de 10 kWh/m^2/année.

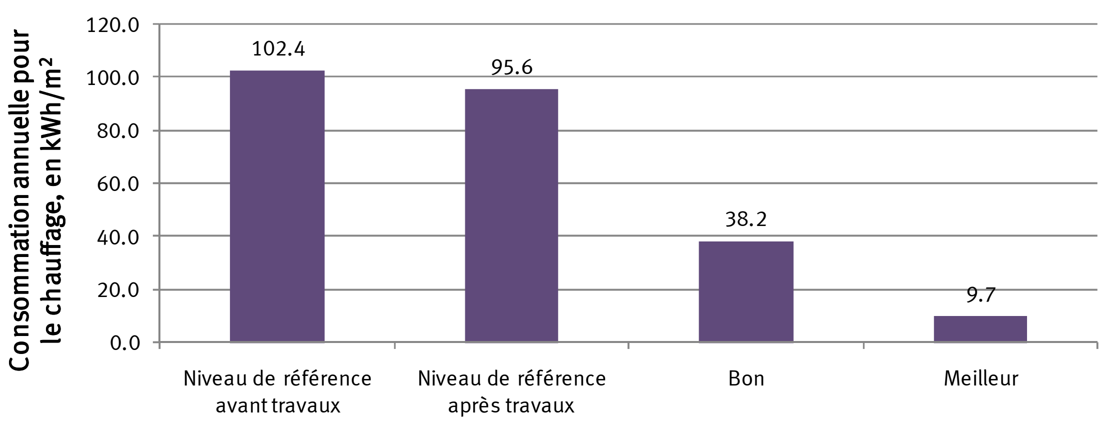


Fig. 1.4 Consommation d'énergie annuelle simulée des bâtiments améliorés, en kWh/m^2/année.

Pour la conception des collectifs d'habitation plus efficaces, il faut une démarche holistique qui tienne mieux compte du comportement des occupants et de l'ensemble des systèmes du bâtiment; unedémarche fondée sur les données réelles de rendement du bâtiment au moyen d'une boucle de rétroaction. Dans le cas des collectifs d'habitation, l'étiquetage de la consommation globale d'énergie du bâtiment, des compteurs d'énergie en temps réel dans les logements, la déclaration des données réelles de consommation d'énergie de même que d'autres caractéristiques de fonctionnement et de rendement du bâtiment devraient être mis à la disposition de toutes les parties, afin de tirer le meilleur parti des améliorations passées. Cette meilleure compréhension du rendement réel des bâtiments suscitera une demande accrue pour des bâtiments plus efficaces et plus durables.

1. INTRODUCTION

In British Columbia, particularly the Lower Mainland, there is a relatively recent trend for people to choose to live in multi-unit mid- and high-rise residential buildings (MURBs) greater than 4 storeys in height. The reasons are many and varied: the shortage of suitable land, the climate, the desire to live close to populated centers, the views, etc. The developments may be private or public and tenure may be partial ownership, rental, or social housing. Preference is for individual ownership of each unit with shared ownership of the common areas, i.e., the walls, roofs, corridors, elevators and stairs, foyer, recreation areas and parking garage. Management is by means of the elected strata council, and maintenance and building operation is typically contracted to property management firms. It is with these types of strata corporations or condominiums, which make-up the majority of multi-family residential housing stock, that the study is concerned.

The Lower Mainland of BC somewhat differs climatically from the rest of Canada. Summers are mild in that air conditioning is rarely necessary and winters are also temperate and mild, but rain is significant in both overall quantity and duration. The electricity and natural gas are comparatively inexpensive and in good supply. This has meant that developers and architects have designed buildings with a high proportion of visible glass, central foyers and shafts, and some degree of symmetry. These towers tend to incorporate reinforced concrete structures, with structural elements also used as components of the building enclosure.

In recent years, many buildings in the Lower Mainland of British Columbia have undergone comprehensive rehabilitation to remedy moisture-related problems. These rehabilitations re-constructed the damaged exterior wall, balcony, deck, and roof assemblies and interfaces, and typically replaced the windows and doors. Due to the financial constraints of the owners, the design of these rehabilitation programs typically focus solely on cost effective remediation, and do not intentionally include upgrades to the buildings, such as upgrades to reduce energy consumption. Therefore, these rehabilitation programs do not take full advantage of the opportunities that exist. Most rehabilitation projects incorporate some improvements to the thermal resistance of a building enclosure due to the nature of the work. In addition, other changes to the mechanical or other service systems have also been undertaken at a few of the buildings, allowing the pre- and post-impact of these improvements to be ascertained. The study of the changes to these buildings presents an opportunity to assess the enclosure and the other service systems from an overall perspective (energy conservation mainly, but also sustainability, maintainability, etc.), and to examine the effects of all of the improvements that might be made.

The findings from the analysis of actual performance data of these in-service buildings provides the basis for recommendations to retrofit other existing buildings, as well as recommendations for the design of new, more energy efficient buildings.

1.1. Objectives

The principal objectives of this research are to review and assess the effects of building enclosure improvements on the space conditioning energy use in typical mid and high-rise multi-unit residential buildings (MURBs) in the Lower Mainland of BC, and to develop better strategies that take into account enclosure repairs, energy conservation and greenhouse gas emissions. The work has been undertaken in two parts, each within multiple phases. This final report incorporates both parts of the study into an overall report.

A literature review was undertaken to establish typical performance characteristics of multi-unit buildings. The review provided a point of departure for the analysis, in terms of the current understanding of energy use in buildings.

Based on this literature review a range of themes have emerged:

- There is a large diversity in the performance of buildings, particularly MURBs. There is limited accurate data on combined energy consumption (gas and electricity) of MURBs.
- The architectural design of high-rise MURBs has changed significantly over the past several decades; however, little is known of the impact of higher glazing areas, increased insulation, and how higher density affects the performance of the buildings, particularly with respect to energy consumption.
- High-rise MURBs are one of the fastest growing housing segments in urban areas, so improving the performance of this building type is crucial. High-rise MURBs make-up a significant percentage of the residential housing stock in the Lower Mainland of British Columbia and other urban areas in Canada and the United States. In the Lower Mainland of BC, high-rise MURB units account for 21% of the total BC Hydro customer residential units. The majority of these MURBs (particularly those constructed after 1990) are strata title ownership instead of rental apartments (more common in the 1960s and 70s).
- There is limited data on the energy consumption of buildings pre- versus post-rehabilitation or retrofit. There is also little understanding of how building enclosure rehabilitation work will affect individual suite owners versus whole building consumption, and the distribution of gas and electricity.
- The importance of air leakage and separate mechanical ventilation systems on heating and total energy usage.
- There is limited data on overall MURB airtightness as there are limited tools to measure building enclosure air leakage within a MURB. The use of operable windows (particularly in temperate climates) further invalidates most estimates of operating building pressures, building enclosure airtightness, and suite ventilation/heating distribution.
- Energy modeling and simulation software is limited in capabilities and may not accurately model energy consumption in mid and high-rise MURBs. For example, corridor pressurization systems and the resulting airflow of heated ventilation air into suites and out through the building enclosure are not well represented. Other limitations include gas fireplace use, air leakage inputs, and input of effective enclosure R-values.

The study gathered and analyzed data on a large number of mid and high-rise multi-unit residential buildings (MURBs) in the Lower Mainland and Victoria, BC in order to ascertain the pre-enclosure repair energy consumption. The data from the analysis of 39 buildings provided baseline consumption data, and an overview understanding of how and where energy is being consumed in multi-unit residential buildings in BC.

The study assesses the impacts of building enclosure upgrades on energy consumption, specifically related to space heating. In order to achieve this objective, sample buildings were selected. For each of the buildings, three-dimensional models were constructed to determine building enclosure quantities. Heat transfer models of building enclosure elements were created to determine thermal resistances. Overall building energy consumption models were assembled based on measured, calculated, test and data from literature reviews.

Although the research considered payback periods for various energy conservation measures, it was decided that due to the volatility of construction industry pricing and anticipated increases in energy costs, any payback information would quickly become outdated and inaccurate. Rather, specific payback information for potential conservation measures should be evaluated on a project by project basis.

The analysis of the data and effects of the changes to the building systems identified areas where the greatest potential for reduction in energy consumption and greenhouse gas emissions exist. These findings will allow for the development of effective strategies for energy efficient enclosure design, policies for energy conservation and incentive programs to reduce energy consumption.

1.2. Background

In Canada, approximately 30% of all secondary energy is consumed in buildings (NRCan 2005). Of this 30%, residential buildings use approximately 16% and commercial and institutional buildings account for approximately 14%. Of the residential portion, 18% is used in apartment buildings. Secondary energy is energy used by final consumers (i.e. operation energy), and does not include the production and intermediate energy.

In the City of Vancouver (pop. 590,000), approximately 50% of the natural gas and 35% of the electricity is consumed in residential buildings. Approximately 32% (16% of total) of the residential gas and 50% (17% of total) of the residential electricity is consumed in mid and high-rise MURBs.

Energy intensity (total annual gas/electric/other fuel energy consumption per unit area) in buildings has been broken down by region and housing type within Canada by Natural Resources Canada (NRCan 2005). The average energy intensity for all types of households in British Columbia is 0.80 GJ/m^2 (222 kWh/m^2), compared to 1.01 (281 kWh/m^2) for the entire country. Specifically related to low-rise apartment buildings (<5 storeys) in British Columbia, the average energy intensity is 0.86 GJ/m^2 (239 kWh/m^2), compared to 1.10 GJ/m^2 (306 kWh/m^2) for all of Canada. Survey data for high-rise apartment buildings (>5 storeys) or condominiums was not collected or specifically identified as part of this previous study. The study also found significant differences in the energy consumption in low-rise apartment buildings based on who paid for the energy. Where someone other than the occupant (i.e. landlord or strata corporation) was responsible for paying at least one of the dwellings energy source, the average energy intensity was 1.62 GJ/m^2 (450 kWh/m^2). In contrast, where occupants pay for all of their energy use the average energy intensity was 0.68 GJ/m^2 (172 kWh/m^2). For this and other reasons, social and rental housing was excluded from the NRCAN survey.

The focus of this report is specifically mid-and high-rise residential buildings. Data from the 2007 BC Hydro REUS study indicate that approximately 21% of the dwelling units in the Lower Mainland are within the mid- and high-rise building range (>5 storeys). In the City of Vancouver the mid- to high-rise residential buildings make-up 25% of the dwelling units.

A typical multi-unit residential building in BC uses natural gas and electricity energy sources in both the suites and in the common areas. Fig. 1.2.2 presents a schematic diagram showing the space-conditioning[1] (i.e. heating and ventilation) systems within a typical MURB. Within each suite, electric baseboard heaters normally provide space heating, and are usually thermostatically controlled. Electricity is also used to power appliances, lights, fans, miscellaneous electrical devices and plug-loads. Natural gas domestic hot water heating is common. Natural gas fired boilers are also typically used in buildings with recreational amenities, including pools and hot tubs. Distribution systems for domestic hot water vary in efficiency, and have a significant impact on the amount of gas used. Buildings may also have in-suite fireplaces for aesthetic or partial space heating purposes.

Natural gas is typically used to heat ventilation air from rooftop gas-fired units. The heated air is distributed to the building corridors and suites by positively pressurizing the corridors. In this ventilation system, gas-fired roof-top make-up air units (MAUs) heat outdoor air up to 15-21°C (year round). The make-up air unit may not be considered by some to be a heating device; however, it does provide a significant quantity of heat energy to the incoming air-stream, which in turn offsets heating required within suites. Heated air from make-up air units is ducted down through shafts to the central corridor spaces on each floor within the building. From a review of the study buildings in-service, a MAU set-point of 20-22°C is typically being set by HVAC service contractors and/or the strata. From the corridors, this pressurized ventilation air is assumed to find its way into suites through door undercuts or other air leakage pathways. Air is exhausted from individual suites by means of exhaust fans, through air leakage paths (both known and unknown) and occupants opening windows and exterior doors. In reality, this pressurized corridor approach suffers from a number of problems relating to the provision and distribution of this heated ventilation air. Air supplied to corridors may or may not find its way into all suites on a

[1] Space-conditioning: Is the general term for heating (to heat the building to some desirable indoor temperature), cooling (to extract heat to cool the building down to a desired temperature) and ventilation (the provision of sufficient air exchange within an interior space). Regardless of the means of generating the desired quality (temperature, humidity, flow rate, and degree of fresh air) the air is said to be conditioned. In parts of BC and other cooler temperate climates where cooling is not required in MURBs, the space is only heated and ventilated.

floor, as door undercuts may be blocked-off, due to pressure imbalances from wind and stack effect, or the fact that the air supplied to the hallways can more easily flow through elevator and other shaft openings than into the suites. Because the pressurized corridor distribution system is relatively ineffective at distributing ventilation air to suites – this ventilation system results in significant energy inefficiencies because the air is heated. These inefficiencies are discussed throughout this report.

Fig. 1.2.1 shows a schematic of air flows within a pressurized corridor approach. As discussed later in this report, this ventilation air which is heated within the make-up air units provides a significant portion of the space heat for the buildings in this study. Whether this is intentional or unintentional by the mechanical designer is not known. Therefore, the efficiency of these units and the distribution system has a significant impact on the buildings' gas energy consumption.

Fig. 1.2.2 illustrates a schematic of a typical high-rise with electric baseboard heat and gas-heated make-up air. Within the two hydronic buildings in the study, hydronic baseboard heaters replace the electric baseboard heaters in the suites and a gas boiler is present in the mechanical room.

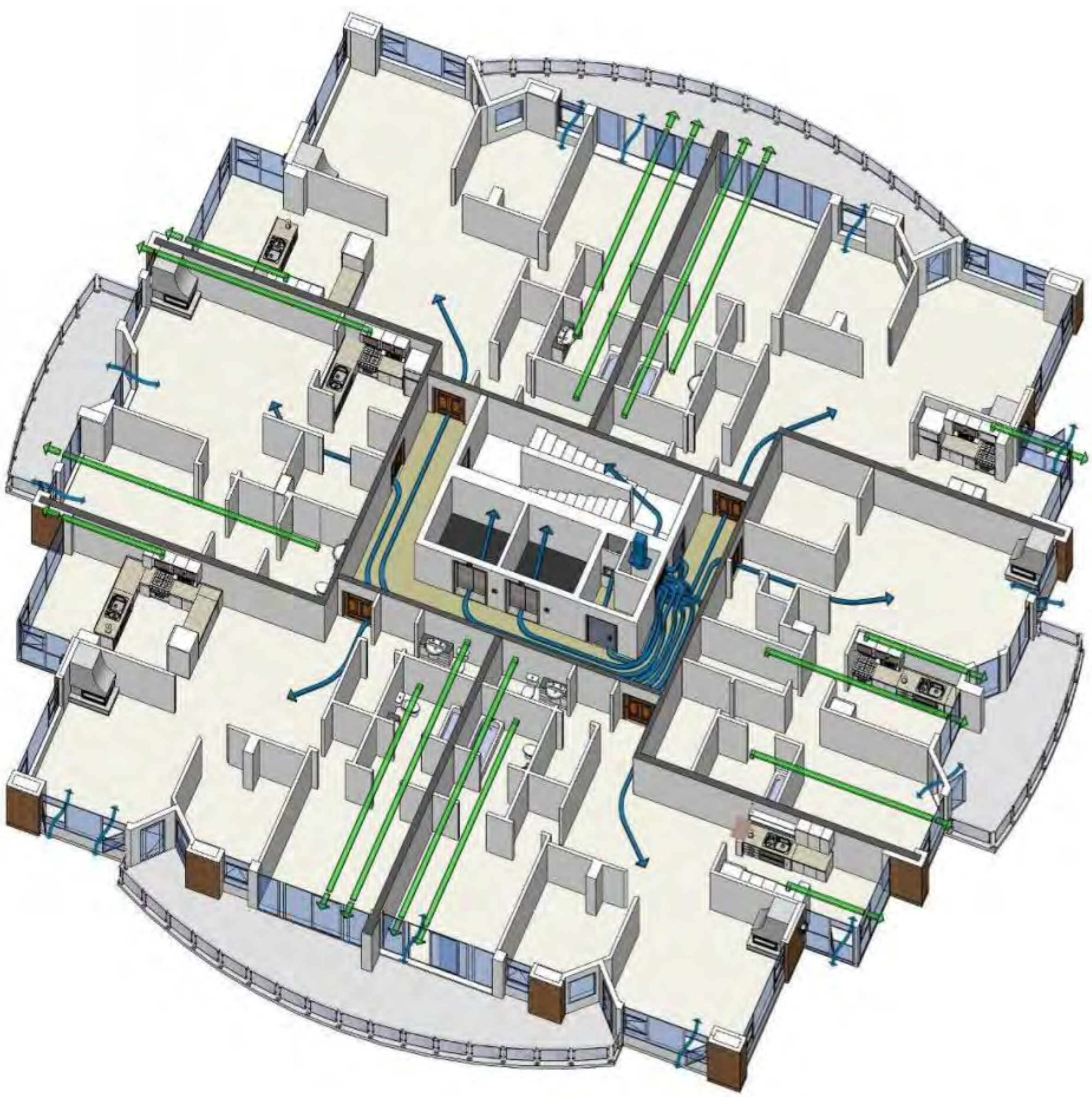


Fig. 1.2.1 Schematic showing a typical Pressurized Corridor Ventilation Approach. Blue arrows show supply air flows and green arrows show exhaust air flows.

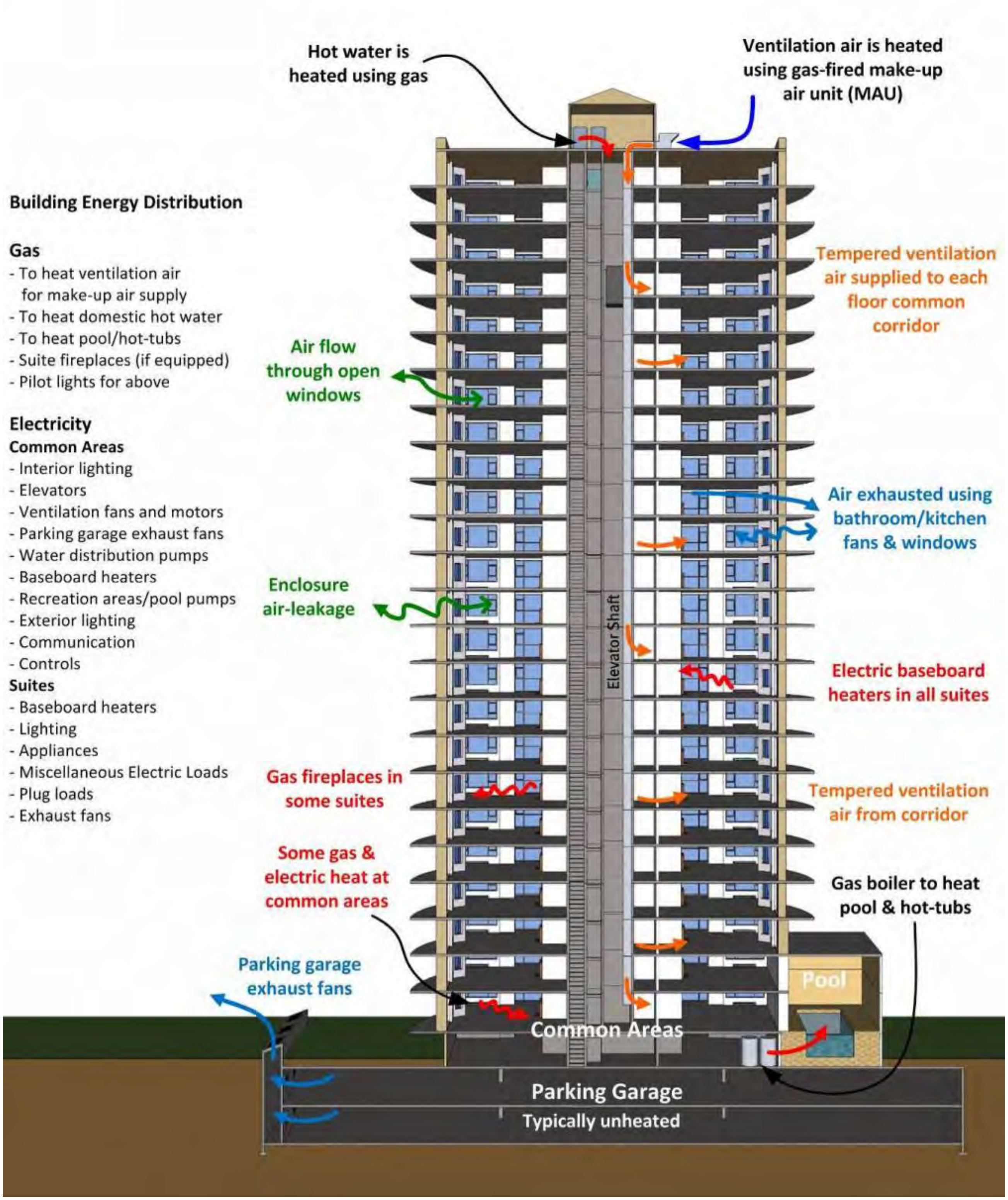


Fig. 1.2.2 Schematic of a Typical MURB Heating and Ventilation System.

2. METHODOLOGY

Sixty-four Multi-Unit Residential Buildings (MURBs) were initially selected for analysis as part of this study. Fifty-one of the buildings are 10 to 33 storeys (high-rise) and 13 of the buildings are 5 to 9 storeys (mid-rise), and they were all constructed between 1974 and 2002. Fifty-six of the buildings are located in Metro Vancouver, and eight in Victoria. The buildings were selected to be representative of typical MURB housing stock and contain buildings of forms common to other mid- and high-rise residential buildings in BC.

Data from 39 of these buildings is covered in this report. Data from the other buildings was deemed unsuitable due to a number of reasons, including: missing or erroneous data, metering issues (i.e. single gas or electricity meters for several buildings grouped in complexes), difficulty in splitting consumption in buildings with mixed energy use (condominium plus commercial space on the same meter), or lack of available data on the buildings. All of the buildings use a combination of natural gas and electrical energy.

The data for the 39 buildings represents an approximate total of 4,400 residential suites with 4.6 million square feet of gross floor area where 173,000 GJ of natural gas and 44 million kWh of electricity are used per year. For reasons of confidentiality, buildings are referenced using a number from one through 64 for the study.

The summary data within this study represents a top-down consumed energy analysis (i.e., the meter readings of the supplied energy are recorded and manipulated to assess usage). No consideration is given to the conversion effectiveness or efficiency, seasonal or otherwise, of any device in the initial analysis of the data. Assumptions are few, and stated where they are made. This is quite different from the bottom-up analysis presented on a sample number of the buildings later in this report, where assumptions are required as part of the analysis.

2.1. Data Analysis Procedure

For each of the buildings, at least 10 years of gas and electricity billing data from 1998 to 2008 was requested. The intent of looking at 10 year data was to understand how climate affects heating consumption in MURBs, and then during the later parts of the study, capture at least two to three years of data post- building enclosure upgrade for comparison of energy savings.

BC Hydro and Fortis BC are respectively the principal suppliers of electricity and natural gas to the buildings in the survey. Meters are read at fairly regular intervals of not more than 62 days, and the billing cycles are monthly. The metered data is divided by the period in days to obtain an average per day, which then may be added in accordance with the calendar and, calendarized. Consumption data is not normalized for weather or other effects, and it is as the name implies raw data. While the gas and electricity meters may not be read on the same date, calendarizing the data allows comparison of the monthly consumption for each. Weather normalization of the data will be performed during later phases of this study, to accurately compare the pre- and post-upgrade energy consumption.

Electricity is metered by suite for each unit (interior lighting, all appliances, heating and domestic hot water if electric) and the electrical demand on all other devices (rooftop, elevators, all common areas including the pool, recreation rooms and outdoor lighting and parking areas) is typically read off one common meter. For each of the buildings, BC Hydro provided the common area consumption and an aggregate suite consumption which summed all of the suites within the building together.

Natural gas is normally metered on a single meter for the entire building. This means that all gas fired heating devices, even the fireplaces and domestic hot water and pools (if any), are included in the single reading. At some of the building complexes in the study, a single meter may be used for several buildings, even mixing in some commercial usage. Where the gas metering was mixed or questionable, those buildings were excluded from the study.

Electricity and natural gas data is combined in spreadsheets and total monthly energy consumption is calculated. Gas data is provided in GJ, but converted to an energy unit of kWh (1GJ = 277.78 kWh) for comparison and analysis in standard units. Monthly data is compared using a standardised month of 365/12 = 30.4167 days long (30.5 days during leap-year) so that all months can be compared equally. Thus the raw data has been both calendarized and standardised. This is especially relevant when, say, comparing January to February consumption.

Analyzing the annual data, we found that a continuous record from August 1st to July 30th provided the best 12 month period for our "calendar year", because this completely and continuously covers the heating period. This has no impact on the average annual energy consumption data provided in this report.

2.1.1 Baseline Load Determination

One of the larger goals of the study is to look at the impacts of energy savings from building enclosure rehabilitation work. We focused on understanding the impacts of heating, or more specifically, direct space heating energy. The seasonal heating contribution is evident for both the electric and gas data for all of the buildings. Assuming, for the moment, that the direct space heating is either turned off or dormant for the summer (July and August and often longer) an average for the non-variable data can be established and subtracted from this heating data. This is likely to be a conservative approach to determining space conditioning heat energy. The gas make-up air unit may operate over the summer, sometimes continuously, and suite electric heat is also provided by lights, appliances, miscellaneous electric loads (MELs), as well as baseboard heaters.

The non-variable data baseline includes non-direct heat, including domestic-hot water and gas appliances for gas, and a baseline for electricity, namely electrical appliances, such as stoves, all lighting, elevators, miscellaneous electric loads, and plug loads, etc. Fig. 2.1.1 presents total monthly energy consumption and Fig. 2.1.2 presents total monthly estimated space heat energy for building 31, a typical MURB in the study.

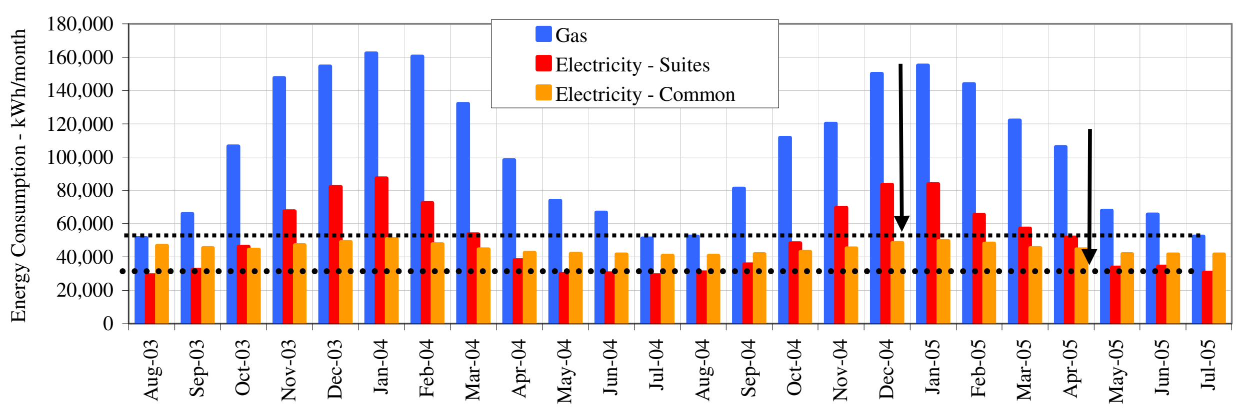


Fig. 2.1.1 Building 31 – Monthly Energy Consumption, August 2003 to July 2005.

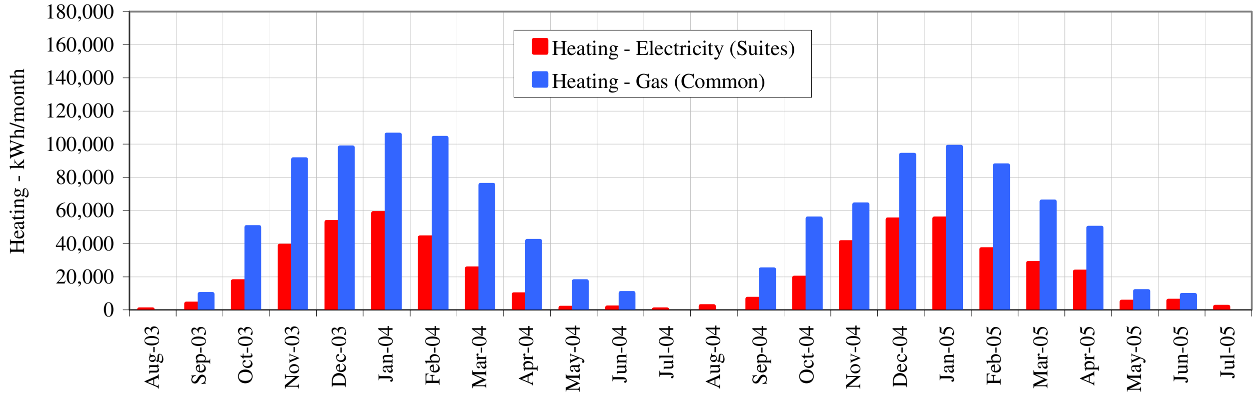


Fig. 2.1.2 Building 31 – Monthly Space Heat Energy Consumption, August 2003 to July 2005.

2.1.2 Baseline Electric Loads and Electric Space Heat

The assumption that baseline electric loads can be simply removed for analysis of space heat was tested. Using data from the two gas hydronic heated buildings (19 and 45), the monthly electricity consumption within a typical MURB can be analyzed without influence of a direct electric space heat component to demonstrate the seasonal variation in lighting and other electricity use. Neither of these buildings has air-conditioning, unless owners have provided their own portable units (which is reportedly uncommon in these suites). It is also typical for some owners to purchase small electric space heaters to supplement baseboard heaters, particularly for unheated rooms such as enclosed balconies.

The monthly energy consumption for all energy sources in Building 45 is presented in Fig. 2.1.3. The electricity component is shown in greater detail in Fig. 2.1.4. Data for Building 19 is similar. Note the difference in the vertical axis scale between the two figures.

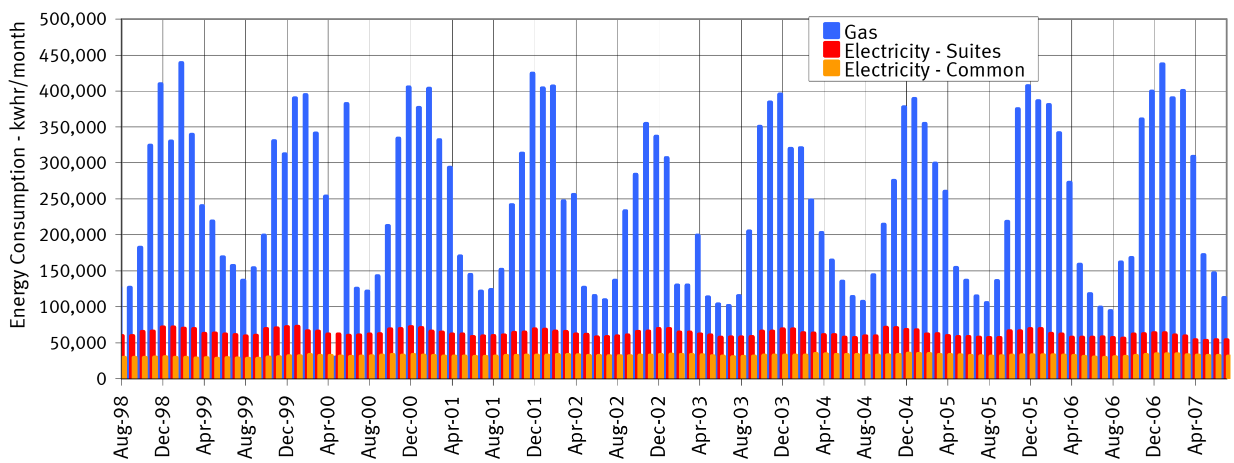


Fig. 2.1.3 Building 45 – Monthly Total Energy Consumption, August 1998 to July 2007.

As shown in the figure, the majority of energy used within Building 45 is gas, accounting for 72% of the total energy used within this building.

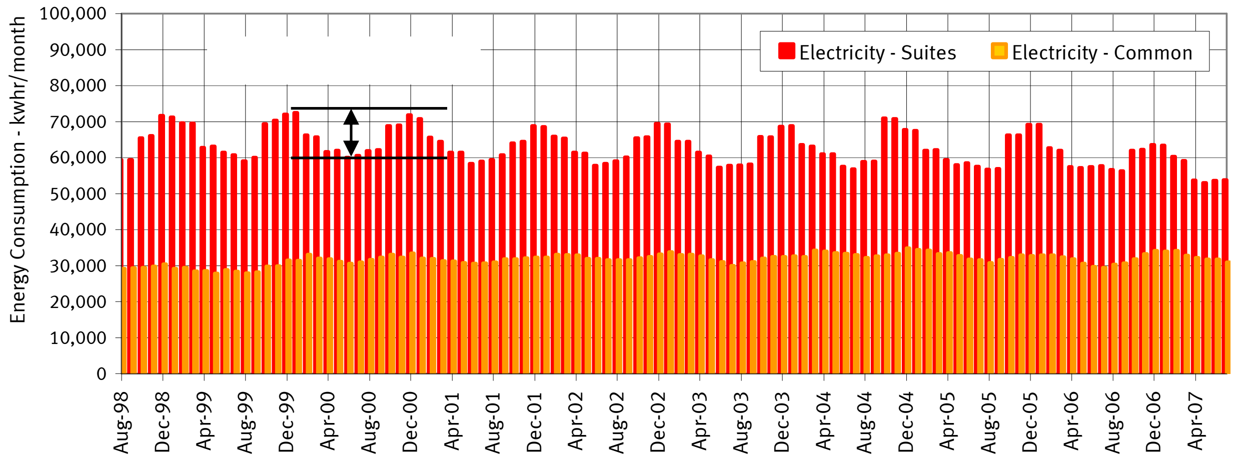


Fig. 2.1.4 Building 45 – Monthly Suite and Common Area Electricity Consumption, August 1998 to July 2007.

In Building 45, on average the seasonal variation was found to be 8% of the total annual suite electricity (annual range from 3% to 10%) and 4% of the annual common area electricity (range from 2% to 8%). In Building 19, on average the seasonal variation was found to be 5% for the total annual suite electricity (range from 2% to 8%) and 6% for the annual common area electricity (range from 4% to 8%). Note that these percentages provided are for buildings where the space heat is provided by gas. In buildings with electric baseboards, where we are actually concerned with this seasonal variation, electric baseboard space heat energy accounts for on average 40% of the suite electricity. As the suite electricity load is on average 50% higher in the electric baseboard heated buildings than these two hydronic buildings (due to the space heat portion), the seasonal variation is estimated to only account for between 1% and 4% of the total electricity. As these seasonal variations are relatively negligible, and attempting to factor out their contribution would add an unnecessary unknown error, the electric space heat can be determined with reasonable accuracy using the baseline method. Moreover, these seasonal variations in lighting and electricity actually contribute to the heating of the building (i.e. incandescent light bulbs) and, in turn, offset the required space heat from other mechanical sources.

2.1.3 Baseline Gas Consumption and Gas Space Heat

To assess the impact of the baseline gas assumption, the total energy consumption is plotted versus monthly heating degree days (an indicator of required space heat energy per month) in Fig. 2.1.5 and Fig. 2.1.6. More correctly, the plot should show heating degree days versus space heat load; however, as we are attempting to determine the baseline load in the gas for zero space heat, these plots are more useful.

Fig. 2.1.5 plots data from Building 45 (hydronic heat), showing a negligible dependence on electricity for space heat. Fig. 2.1.6 plots data from Building 21 (typical suite electric baseboard, with gas heated common make-up air), where a relationship between heating degree days and energy consumption exists for both gas and electricity.

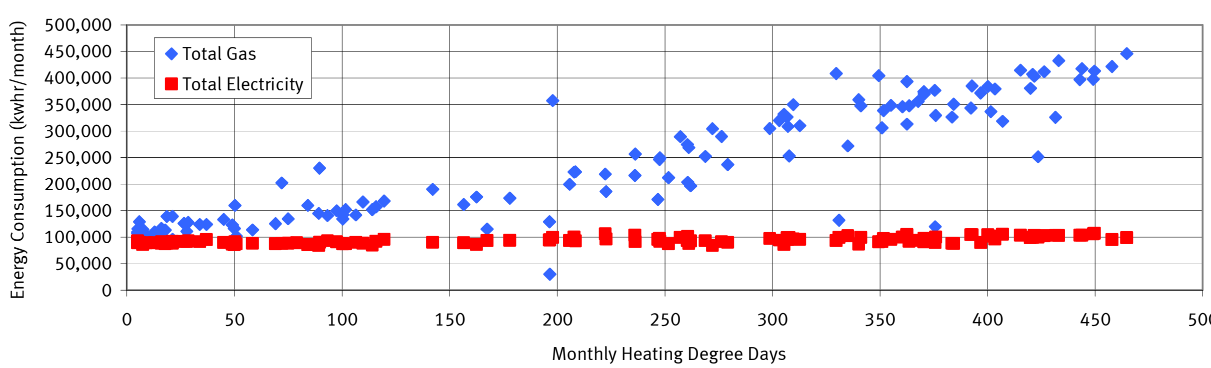


Fig. 2.1.5 Building 45 – Total Monthly Energy Consumption versus Heating Degree Days (Celsius).

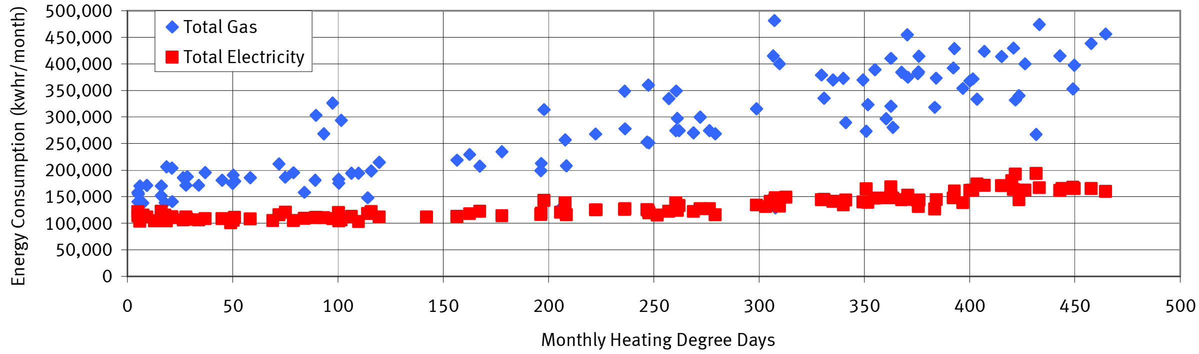


Fig. 2.1.6 Building 21 – Total Monthly Energy Consumption versus Heating Degree Days (Celsius).

Significant scatter exists in the relationship between gas consumption and heating degree days during the heating months, however, trends are apparent. Electricity consumption is typically more predictable and correlates well with the heating degree day value. During the summer months (HDD ‹50), the scatter in gas consumption diminishes and a baseline energy load for only the domestic hot water portion of the natural gas becomes apparent, particularly below 10 HDD. An average of the gas consumption at only the lowest HDD values is calculated as an appropriate baseline indicating zero heat for each building. This is equivalent to weather normalizing the data and selecting the minimum baseline value. The baseline gas value is the monthly energy required for heating the domestic hot water, cooking with gas stoves and indoor pool water heating.

Once baseline consumption values of electricity and gas are determined, the monthly total and heating energy consumption data is determined. This is broken down into the following for each building on a monthly and annual basis:

- Total Gas Consumption
  - Total gas for baseline usage (i.e. for heating of domestic hot water, gas stoves, heating of indoor pools and hot tubs).
  - Total gas for space heating (i.e. for heating of ventilation air within rooftop make-up air units, gas for hydronic heated buildings, and for gas fireplaces in some suites).
- Total Electricity Consumption
  - Total Suite Electricity
    - Suite electricity for other baseline non-primary or non-direct heating uses (i.e. baseline lighting, appliance, and plug loads).
    - Suite electricity for heating (i.e. electric baseboards).
  - Total Common Area Electricity
    - No baseline was obtained for this as the seasonal difference was small and there was not a clear cut delineator between the two main uses described as follows:
    - Common baseline electricity for other devices (i.e. fans, ventilation systems, pumps, elevators, indoor and outdoor lighting, parking garage etc.).
    - Common variable electricity for space heating (if electric re-heat or baseboard heaters are used in the corridors or elsewhere).

Note that the conversion effectiveness of raw energy purchased to energy consumed in the building can be taken as 100% for electric devices while the seasonal conversion efficiency of the gas heating plant and appliances depends on the device and varies between about 40% and 90%. For this part of the study, we are only concerned with the supply of energy, and even though 1 GJ of gas purchased does not equal 1 GJ of gas energy output, it does not affect the analysis of the consumption data reported here.

Statistically, the data set is variable, like the buildings chosen for the study; however, as the buildings are all within the same geographical and weather region and all are privately owned residential buildings, the variability of the used energy consumption data is fairly good. Average (mean) values are close to median values.

2.2. Thermal Accounting: Pre- and Post-Rehabilitation Enclosure R-values

To assess the energy consumption and space heat load within selected study buildings, detailed thermal calculations were performed to calculate effective pre- and post-rehabilitation building enclosure R-values. This concerns the 13 MURBs analyzed in greater detail within Section 6 of the report (Buildings 7, 11, 17, 18, 19, 20, 21, 28, 32, 33, 39, 41 and 62).

Energy calculations require the use of an overall effective thermal transmission (U-value) or thermal resistance (R-value, the inverse of U-value) of a building to determine the energy loss/gain through the building enclosure. The overall U-value for a building is determined by area-weighted averaging each of the component U-values that make-up the building enclosure.

Conductive heat flow through the building enclosure is determined by multiplying the U-value by the area and the difference in temperature. This heat flow makes up the majority of space heat loss in a MURB and is therefore critical in understanding differences in energy consumption between buildings and the influence of building enclosure rehabilitations or improvements on space heat energy use. Overall effective R-values for windows, wall and roof assemblies are also used as inputs for energy modeling.

The building industry uses a mix of SI and IP units for R/U values and units of energy, largely due to US influence in building materials and mechanical equipment. This report uses both IP and SI units consistent with the building industry in Canada. Selected conversion factors between SI and imperial are provided in Table 2.2.1.

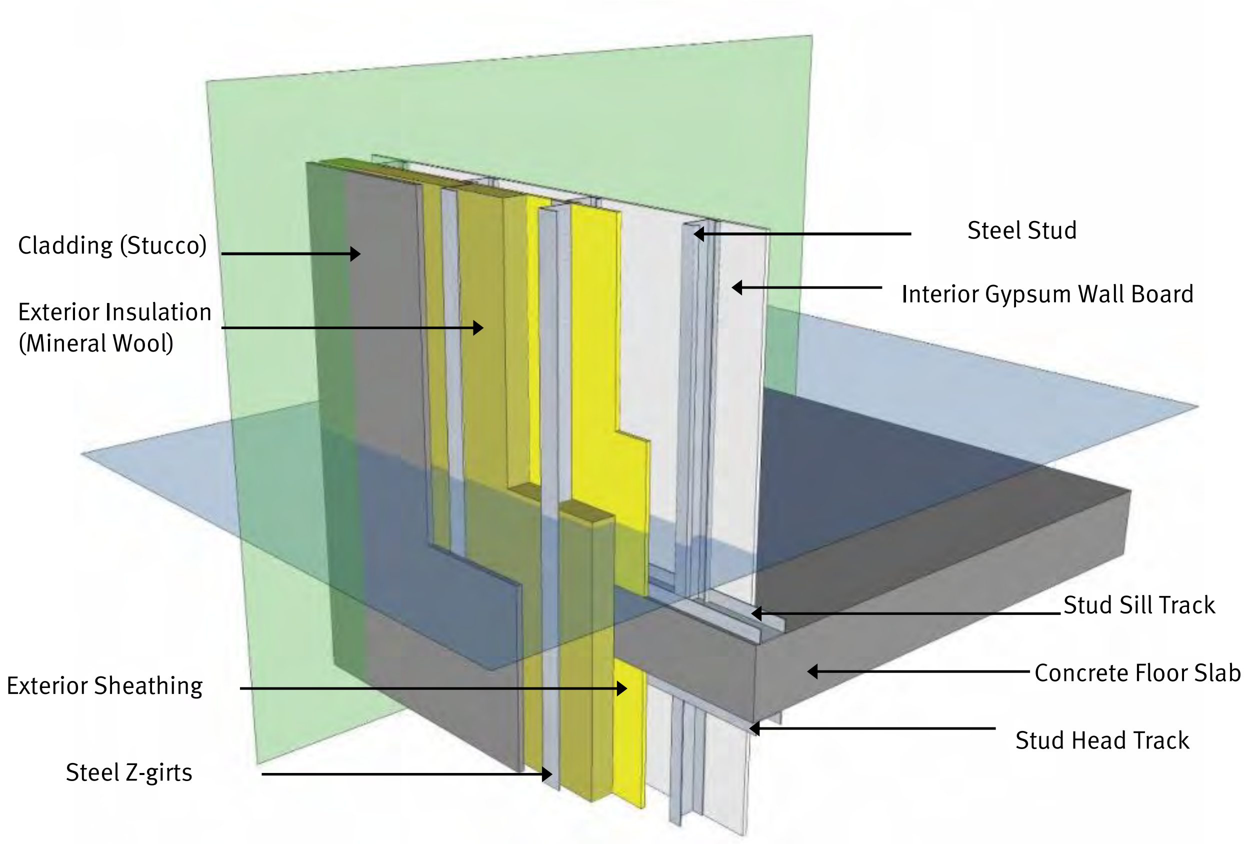
Table 2.2.1 Selected Energy Conversion Factors

To Convert From		To Obtain
Imperial R-value, hr ft^2 °F/Btu	Divide by 5.678	Metric R-value, RSI, m^2 K/W
Imperial U-value, Btu/ hr ft^2 °F	Multiply by 5.678	Metric U-value, W/m^2 K
GJ	Multiply by 277.78	kWh
kWh	Multiply by 3.412	kBtu
kWh/m^2/yr	Multiply by 0.317	kBtu/ft^2/yr

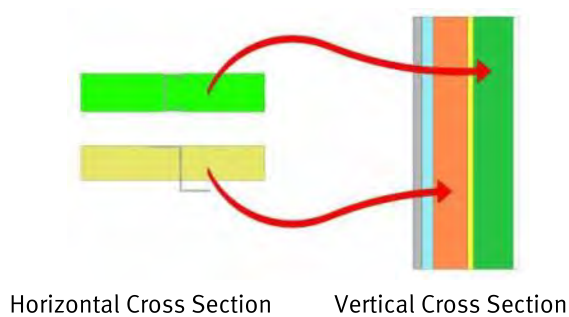
Calculating the effective U-value for the entire building enclosure of a large building is a complicated task of thermal modeling and quantity accounting due to the numerous assemblies, arrangements, interfaces, materials, and thermal bridges which need to be accounted for. It has been common practice to use nominal "insulation only" center of wall U-values for walls, roofs, floors and standard sizes of fenestration for energy calculations; however, center of wall U-values are not indicative of overall performance due to the overall effect of thermal bridging at details, interfaces, slab edges, corners, etc., which dominate the overall heat flow and the overall U-value. Similarly, standard window size U-values tend to be more conservative than the actual window U-value and do not account for high-rise window types. As a result of these simplified assumptions, the actual thermal performance of the building enclosure is commonly over-estimated, resulting in significant errors in energy modeling and resulting estimates for energy consumption or savings potentials. Anecdotal evidence suggests that the more detailed the thermal analysis, the worse the calculated enclosure performance will be, mainly because of the thermal bridges at all of the detail conditions.

To determine an accurate approximation of the effective enclosure U-value (and R-value) for each of the study buildings, each building's enclosure is divided by assembly type into smaller areas. Each of these assemblies corresponds with a U-value that is determined by thermal modeling. Detailed thermal modeling of enclosure assemblies and details requires the use of either a three-dimensional thermal model such as HEAT 3D or a simpler two-dimensional model such as THERM where 3D details are simplified into two-dimensional sections. Two-dimensional modeling can represent 3D details using effective material properties for thermally bridged elements out of plane. Using this methodology, effective U-values for various cut sections through the building enclosure arrangements can be performed, such as sections through roofs, walls, balconies, decks and windows; however, window U-values are determined in separate detailed calculations.

Due to the three-dimensional nature of building components, in many cases, multiple thermal models were needed for a single building component. This method is referred to in THERM as the concept of isothermal planes and is accepted by the industry as being the current "best" practice for determining U-values of three-dimensional wall assemblies. An illustration of this method is shown in Fig. 2.2.2 used for both horizontal and vertical enclosure assemblies.



1) A cross-section is created on the horizontal "blue" plane.
2) Components that vary along the length of the wall are modeled using THERM and equivalent homogeneous materials are created.



3) A cross-section is created on the vertical "green" plane.
4) The assembly is modeled on this plane using THERM and the equivalent homogeneous materials created in step 2 are used in place of inhomogeneous components as illustrated at left.

Fig. 2.2.2 Sample wall assembly illustrating the isothermal planes modeling technique.

By using the thermally equivalent homogeneous materials in the vertical cross sections, the models are able to account for inhomogeneous materials in all three dimensions and thus determine an overall U-value for these assemblies. Typical results using this approach were verified using both three-dimensional models and by comparing to previously published modelling results. Variations of this methodology were sometimes necessary for more complex cases.

The THERM models are divided into the initial cross sections used to determine equivalent homogeneous materials and then the overall wall assembly models for each building which are further subdivided into pre- and post-rehabilitation assemblies. Each model is shown twice to illustrate both the assembly construction and the temperature gradient isotherms. The U-values presented are for the projection of that component onto the building enclosure. For vertical cross sections this is a projection onto the vertical y-axis, and for horizontal cross sections this is a projection onto the horizontal x-axis. This method works well for most wall and roof assemblies and compared well against HEAT 3D three-dimensional models, and where continuous framing members are used (i.e. girts or studs). Following much of the initial work to develop two-dimensional THERM models, supplementary work to develop comparable HEAT 3D three-dimensional models was performed and results were validated with laboratory hot-box testing of simple steel framed wall assemblies. Three-dimensional modeling was performed to model more complex and non-continuous cladding supported wall assemblies such as discrete cladding support clips or crossing z-girts shown in Fig. 2.2.3 and Fig. 2.2.4 and other assemblies, including balconies and proprietary cladding attachments.

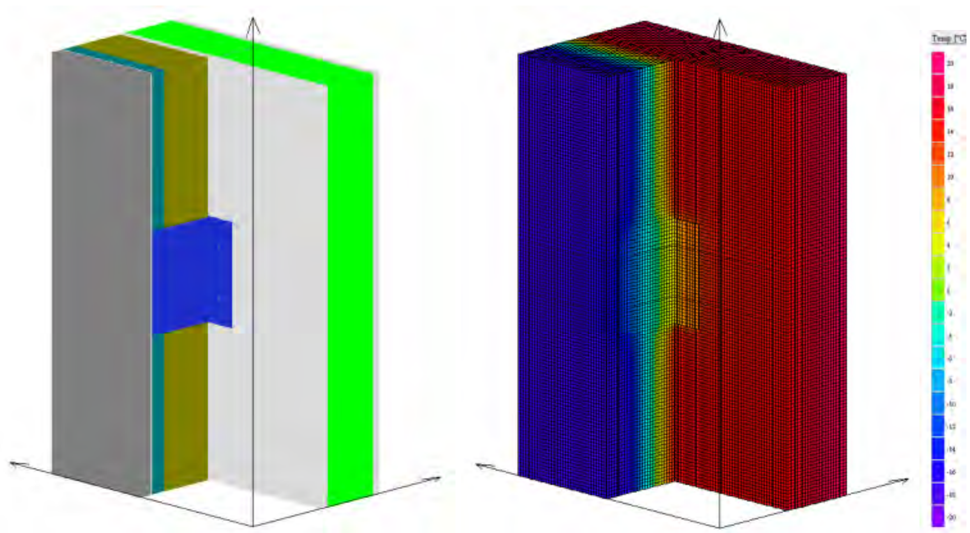


Fig. 2.2.3 Heat 3D model for Clip Cladding Supported Exterior Wall Assembly

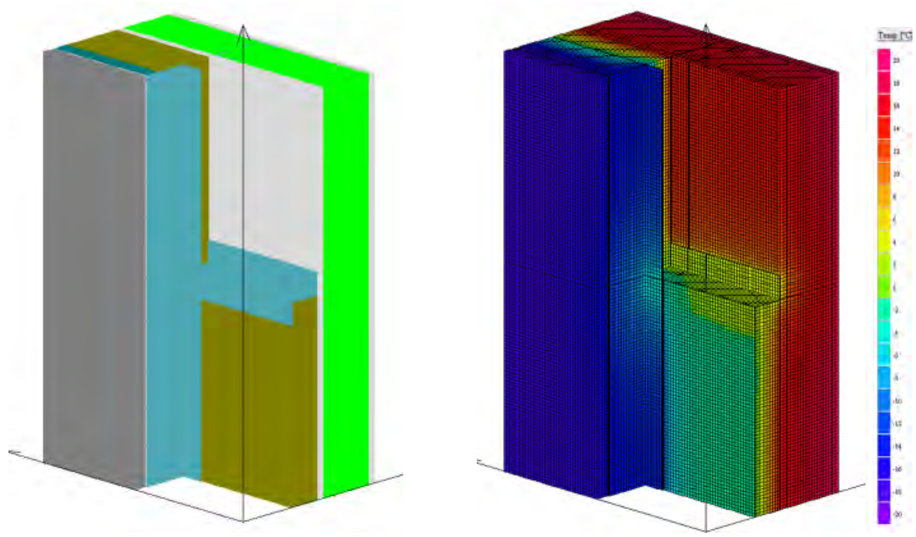


Fig. 2.2.4 Heat 3D model for Crossing-Z-girt Exterior Wall Assembly

2.2.2 Windows

Window U-values must consider both the effect of the insulated glazing unit (IGU) and frames. In the past, the use of center of glazing U-values may have been used as the overall window U-value; however, the effects of framing are so profound that they must be considered in thermal calculations. Because windows play such a large role in the overall thermal performance of a building, it is critical to accurately determine the effective U-values of each window configuration as installed.

Window fabricators are required to provide National Fenestration Rating Council (NFRC) certified ratings for their windows, often with different glazing options for both fixed and operable window types in standard sizes. NFRC ratings are determined using NFRC Procedure 100, which uses computer simulation which has been calibrated from laboratory testing and reviewed by a third party agency. This modeling is completed using detailed glazing and IGU properties from WINDOW combined with frames drawn in THERM to calculate overall U-values and SHGC factors.

The NFRC standard size fixed window is 47" wide by 59" tall and an operable lite is 24" wide by 59" tall. These sizes were selected by the NFRC as typical single-family residential window sizes; however, most multi-unit residential and commercial buildings use windows which differ from these sizes which has a significant impact on the thermal performance. NFRC modeling also fails to account for the thermal effects of corner posts, extra intermediate mullions, deflection channels typical with window-wall assemblies and current architectural style. Window manufacturers do not typically provide this data as it is not required by Building Code or most project specifications, and typically shows less favourable results than NFRC standard size values (i.e. due to additional intermediate framing members, small operable or fixed lites, reinforced frames).

Therefore, for each of the study buildings, detailed calculations were performed which accounted for the actual window sizes and configurations. The process for the study buildings included modeling each of the frame components in THERM, the IGU properties in WINDOW and combined using area-weighted U-value calculations consistent with NFRC Standard 100. Spandrel panels were also modeled in a similar method as part of window-wall assemblies.

2.2.3 Quantities and Overall R-values

After the U-value of each building enclosure component is calculated, its corresponding area must be accounted for to calculate an area weighted U-value. The type of quantity calculations performed for material take-offs or budget purposes often do not contain sufficient detail for detailed thermal calculations as the quantity take-offs must consider the subdivision of areas by thermal performance, or areas subdivided by the U-values determined by the thermal modeling.

The use of simple and free 3D architectural modeling software, such as Google Sketch-up, provides a tool to draw and prepare detailed quantity take-offs of even the most complicated buildings with relative ease. Preparing a 3D model to calculate areas for thermal calculations is relatively straightforward. Areas of the enclosure are assigned a corresponding U-value and the areas are used in U·A calculations to determine the overall effective enclosure U- and R-values. Fig. 2.2.5 presents a graphical summary of the pre-rehabilitation building enclosure R-values.

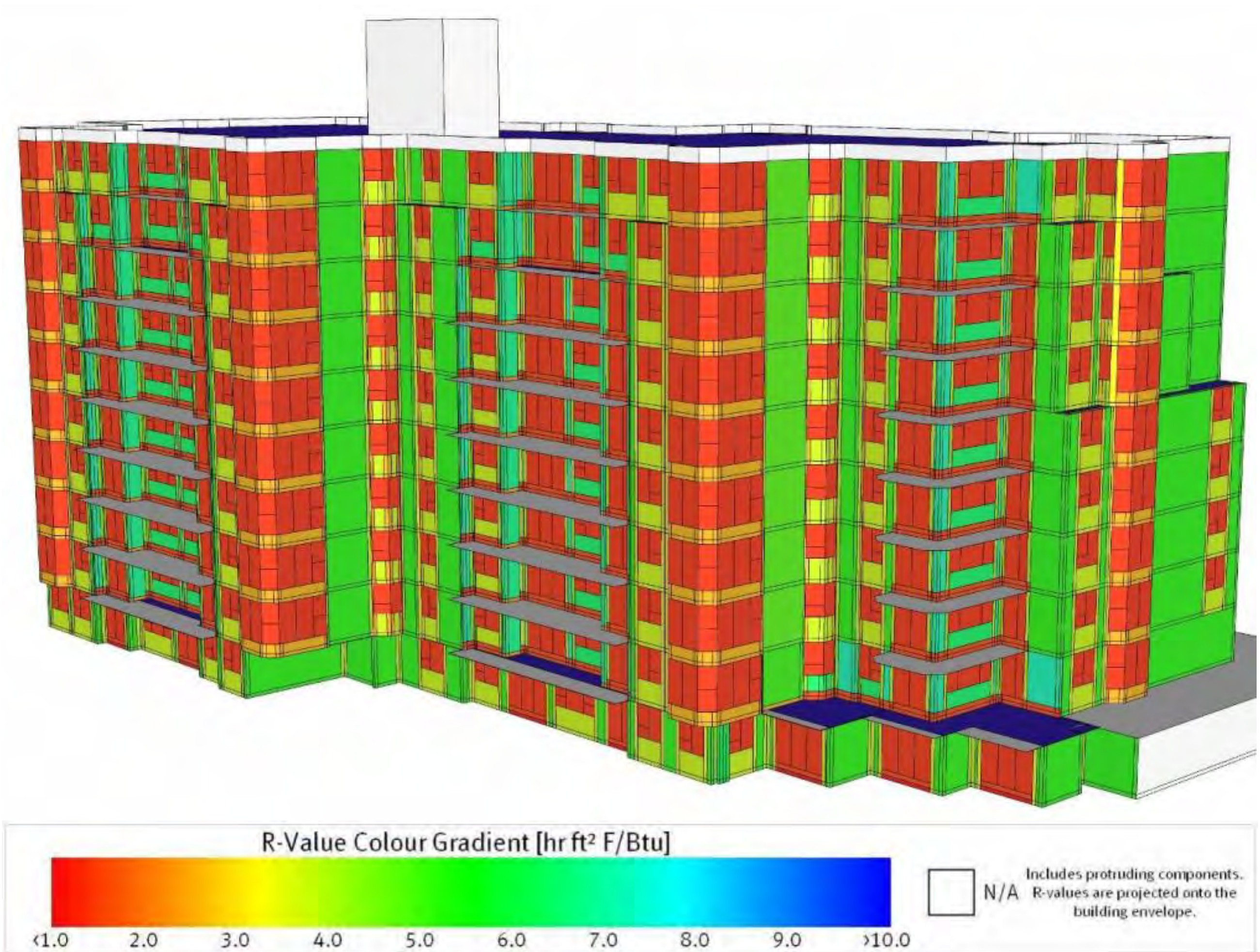


Fig. 2.2.5 Pre-Rehabilitation Thermal Modeling Results for Building 19 of the Study (Overall Effective R-value = 2.92).

The overall effective U-values/R-values were calculated in great detail for each of the thirteen MURBs analyzed in Section 6 of this report (Buildings 7, 11, 17, 18, 19, 20, 21, 28, 32, 33, 39, 41 and 62). Overall R-values were determined for the entire building from the 3D models.

To simplify the procedure, the effective wall R-values of Buildings 11, 21 and 28 were modeled using only a typical representative floor instead of the whole building. The accuracy of this assumption was tested by comparing the whole building U-values to the typical floor U-values for the other buildings analyzed in greater detail. An analysis was performed on the other buildings used for the energy modeling and it was determined that the typical floor of a building on average predicts the overall U-value of the building within 1% (Table 2.2.2).

Table 2.2.2 Typical Floor to Whole Building U-Value Comparisons

Typical Floor to Whole Building U-Value Comparison															
	7		17		18		19		20		32		39		62
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Pre	Post
Typical Floor															
Walls	0.22	0.19	0.26	0.18	0.25	0.15	0.26	0.20	0.28	0.23	0.28	0.16	0.45	0.29	0.23
Glazing	0.62	0.47	0.76	0.59	0.51	0.44	0.73	0.46	0.75	0.46	0.74	0.48	0.62	0.74	0.59
Full Building															
Walls	0.22	0.19	0.26	0.18	0.23	0.15	0.25	0.19	0.30	0.25	0.26	0.14	0.45	0.29	0.22
Glazing	0.62	0.46	0.78	0.63	0.51	0.44	0.73	0.46	0.75	0.46	0.74	0.49	0.61	0.74	0.60
Full Building % Difference															
Walls	-1%	-1%	-1%	0%	-8%	-1%	-2%	-3%	7%	9%	-7%	-9%	1%	-1%	-2%
Glazing	0%	-1%	4%	6%	0%	1%	0%	0%	-1%	0%	1%	2%	-2%	0%	2%
Average differences, -1% for walls, +1% for glazing															
Comments									Penthouse level walls have high U		Balcony only on typical floor				

Building quantities (areas, volumes, etc.) were found using the three-dimensional models. In some cases these models omitted a section of the building (typically a portion of the first floor) for simplicity and thus the quantities from the model are not representative of the actual quantities of the building. Therefore, while the modeled quantities were used to calculate U-values as this calculation only used the areas as a weighting factor, the quantities were extrapolated to include the omitted sections of the building so that the values were correct for other calculations. Because different areas were used for different calculations, it is possible that area values may appear inconsistent when in fact it is simply due to the above mentioned adjustments needed to perform the calculations correctly.

2.3. Towards an Understanding of Building Enclosure Airtightness in High-Rise Buildings

Airtightness is a measure of the air-porosity of the assemblies that make-up the building enclosure at a certain pressure difference. Airtightness can be visualized in terms of an equivalent sized hole in the building enclosure. Typically airtightness is measured at a standard test pressure of 50 or 75 Pa to overcome the effects of wind and stack effect and obtain a repeatable measurement. The measured effective airtightness rate changes with building pressurization (both positive and negative) due to deformation of air barrier elements (i.e. membranes or gaskets) and as the result of complicated flow regimes through wall, roof and window assembly elements.

Air leakage is defined as the uncontrolled flow of air through the building enclosure (i.e. infiltration or exfiltration) as the result of building pressurization and the enclosure airtightness. Air leakage results in natural ventilation (albeit with limited ventilation effectiveness and mixing) and is separate from mechanical ventilation. Mechanical ventilation systems induce pressures across the building enclosure which also result in air leakage, in addition to uncontrolled natural infiltration/exfiltration (caused by stack or wind pressures). The air leakage rate for a building at a certain point in time is determined from the airtightness of the enclosure and the pressure that the building is operating under.

In terms of energy consumption, air that exfiltrates the building results in a direct loss of heat energy because the building requires additional heat energy to bring it to indoor conditions. In a MURB, the heat energy input required to offset air leakage energy loss may not always be required in the suite which it was lost from. For example, under winter-time stack-effect, air will typically infiltrate lower floor suites and exfiltrate at upper floor suites resulting in additional heating required at lower suites whereas upper floor suites may be too hot. Similarly wind and mechanical pressurization will also affect infiltration and exfiltration through suites in the building and vary with time and season. Additionally, taking into account the compounding influence of operable windows and occupant behaviour (such as opening windows to reduce heat at the upper floor suites), the effective airtightness becomes very difficult to determine, as does the building pressurization (suite and whole building) used to predict the air leakage rate of a MURB.

Because of the difficulty and costs associated with measuring MURB assembly airtightness under operating conditions, and the limited number of field measurements of natural infiltration/exfiltration rates and building pressures over extended periods, the quantitative understanding air movement and air leakage in MURBs is limited. While there is a general understanding of the air flows and pressure regimes in MURBs, there is a lack of qualitative air leakage and inter-building air flow data for MURBs. Further research is needed in this field

There are two general methods to airtightness testing of MURBs, either by whole building at once by parts using a neutralizing test procedure (Finch 2007) shown in Fig. 2.3.1. Testing of whole large MURBs at once is difficult in practice for an occupied building or even during construction. Gaining access to all suites to open suite doors and close all windows is logistically difficult in an occupied building. In addition, the testing results will be dominated by large mechanical openings, mechanical ducts and open windows if not closed off, potentially giving little actual indication of enclosure tightness. To overcome some of the issues with testing whole large buildings, portions of the building may be tested (i.e. individual floors, individual suites etc.) using an incremental normalizing procedure where addition fans are used to pressure neutralize adjacent spaces. This testing method also provides data on the airtightness of interior partitions which tend to be as or more air-leaky than the exterior enclosure.

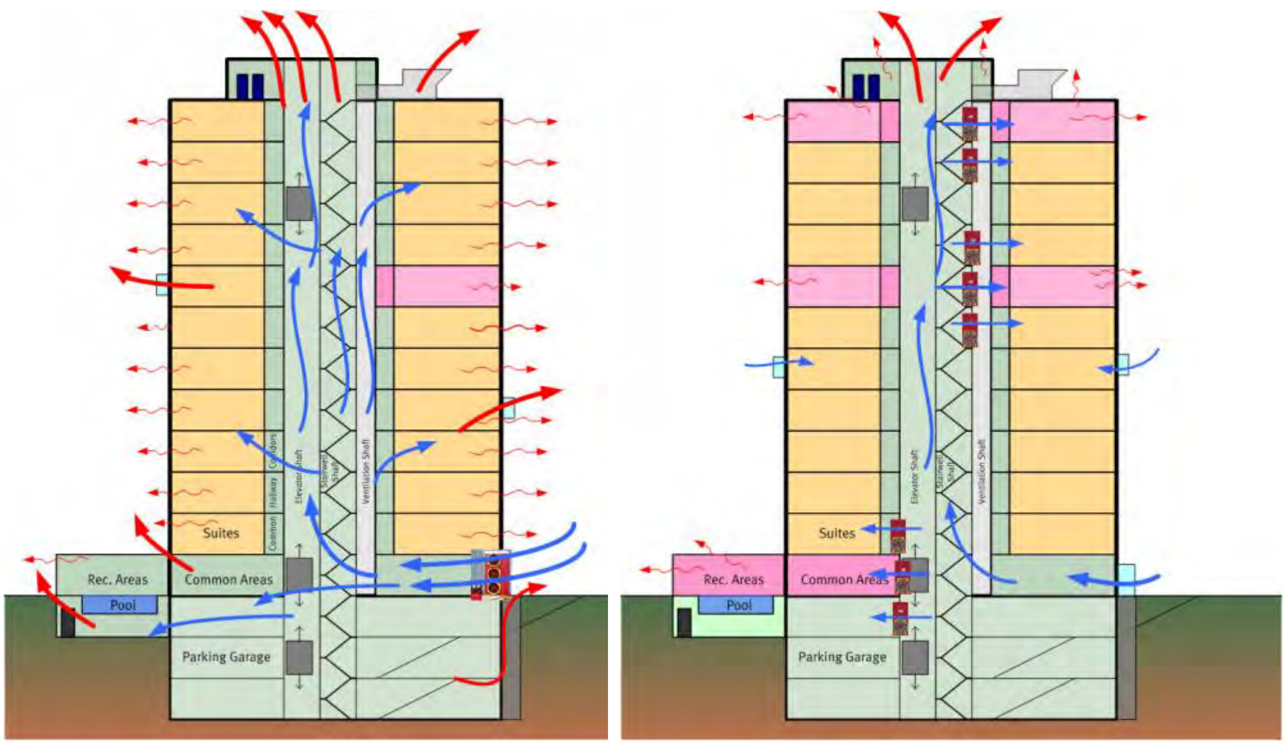


Fig. 2.3.1 Methods for Airtightness Testing of Large Tall Buildings – Whole building (LEFT) and Individual Zones/Compartments (RIGHT).

Air leakage testing of whole or part of high-rise buildings has been performed primarily on a research basis since the 1970's but is not performed on a widespread basis primarily due to the high cost, time and equipment involved and logistics of such obtrusive tests to tenants. It is estimated that less than 100 high-rise buildings across Canada have been air leakage tested in the past 40 years; however, buildings which have been tested and results published, provide useful data and useful insight into enclosure tightness under test conditions and assumed average building pressures.

A literature review of published data going as far back as the early 1970's was performed and is combined with high-rise air leakage testing performed by RDH on recently rehabilitated buildings. The wall and window assemblies in the buildings tested by RDH are typical of the rehabilitated buildings in the study and the air leakage rates are similar to other buildings across the country, which is useful for predicting air leakage rates and the effect on energy consumption in this study.

Building 33 of the study underwent a full building enclosure rehabilitation in 2007. Building 32 underwent the same rehabilitation and has the same construction details as Building 33 and is representative of the other pre- and post-rehabilitation study buildings. RDH performed air leakage testing on a representative suite within Building 33 using multiple fan doors and a pressure neutralizing procedure to be able to measure the air leakage individually through the exterior enclosure and the interior walls and floor/ceiling.

A mid-rise building of another RDH research study (Finch 2005) underwent full building enclosure rehabilitation in 2002. The building enclosure is typical of most rehabilitated and new mid- to high-rise buildings (exterior insulated, self-adhered membrane air barrier on gypsum sheathing, air-tight thermally broken aluminum windows). RDH performed air leakage testing on three representative suites in this building using multiple fan doors and a pressure neutralizing procedure to be able to measure the air leakage individually through the exterior enclosure and the interior walls and floor/ceiling.

Building 35 of the study underwent a window-replacement renovation in 2008. Building 35 is a 1970's exposed concrete tower with strip windows occupying 34% of the wall area. The renovation consisted of replacing the original inefficient and air-leaky single glazed aluminum windows with new air-tight double glazed thermally broken aluminum windows. Air leakage testing was performed on individual suites (without pressure neutralizing adjacent surfaces due to the cost of additional fans) solely to measure the pre- and post-retrofit air leakage change as a result of replacing only the windows. Additional tests were performed to determine the relative effect of cracking open a window on the effective enclosure airtightness. Because the only component that changed was the windows, the effective air leakage reduction of the window replacement was determined.

Air leakage rates can be presented numerous ways in various unit combinations which make comparing different study results or even different industry standards cumbersome. In terms of uncontrolled in/exfiltration through the building enclosure, a measurement of the normalized airtightness of the exterior building enclosure component is needed at a standard pressure (typically at 50 or 75 Pa). The airtightness at normal air-pressures can be estimated using the formula: $Q = C \cdot P^n$.

Where 'C' is a constant for each test/building, which allows extrapolation from a standard test pressure to more typical operating pressures of between 5 to 10 Pa. The exponent 'n' is determined from a multi-point pressure test, or is typically assumed to be in the range of 0.65 (per industry accepted standards and empirical testing results) for most buildings representing a combination of small and large air leakage openings. More air-tight buildings will have n values closer to 0.5 and looser up to 1.0. Because it is can be difficult to multi-point test large multi-unit buildings, testing may only be performed at a single pressure of 50 or 75 Pa. As a result the industry accepted 'n' factor of 0.65 is assumed here to extrapolate the historical test data to a lower normal operating pressure range in this report. In actuality, airtightness tests for most large buildings will range from 0.55 to 0.70. The accuracy of this assumption for 'n' is not that critical in the overall accuracy and intended use of this value as shown in Fig. 2.3.2.

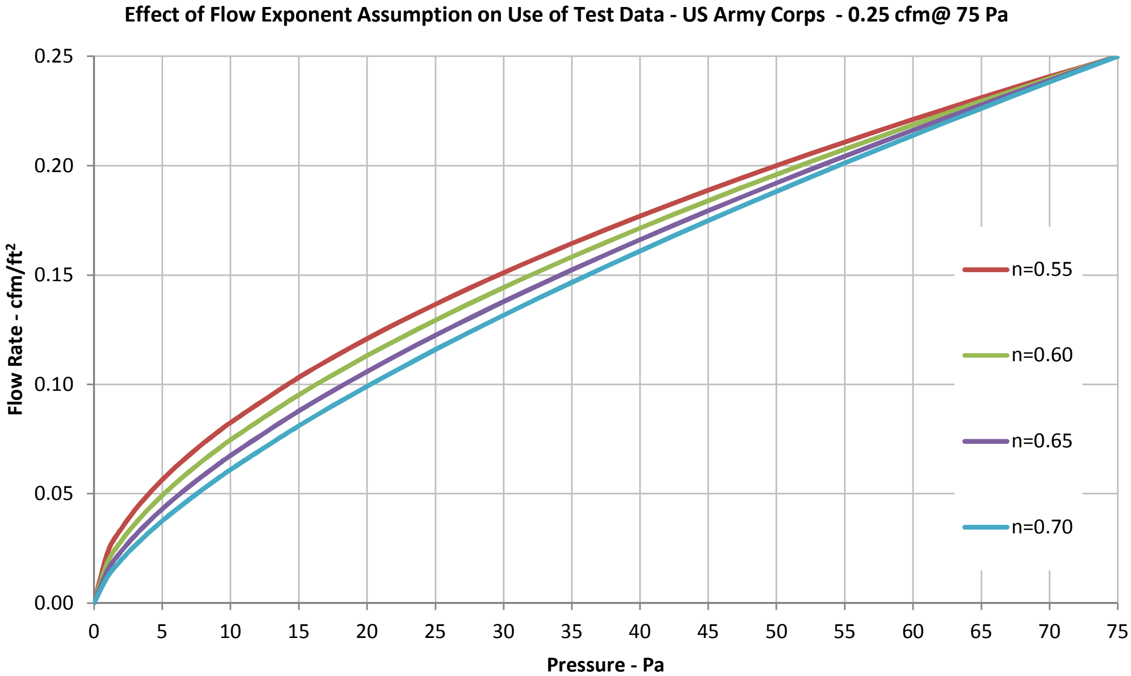


Fig. 2.3.2 Impact of ‘n’ value exponent on assumed flow rate with pressure.

Normal operating pressure for a high-rise building varies over time (from positive to negative) with height due to stack effect, wind speed, building shell and interior airtightness and mechanical systems; therefore, it is difficult to determine an average net difference in pressure over the course of a year. For small one to two storey buildings a pressure of 4 Pa is often assumed from empirical research. Pressures across the suite enclosure in high-rise buildings become increasingly more complex. Pressure will vary with building height, wind exposure, season and the relative airtightness of the interior and exterior components of the building. A more air-tight building will typically be under a higher pressure than a leakier one. This pressure may be induced mechanically by an imbalanced ventilation system (i.e. supply or exhaust air only) or passively by wind or stack effect. Uniformly opening windows will make the building enclosure less air-tight and hence the building will be under a lower pressure which will in turn lower the air leakage rate. The acting environmental pressures and resulting air flow paths and air leakage is shown schematically in Fig. 2.3.3 and specifically the pressures in Fig. 2.3.4 and Fig. 2.3.5.

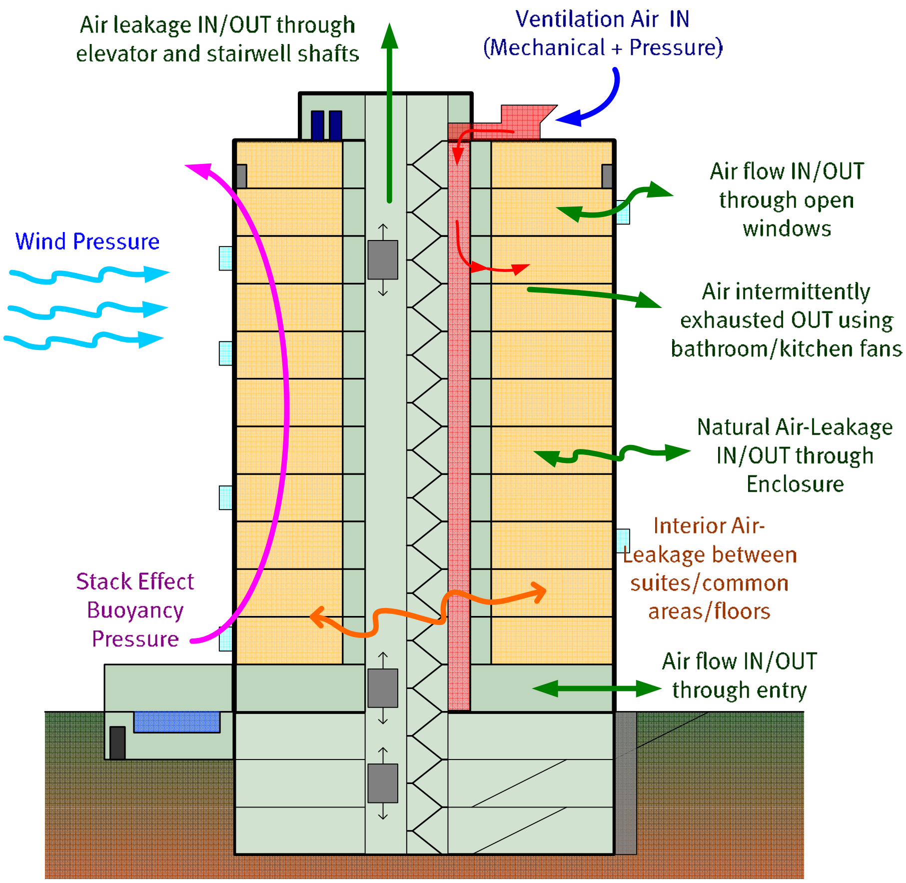


Fig. 2.3.3 Building Pressures Caused by Wind, Stack Effect and Mechanical Equipment and the Resulting Air flow and Air leakage.

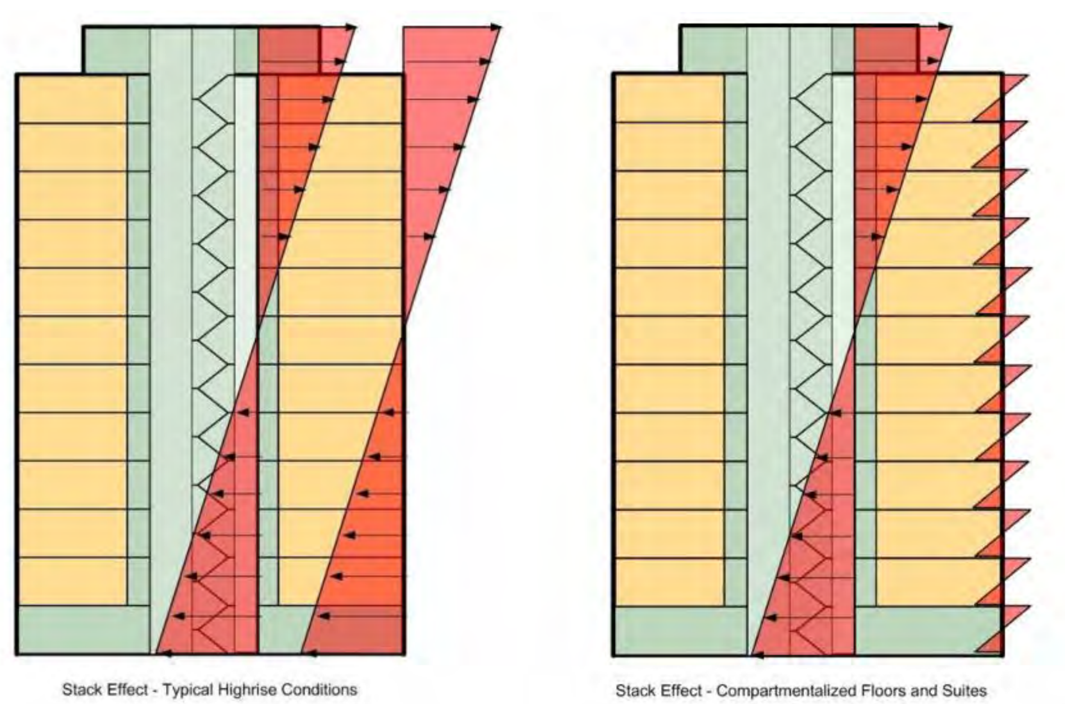


Fig. 2.3.4 Stack Effect Pressures – Typical conditions and for a compartmentalized MURB. Actual pressures within a building will vary between the two depending on level of inter-floor airtightness and floor-by-floor and suite compartmentalization.

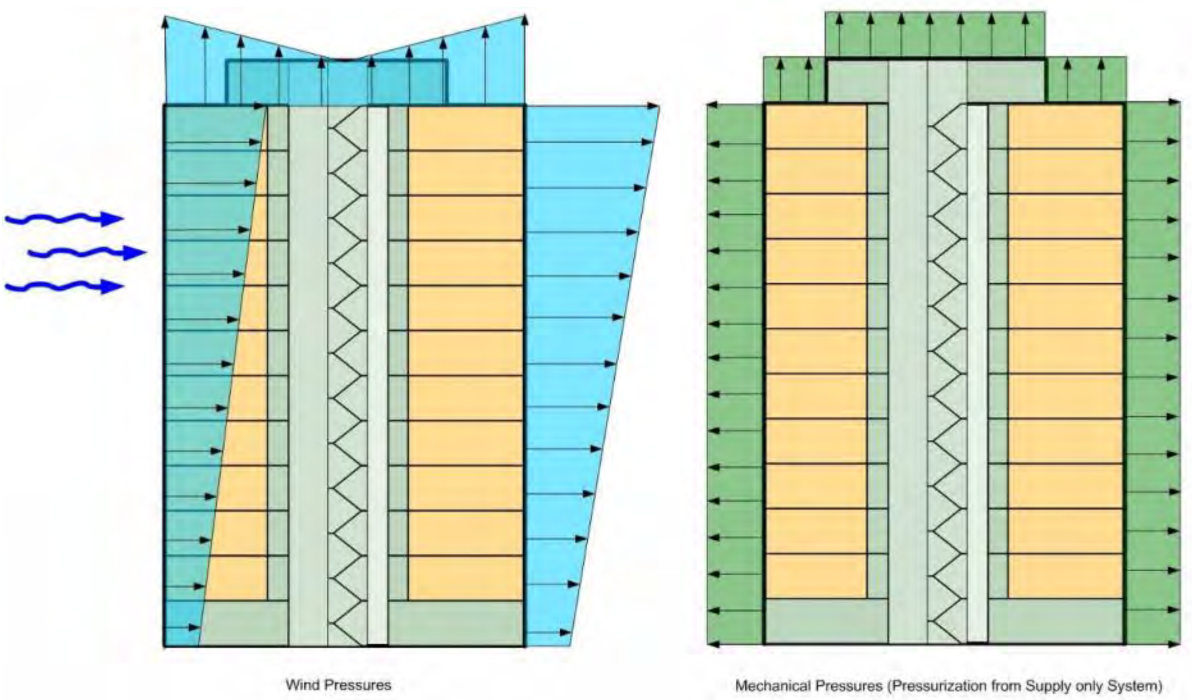


Fig. 2.3.5 Schematic of Wind and Mechanical Pressures on a high-rise MURB.

An understanding of the actual hourly or even annual average pressures within mid- to high-rise buildings in temperate climates such as the Lower Mainland of BC is limited. There is a good qualitative understanding of the airflows and pressures within a MURB; however, quantitative values are difficult to predict. Stack effect pressures are constant and tend to dominate infiltration pressures over the course of the year while wind events act for short periods. Windows are regularly opened year round, and affect airtightness and pressure regimes within a building.

Wind effects are taken into account within most energy models and are accounted for by boosting the natural infiltration rate. Mechanical pressures (i.e. as the result of an unbalanced supply or exhaust system) are also accounted for separately within energy models (i.e. by total cfm and not cfm/ft^2 of enclosure area).

To use the airtightness test data, an average net pressure difference of 5 to 10 Pa is assumed for infiltration or exfiltration pressures based on building height shown in Table 2.3.1. This is based on the average heating season stack effect pressure for a 10 to 20 storey high-rise. Note that the average study building height is 18 storeys.

Table 2.3.1 Average Theoretical Stack Pressures across the Building Enclosure – Vancouver, BC Climate Data.				
		Average Stack Pressure Across Enclosure		
Month	**Average Outdoor Temperature**	**10 Storey High-rise, 26m**	**20 Storey High-rise, 52m**	**30 Storey High-rise, 78m**
January	3.3	4.9	9.8	14.7
February	4.8	4.5	8.9	13.4
March	6.6	3.9	7.9	11.8
April	9.2	3.2	6.4	9.6
May	12.5	2.3	4.6	6.8
June	15.2	1.5	3.1	4.6
July	17.5	0.9	1.8	2.8
August	17.6	0.9	1.8	2.7
September	14.6	1.7	3.4	5.1
October	10.1	2.9	5.9	8.8
November	6	4.1	8.2	12.3
December	3.5	4.8	9.7	14.5
Average Annual		**3.0**	**6.0**	**8.9**
Average Heating, Oct-Mar		**4.2**	**8.4**	**12.6**

Using a representative enclosure airtightness rate at an average building pressure of 5 Pa, natural air leakage rates can be determined in terms of a flow (cfm) and hourly air-exchange rate (ACH). In addition to natural air leakage, air leakage caused by mechanical ventilation must also be considered. To account for a typical MURB ventilation system, the mechanical ventilation air-exchange rate is added to the natural air leakage at 5 Pa. Interestingly, the equivalent overall pressure that should result from natural and mechanical air leakage would be between 5 and 10 Pa for a relatively air-tight building.

Various units for representing normalized enclosure airtightness are possible but are typically represented as an air flow rate or equivalent orifice hole size per area of enclosure. Normalizing airtightness to airflow per enclosure area is most useful as this can quickly be converted into a total airflow rate and hence effective air-exchange rate for the building/suite by uncontrolled in/exfiltration. The industry has adopted an airtightness rating of cfm/ft^2 of enclosure area as one such measure. Multiply the airtightness by the enclosure area and by 60 min/hour and divide the sum by the building volume to determine an hourly air-exchange rate which can be input into most energy models.

A review of current test standards and previous literature on air leakage testing of mid- to high-rise buildings was performed. From this previous work, reported airtightness rates are converted into consistent units (where required) and are summarized and compared in Table 2.3.2, Table 2.3.3, and Table 2.3.4. Italic font indicates where data was extrapolated using an 'n' of 0.65 from a reported test pressure (i.e. 75 Pa) to a different pressure (i.e. 5 or 10 Pa) to fill in the table.

Table 2.3.2 Summary of Industry Standard Airtightness Rates.

Standard / Source	Test Type/ Comments	Measured Airtightness at Test Pressure cfm/ft^2 of Enclosure		Estimated Airtightness at Normal Pressure cfm/ft^2 of Enclosure		Corresponding Air Exchange Rate for a Tested Building at Pressure (where sufficient data given)		
		cfm/ft^2 @50Pa	cfm/ft^2 @75Pa	cfm/ft^2 @5Pa	cfm/ft^2 @10Pa	ACH_{50}	ACH_{10}	ACH_5
Industry Standards and Guidelines								
US Army Corps Standard	Building	0.19	0.25	0.043	0.067			
ASHRAE “Leaky”	Building	0.46	0.60	0.103	0.162			
ASHRAE “Average”	Building	0.23	0.30	0.052	0.081			
ASHRAE “Tight”	Building	0.08	0.10	0.017	0.027			
R2000 Standard	House	0.10	0.13	0.022	0.035			
1997 MNEBC Assumption of Natural Ventilation	Building			0.05				
IECC Max Recommended	Building	0.31	0.40	0.069	0.108			
ASTM E-2178, maximum	Material Standard	0.003	0.004	0.001	0.001			
ASTM E-2357, maximum	Wall Assembly	0.03	0.04	0.007	0.011			
ASTM E-779, maximum	Building	0.31	0.40	0.069	0.108			
NBCC Canada 1995	Wall / Window Assembly	0.015	0.02	0.003	0.005			

Table 2.3.3 Summary of Research Air leakage Testing Data for High-Rise Buildings by Others								
Building(s)	**Test Type/ Comments**	**Measured Airtightness at Test Pressure cfm/ft² of Enclosure**		**Estimated Airtightness at Normal Pressure cfm/ft² of Enclosure**		**Corresponding Air Exchange Rate for a Tested Building at Pressure (where sufficient data given)**		
		cfm/ft² @50Pa	**cfm/ft² @75Pa**	**cfm/ft² @5Pa**	**cfm/ft² @10Pa**	**ACH_{50}**	**ACH_{10}**	**ACH_5**
Research Air leakage Testing of High-Rise Buildings by Others								
CMHC study, Average of 18 various age MURBs across Canada – Proskiw	12 Building Average	*0.48*	0.63	***0.108***	*0.170*			
	3 Building Average	*0.61*	0.79	***0.136***	*0.213*			
	6 Partial Building Average	*0.49*	0.64	***0.110***	*0.173*			
CMHC Wardrop Study, Average of several 1970s MURBs	Building Low Average	0.41	*0.53*	***0.091***	*0.143*			
	Building High Average	0.62	*0.81*	***0.139***	*0.218*			
Tamura and Shaw, 1976. Eight Commercial high-rise buildings (precast/ curtainwall/ steel stud)	Building Lowest Average	*0.09*	0.12	***0.021***	*0.032*			
	Building Highest Average	*0.37*	0.48	***0.083***	*0.130*			
Parekh and Woods, 1992. Ottawa 20 storey MURB rehab, test at 10 Pa	Pre Rehab Building	*0.36*	*0.46*	***0.080***	0.125	*1.12*	0.39	*0.25*
	Post Rehab Building	*0.24*	*0.31*	***0.054***	0.085	*0.76*	0.27	*0.17*
Parekh and Woods, 1992. Toronto 10 storey MURB rehab, test at 7 Pa	Pre Rehab Building	*0.26*	*0.34*	***0.059***	0.092	*0.96*	0.22	*0.34*
	Post Rehab Building	*0.18*	*0.23*	***0.039***	0.062	*0.59*	0.13	*0.21*
NRC Trial Whole Building Test, 1990	Partial Building	0.91	*1.18*	***0.203***	*0.318*			
Gulay et al. 1996. Suites in 10 Buildings	Partial Building, Low Range	0.41	*0.54*	***0.093***	*0.145*			
	Partial Building, High Range	0.62	*0.81*	***0.139***	*0.218*			

Table 2.3.4 Summary of Research Air leakage Testing Data of High-Rise Buildings by RDH								
Building(s)	**Test Type/ Comments**	**Measured Airtightness at Test Pressure cfm/ft² of Enclosure**		**Estimated Airtightness at Normal Pressure cfm/ft² of Enclosure**		**Corresponding Air Exchange Rate for a Tested Building at Pressure (where sufficient data given)**		
		cfm/ft² @50Pa	**cfm/ft² @75Pa**	**cfm/ft² @5Pa**	**cfm/ft² @10Pa**	**ACH_{50}**	**ACH_{10}**	**ACH_5**
Research Air Leakage Testing of High-Rise Buildings by RDH								
Building 33 of MURB Study, Suite 802, typical unit (mid floor). Exterior Insulated, SAM on sheathing air barrier, windows, ducts	Post-Rehab Exterior Wall	0.29	*0.38*	***0.066***	*0.103*	0.91	*0.32*	*0.20*
Building 3 of RDH Rainscreen Study, Suite 311 (middle floor). Exterior Insulated, SAM on sheathing air barrier, windows, ducts	Post-Rehab Exterior Wall	0.28	*0.36*	***0.062***	*0.097*	1.36	*0.48*	*0.31*
Building 3 of RDH Rainscreen Study, Suite 611 (top floor). Exterior Insulated, SAM on sheathing air barrier, windows, ducts	Post-Rehab Exterior Wall	0.45	*0.59*	***0.101***	*0.159*	2.24	*0.79*	*0.50*
Building 3 of RDH Rainscreen Study, Suite 608 (top floor), partially rehabilitated wall area. Exterior Insulated, SAM on sheathing air barrier, windows, ducts	Partial Post-Rehab Exterior Wall	0.52	*0.68*	***0.117***	*0.184*	3.12	*1.10*	*0.70*
Building 2 of RDH Rainscreen Study, middle floor typical suite – Wood-frame, windows, ducts	Post-Rehab Wood-frame – Poly & Bldg Paper Air Barrier	1.41	*1.84*	***0.315***	*0.490*	11.12	*3.91*	*2.49*
Building 4 of RDH Rainscreen Study, top floor corner suite – Wood-frame wall/cathedral ceiling, windows, ducts, fireplace	New Wood-frame – Poly & Tyvek Air Barrier	2.39	*3.11*	***0.530***	*0.840*	6.44	*2.26*	*1.44*
Building 35, average difference in pre-post cfm/ft² as the result of new windows. Normalized to exterior wall area. Concrete/window	Average change in wall airtightness from new windows	-0.52		**-0.12**				
Building 35, difference as the result of opening a casement window 36" tall window by 1" for 50 Pa test. Normalized to exterior wall area.	Change in suite airtightness from opening a window	+2.43		**+0.54**				

Table 2.3.5 Expected Range of Airtightness for Non-Combustible MURBs – Includes Exterior Walls, Windows, Exhaust Ducts as Operated Conditions.		
Type	**5 Pa, Normal Operating, cfm/ft² of enclosure**	**10 Pa, Normal Operating, cfm/ft² of enclosure**
Lowest Expected	0.02	0.03
Low Average	0.05	0.08
Mid Average	0.10	0.16
High Average	0.15	0.24
Highest Expected	0.20	0.31
Effect of Open Windows – Estimated	›0.40	›0.63

Some simple rules of thumb become apparent in the analysis:

- The ratio of ACH 50 or cfm/ft^2@50 Pa to a normal pressure of 5 Pa is a factor of approximately 4.5 when utilizing an n factor of 0.65. The ratio of 50 to 10 Pa is a factor of approximately 2.8.
- The airtightness of a modern MURB should be in the range of 0.05 to 0.20 cfm/ft^2 at 50 Pa. If an air leakage rate of 0.20 cfm/ft^2 at 50 Pa is tested, it would likely correspond to a significant deficiency in the air barrier or an open window.
- Open windows significantly influence the effective airtightness of the building enclosure, and when open will increase the effective airtightness by an order of magnitude. Correspondingly, this reduced airtightness drops the building pressure and air leakage rate slightly.

Consider the following example to demonstrate the importance of open windows on the air leakage rate:

- The post-rehabilitation shell air leakage rate of Building 33 as tested by RDH was found to be 0.066 cfm/ft^2 at 5 Pa. This airtightness as measured is equivalent to a leakage area of 2.73 in^2/100 ft^2 of enclosure.
- For this 20 storey, 135 suite high-rise building with an enclosure area of 73,000 ft^2, the total leakage area of the building enclosure would be on in the order of 2000 in^2.
- For comparison one of the 2x4 casement windows when fully open has an area of 1152 in^2 or a 6-6” tall sliding door cracked open 6” has an area of 468 in^2.
- Estimating that at least one window per floor is open, the total open window/door area is 23,040 in^2, more than 11 times higher than the enclosure leakage area (of 2000 in^2) at 5 Pa for the 20 storey sample building. This demonstrates the importance of open windows on effective enclosure airtightness.
- Interestingly, a very air-leaky building enclosure would have an air leakage rate of 10 to 20 in^2/100 ft^2 of enclosure (5 to 10 times higher as measured in some wood-frame buildings). Therefore, open windows may have a lesser effect than anticipated due to the reduced pressures as a result of the leakier building enclosure.

2.4. Pre- and Post-Rehabilitation Energy Assessment

This procedure for assessing the impact of the building enclosure rehabilitation on the total energy consumption and specifically the space heat energy builds on the methodology presented in Section 2.1. For the rehabilitated buildings, the data during the rehabilitation is ignored and the years prior to and after the rehabilitation are analyzed separately. The total energy consumption and space heat energy is then compared pre- and post-rehabilitation to determine the energy savings.

This is performed using two different techniques: the first, a rigorous statistical assessment of the pre- and post-rehabilitation data, weather normalized to a common heating-degree day year; and the second, a visual review and analysis of average energy consumption pre- and post-rehabilitation as a check.

As discussed in Section 2.1, the portion of energy used for space heat can be determined by taking the monthly consumption and subtracting a non-space heat baseline value. The non-space heat baseline is determined from lowest of the July and August consumption when typically the space heat system operates at a minimum or is turned off. This baseline value is determined by statistical analysis and confirmed visually, and typically the average of the lowest monthly consumption values occurring each year. For most buildings the gas baseline is primarily associated with domestic hot water use (and potentially gas fireplace pilot lights), and the electrical baseline associated with all non-space heat energy.

Using gas billing data from Building 62 as an example in Fig. 2.4.1, the rehabilitation period, and baseline pre and post monthly consumption is noted on the consumption data.

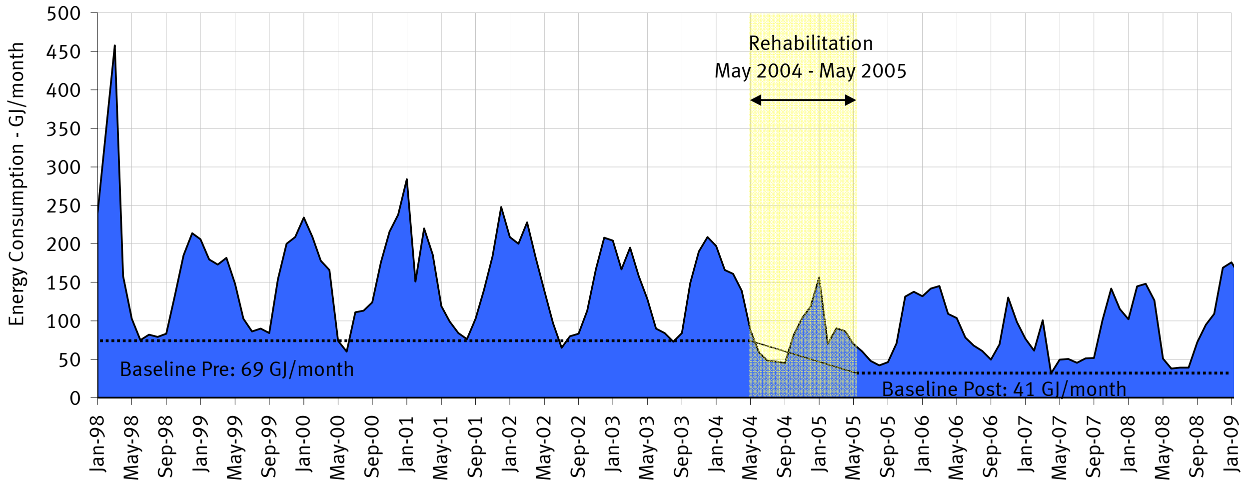


Fig. 2.4.1 Monthly Gas Consumption Billing Data for Building 62, January 1998 to January 2009.

As shown, the rehabilitation had a significant visible reduction in the monthly gas consumption. When plotting the monthly gas consumption versus the HDD value, the reduction becomes even more apparent (Fig. 2.4.2). Various regression analyses are performed to best approximate an equation to the data which relies on the HDD variable input. For the data analyzed in this study, typically a linear or exponential relationship best approximates the monthly energy-HDD relationship for gas and common area electricity and an exponential or 2nd or 3rd order polynomial best approximates suite electrical consumption.

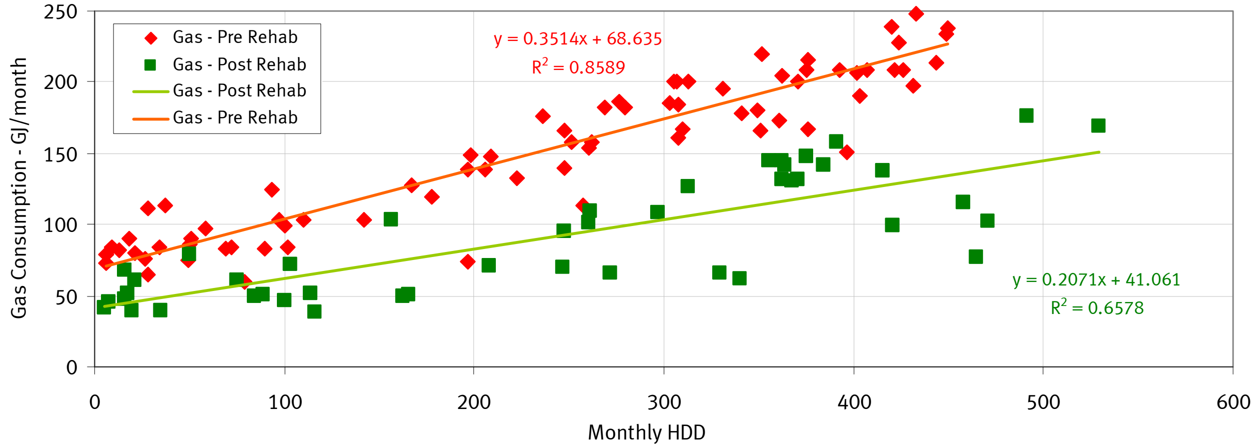


Fig. 2.4.2 Monthly Gas Consumption vs HDD for Building 62, Pre- and Post-Rehabilitation with linear relationships best predicting the gas consumption data.

An analysis is also performed on the electrical billing data. Suite and common electrical data from Building 62 is plotted as an example in Fig. 2.4.3 and Fig. 2.4.4 and versus HDD in Fig. 2.4.5 and Fig. 2.4.6. The rehabilitation period, baseline pre- and post-monthly consumption is noted on the consumption data.

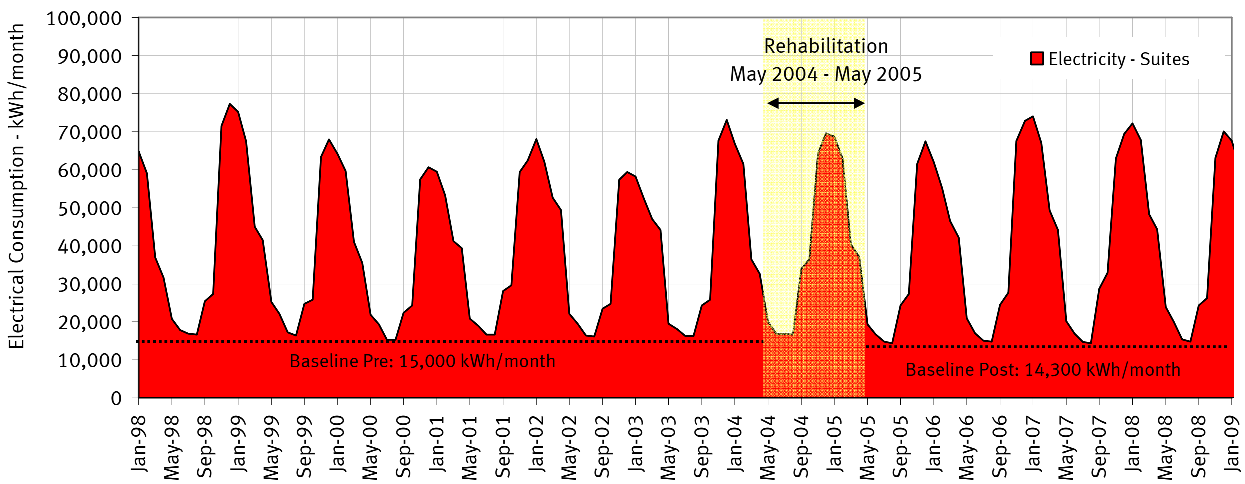


Fig. 2.4.3 Monthly Suite Electrical Consumption Billing Data for Building 62, January 1998 to January 2009.

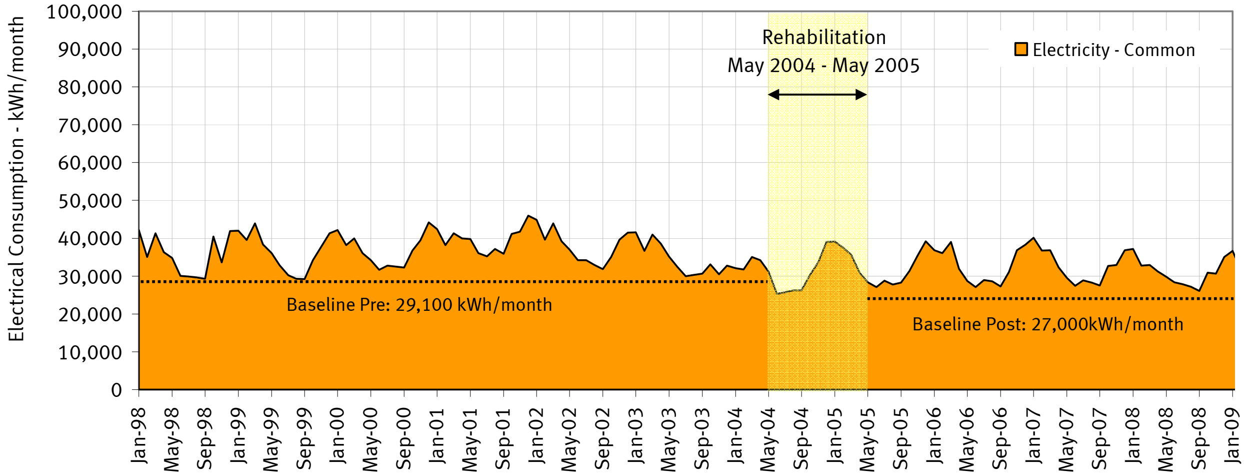


Fig. 2.4.4 Monthly Common Electrical Consumption Billing Data for Building 62, January 1998 to January 2009.

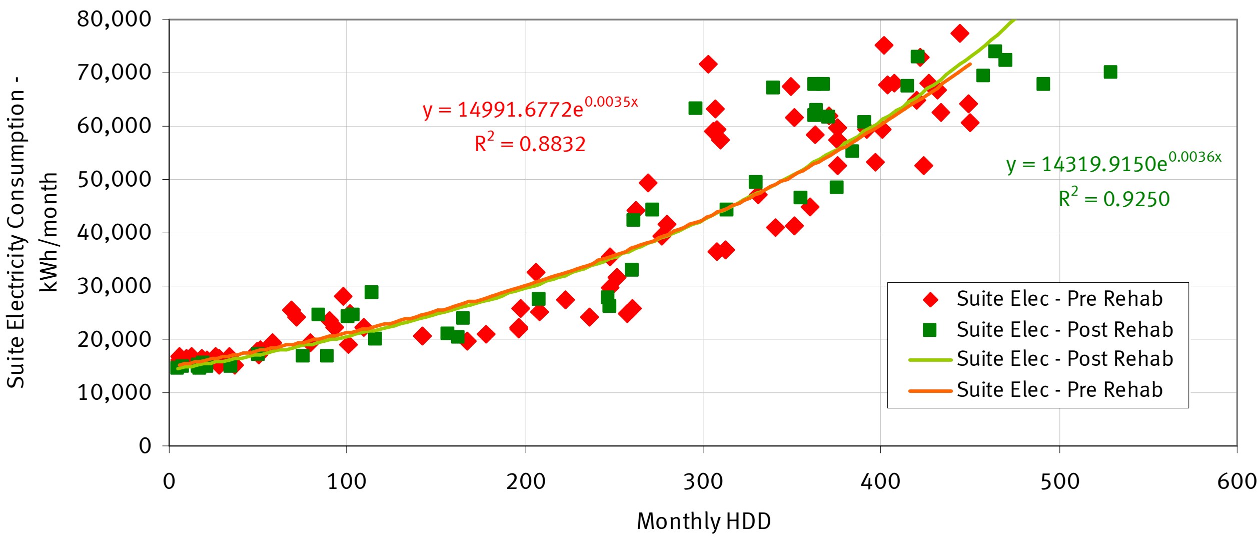


Fig. 2.4.5 Monthly Suite Electrical Consumption vs HDD for Building 62, Pre- and Post-Rehabilitation with exponential curves best approximating the data.

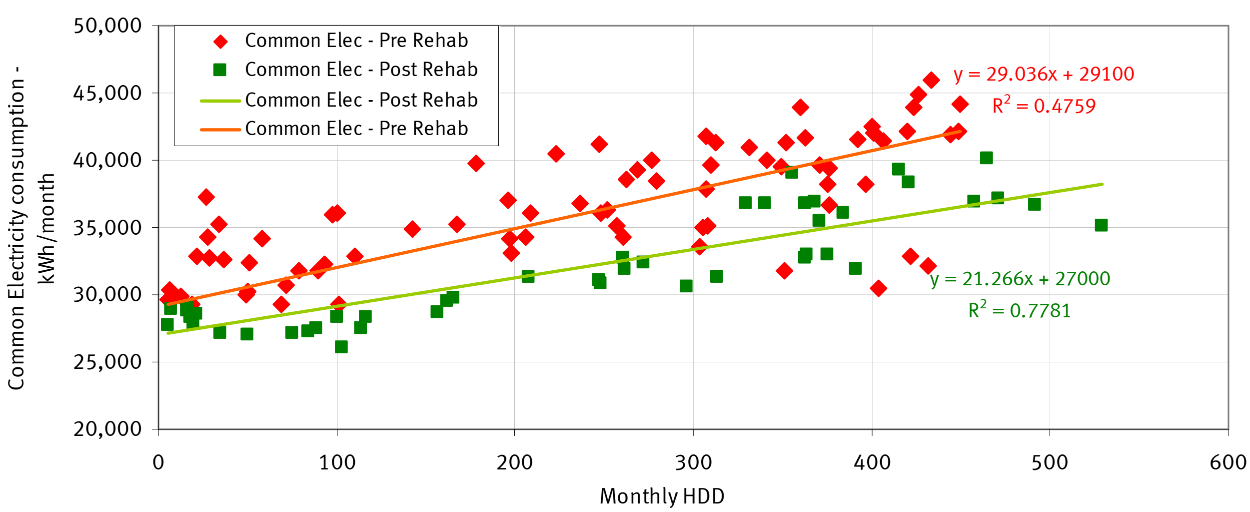


Fig. 2.4.6 Monthly Common Electrical Consumption vs HDD for Building 62, Pre- and Post-Rehabilitation with linear relationships best-approximating the data.

Using the relationships determined for the gas and electrical consumption versus heating degree days, the energy monthly gas and electrical consumption is calculated for a weather normalized year which can then be input into an energy model (which also uses the same weather year for analysis). For Vancouver, this is from the CWEC weather data file and has a total of 3019 HDD. This is higher than the average Vancouver HDD of 2750 observed over the past 10 years. While the relative percentage of savings are the same regardless of the HDD, the dollar energy savings estimates are also calculated for a more typical 2750 HDD average year.

The weather normalized pre- and post-rehabilitation energy consumption is then plotted and compared to determine potential energy savings. This is further shown in Section 6 of this report for each of the 11 case-study buildings that underwent rehabilitation, and the two additional newer buildings.

2.4.2 The Influence of Occupant Behaviour and Control on Space Heating

In analyzing pre- and post-gas and gas and electrical consumption for the 11 detailed study buildings discussed in Section 6, some trends have become apparent in the relationship between Heating Degree Days and space heating energy consumption. This is useful when performing weather normalization of energy data for energy modeling and simulation or for utility demand forecasting.

Typically, it has been assumed that space heating is linearly related to heating degree days to weather normalize utility data. From the analysis of the MURBs in this report, this holds true for space heating energy that is controlled on a thermostat which remains at a constant set-point year round. Make-up air units are a good example of this, as the MAU set-point is based solely on exterior air temperature which is directly proportional to the Heating Degree Day value. Make-up air unit gas consumption tends to dominate the gas space heating use in MURBs so gas use can typically be approximated using linear relationships to Heating Degree Days based on billing data. This linear dependency is shown for Buildings 11 and 18 as is shown in Fig. 3.4.7 and Fig. 3.4.8.

Adjustment of the baseline heating degree day value (i.e. from 18°C to say 15°C or 12°C) does not affect the relationships discussed below. A lower HDD baseline compresses the data at lower HDD values which reduces resolution of the summer to spring/fall months but does not change the relationship. For MURBs it was found for all cases that a 18°C baseline best correlates with the space heating data (gas or electrical). A sensitivity analysis was performed for all buildings on this assumption.

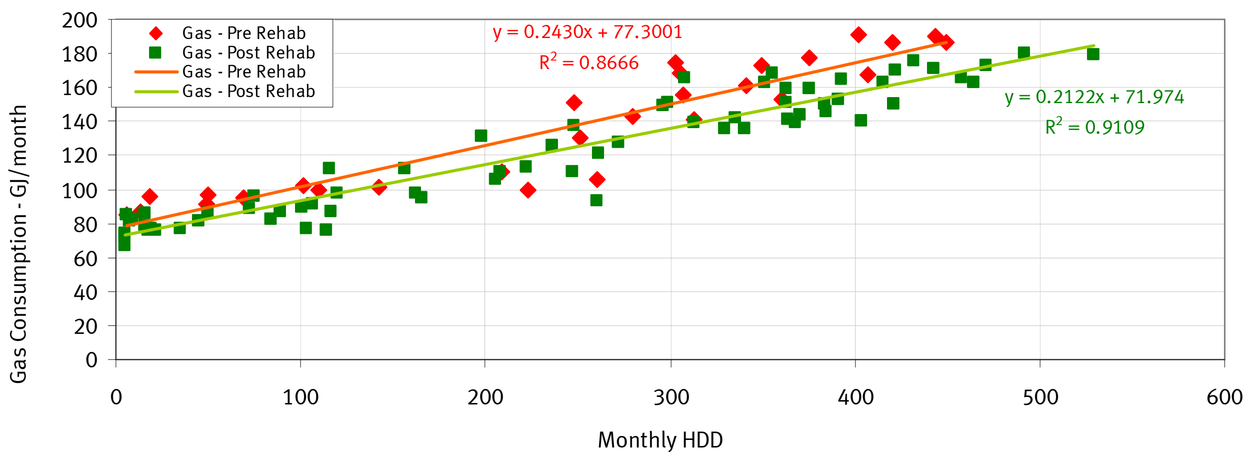


Fig. 2.4.7 Monthly Suite Gas Consumption vs. HDD for Building 11 (Make-up Air Gas Heat Only).

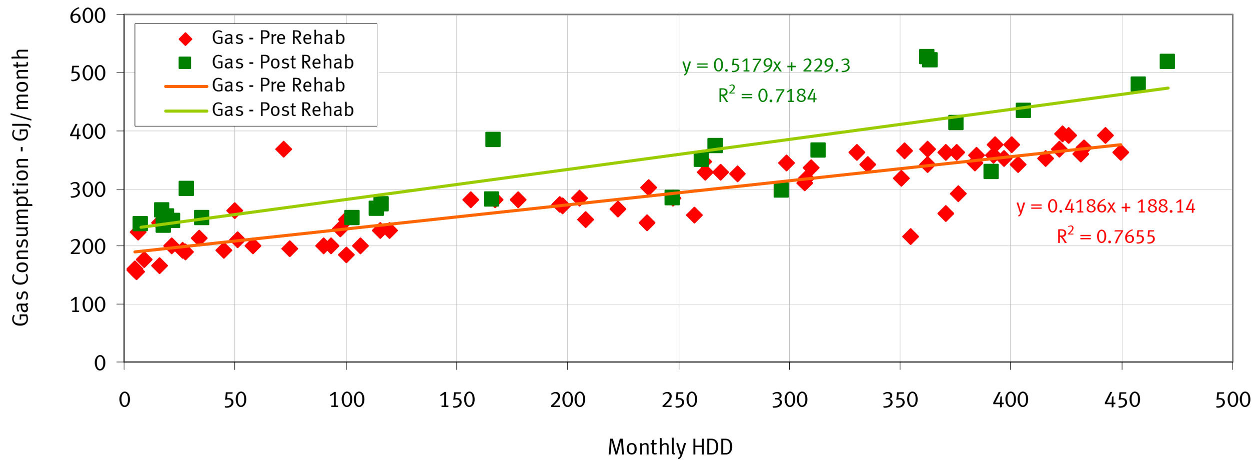


Fig. 2.4.8 Monthly Suite Gas Consumption vs. HDD for Building 18 (Make-up Air Gas Heat Only).

This linear HDD-Space Heat relationship assumption becomes less accurate, however, when looking at MURBs with gas fireplaces. Gas fireplace use is occupant controlled and the relationship between heating degree days and Space heat Consumption is subsequently affected. While gas fireplaces are a space heating appliance, they are often used for decorative/comfort purposes and may only be used at certain times of the day (i.e. when home or during evenings etc.). Pilot lights may also be shut-off during the summer months resulting in zero or low use during months with heating degree days less than 100. Even summer months have some low heating degree day value (typically less than 50 in Vancouver). As a result, the HDD space heating dependency becomes a 2nd or 3rd order polynomial or exponential relationship. This is demonstrated for Building 17 in Fig. 2.4.9 where the only gas use in the building is for fireplaces and for Building 21 in Fig. 2.4.10 where both make-up air and gas fireplaces (in all suites) are present.

The linear HDD-Space Heat relationship assumption also becomes less accurate for hydronic heated buildings as well. Occupants have control over the baseboard thermostat, and make adjustments accordingly during different seasons. Fig. 2.4.11 for Building 19 demonstrates this relationship.

Note that for both Buildings 21 and 19, a linear approximation can approximate space heating with reasonable accuracy because of the dominance of the make-up air heating (linear dependent) space heating in proportion to the fireplaces (occupant controlled non-linear relationship).

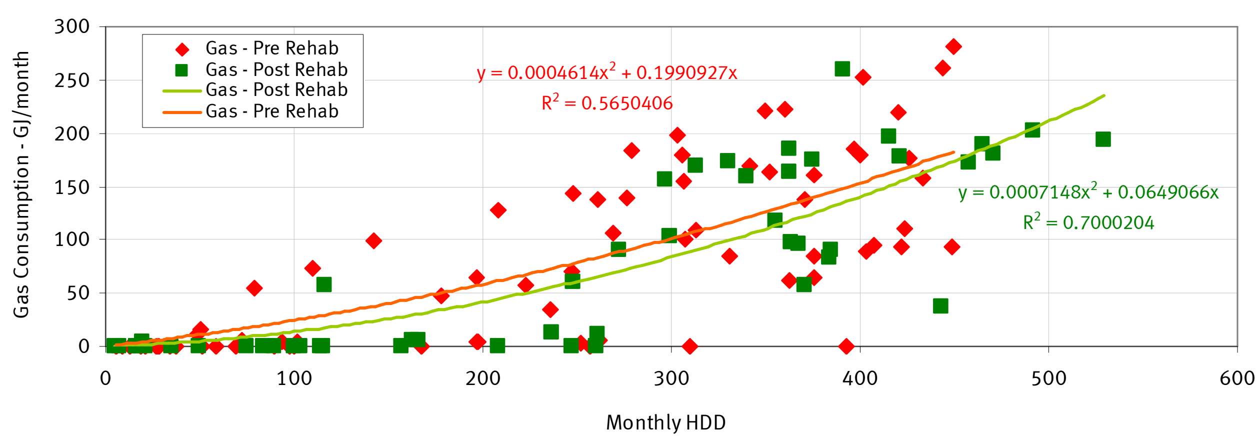


Fig. 2.4.9 Monthly Gas Fireplace Consumption vs. HDD for Building 17 (Fireplaces Only, No Make-up Air).

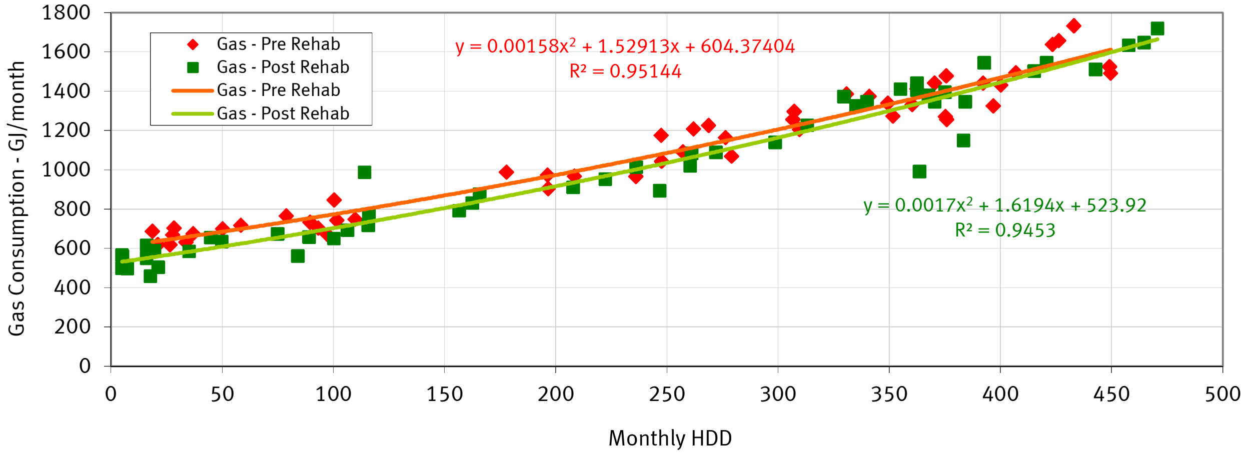


Fig. 2.4.10 Monthly Gas Fireplace Consumption vs. HDD for Building 21 (Make-up and High Proportion of Gas Fireplaces).

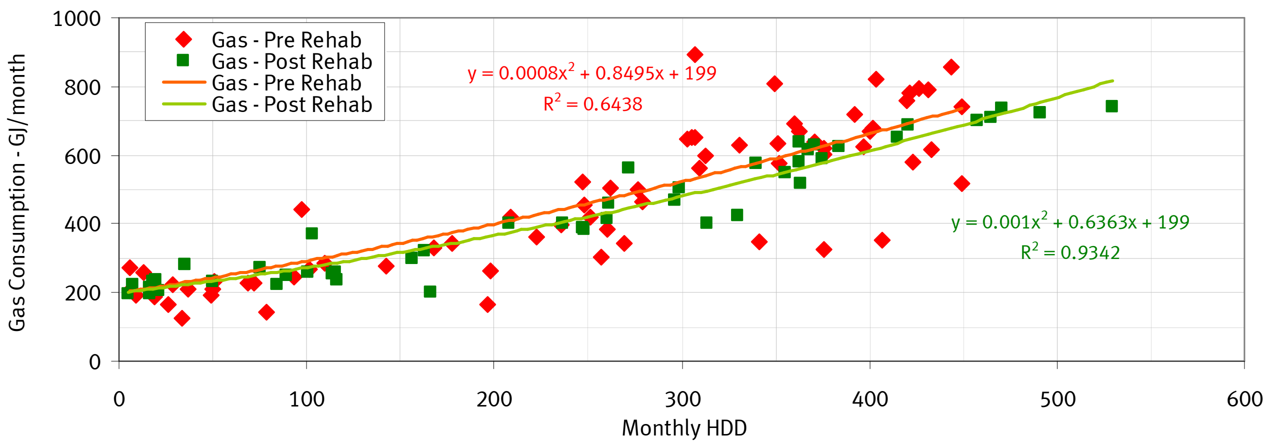


Fig. 2.4.11 Monthly Gas Consumption vs. HDD for Building 19 (Hydronic Gas and Make-up Air Gas).

When analyzing suite electrical data with electric baseboard heating, the relationship between heating degree days is not linear. This is regardless of the baseline HDD value (i.e. 18°C).

From an analysis of the pre- and post-rehabilitation data for 13 buildings, the resulting best-fit HDD-Space Heat relationship is consistently a 2nd or 3rd order polynomial (recall that a linear relationship is a 1st order polynomial) or in a few cases exponential (though a polynomial would also represent the data but not as well). This is concluded based on an analysis of how the best-fit curve visually approximates the data (i.e. representation during all months, particularly swing season), and a review of the R^2 values.

This non-linear correlation accounts for several occupant behaviour factors and how electric baseboard heaters are controlled and condo suites are heated. This includes night-time, zonal, or seasonal thermostat setbacks and seasonal effects during the summer and late spring/early fall months when space heat is off or infrequently used even though there may be a time when the exterior temperature drops below the HDD baseline (i.e. 18°C). In Vancouver, the exterior temperature is frequently below 18°C all year (nights all year round) and even during summer months. Due to thermal mass of these buildings, and the fact that baseboard thermostats are often turned off (or to a very low setting), as much space heat as should be used in the summer and spring/fall is not being used. This is demonstrated for Buildings 32, 17, and 33 within Fig. 2.4.12, Fig. 2.4.13, and Fig. 2.4.14 correspondingly.

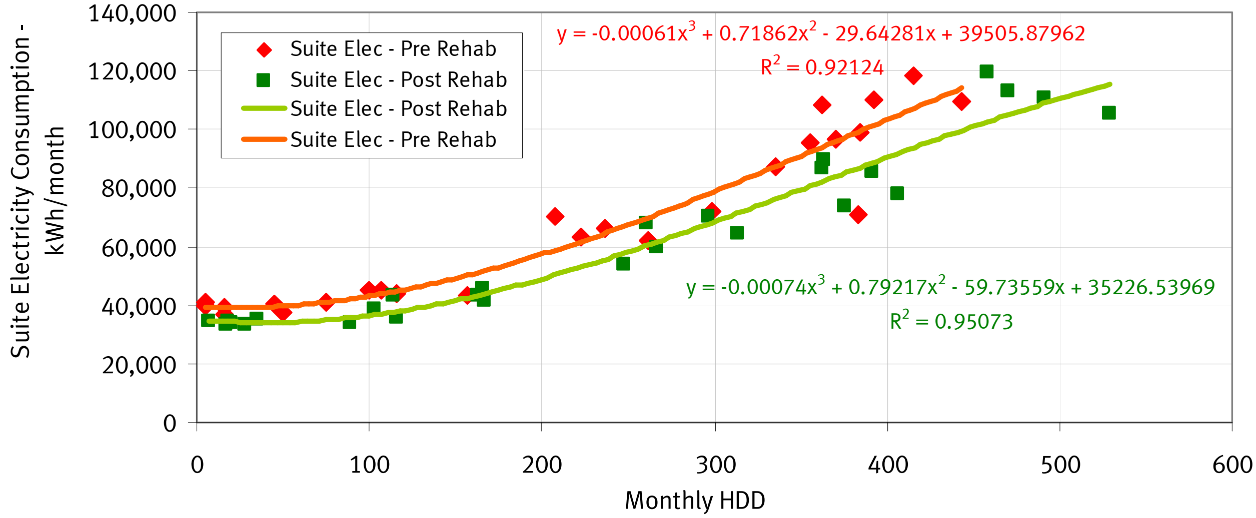


Fig. 2.4.12 Monthly Suite Electrical Consumption vs. HDD for Building 32 – 3rd order polynomial relationship.

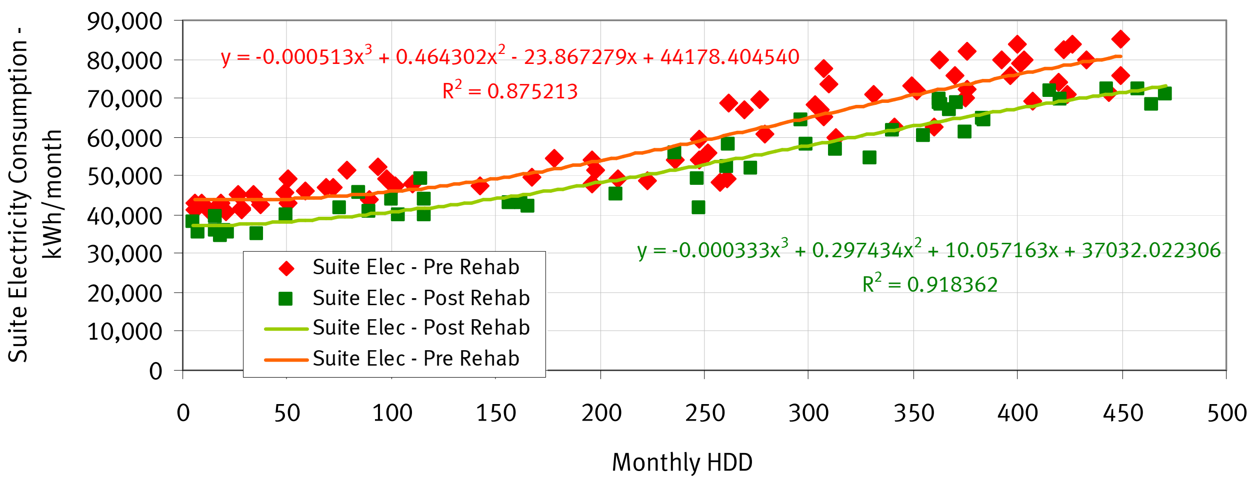


Fig. 2.4.13 Monthly Suite Electrical Consumption vs. HDD for Building 17 – 3rd order polynomial relationship.

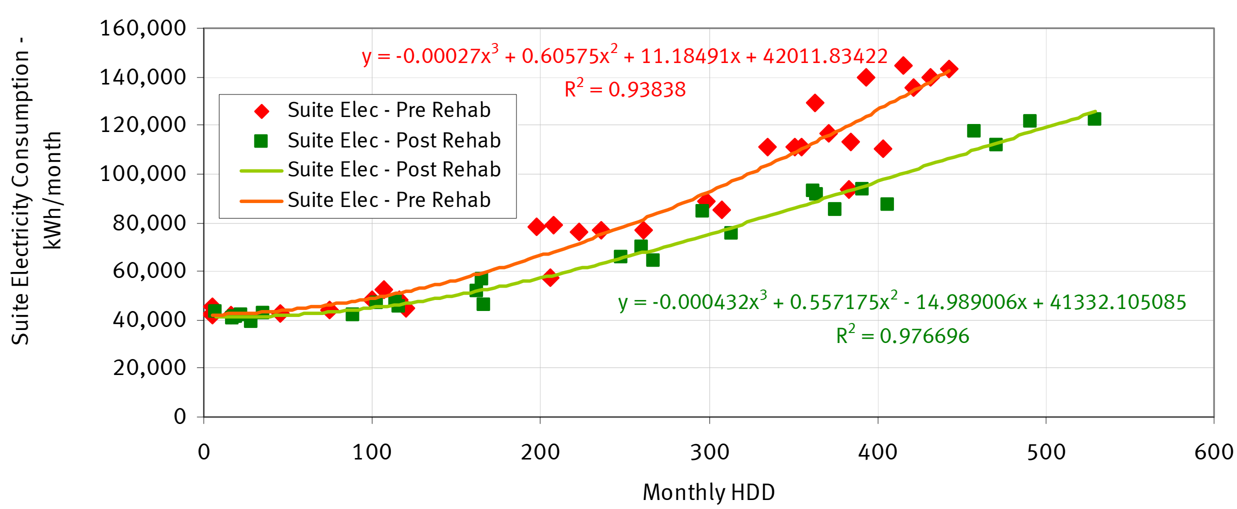


Fig. 2.4.14 Monthly Suite Electrical Consumption vs. HDD for Building 33 – 3rd order polynomial relationship.

When analyzing common electrical data, the relationship between heating degree days and energy use tends to be linear. In addition, the correlation tends to be poor to HDD as space heating energy makes up only a small fraction of the total energy. Therefore when weather normalizing common area electricity there is some uncertainty in the data, and only an average use can be determined.

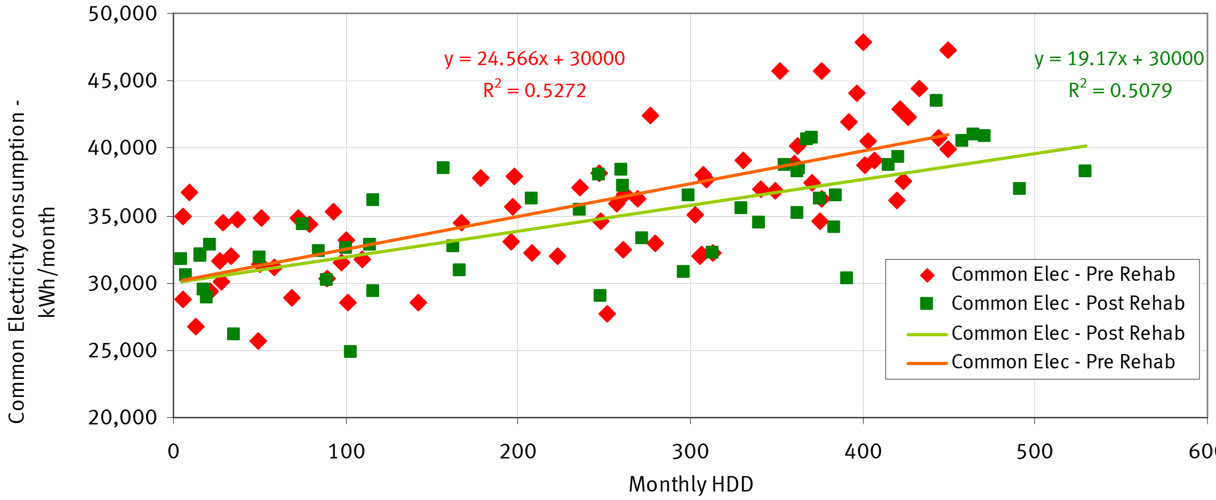


Fig. 2.4.15 Monthly Common Electrical Consumption vs. HDD for Building 17- Linear Approximation.

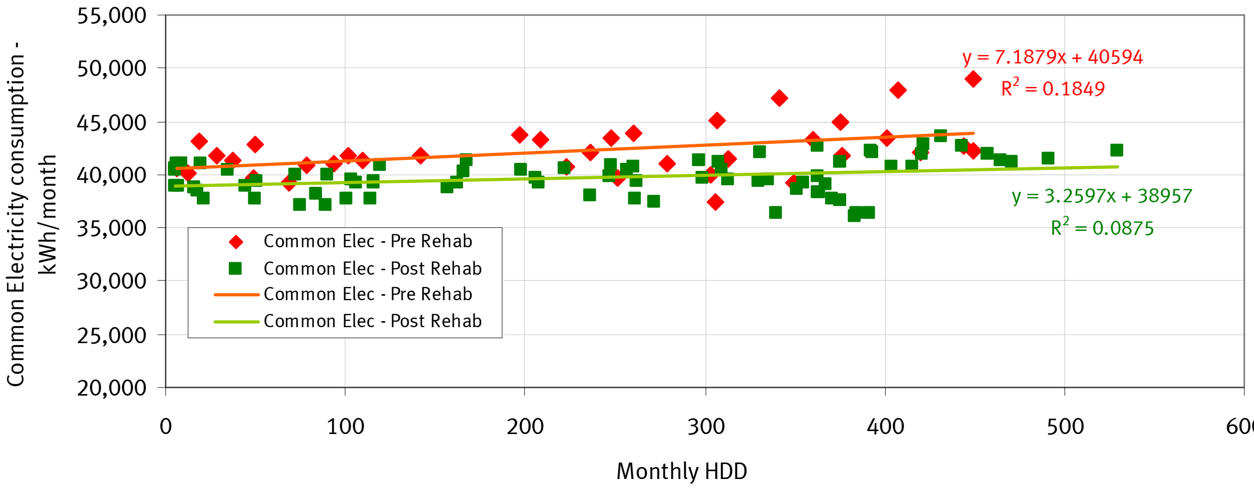


Fig. 2.4.16 Monthly Common Electrical Consumption vs. HDD for Building 11- Linear Approximation.

In summary, the following trends can be applied when using heating degree day to space heating relationships to weather normalize energy data for MURBs. In all cases a review of the best-fit curve should be made to ensure that the approximation represents all seasonal energy use.

- Make-up air gas heat is linearly related to heating degree days. The make-up air set-point temperature is directly related to the exterior temperature. Because make-up air is the most dominant gas space heating energy use, it can overshadow fireplace or even hydronic space heat trends.
- Fireplace gas heat is non-linearly related to heating degree days. Fireplace use is based on occupant behaviour and the relationship tends to be a 2nd or 3rd order polynomial.
- Hydronic gas heat is non-linearly related to heating degree days. Suite space heat use is based on occupant behaviour and the relationship tends to be a 2nd or 3rd order polynomial.
- Suite electric heat is non-linearly related to heating degree days. Suite space heat use is based on occupant behaviour and the relationship tends to be a 2nd or 3rd order polynomial.

- Common electric heat is typically linearly related to heating degree days. Thermostats tend to be set and left at fixed constant temperatures year round. In addition, the amount of common electric heat is so small that any seasonal effects are overshadowed by larger end uses such as elevators, lights etc.

2.5. Site and Source Energy

The differences between site and source energy needs to be considered when assessing whole energy performance of buildings. The energy consumption analysis performed within the report only discusses the site energy for reasons discussed later; however, a discussion of the concept and implications of source energy is necessary as it applies within the Province and BC, and to the rest of Canada and the US. Site to source energy typically affects grid-electricity as the energy required to produce and deliver electricity to a building is much higher than used at the building.

Site energy is the energy used within the building which appears on the monthly bill. For the study buildings this is equal to so many kilowatt-hours of electricity and gigajoules of natural gas.

Natural gas is consumed on site; however, it was extracted from a global source and transported to the building through a transportation and distribution network. Natural gas is a site energy source as the gas is converted into equivalent energy onsite (and therefore has energy conversion efficiency). The site to source ratio for North American natural gas is estimated between 1.047 and 1.09 based on the site-to-source ratios reported respectively by the US EPA EnergyStar Portfolio Manager (2009) and Deru & Torcellini (2007). This factor represents the energy required to extract, process, and deliver the fuel to the building per unit of energy in the fuel assuming normal heating values. The factor of 1.047 to 1.09 is a US national average and does vary by the location of city to the natural gas source; however, if the natural gas were to be sourced, processed and delivered closer to site (i.e. from Alberta direct to BC) this factor would be lower. Fortis BC (Terasen Gas) reports a lower site to source factor of approximately 1.03 for pipeline natural gas within BC on an annual basis which accounts for extraction energy and pipeline and distribution losses.

Electricity is generated at a power-plant and delivered to a site through a series of transmission lines. Within BC, the majority of electricity is produced by hydro-electric dams and, therefore, the power delivered to the Lower Mainland of BC has a low site to source ratio. Hydro-electricity has a source energy factor 1.0, similar to other renewable wind and solar energy. Transmission and conversion losses within BC reduce the amount of electricity that is delivered to site, and BC Hydro publishes a site to source ratio of 1.11 for the Lower Mainland of BC. This will vary with time of day and season and influence of purchasing power from Alberta and the US which has a higher site-to-source factor.

The site to source ratio for electricity delivered within BC is quite low compared to the rest of Canada and North America. These ratios vary state by state, by season and even hourly. This occurs because the power mix is constantly changing to meet daily or seasonal peak loads.

For comparison, the average annual electricity site to source ratios for both Washington and Oregon states is approximately 1.7, higher than BC at 1.11, where the electricity generation make-up is mainly hydroelectric and also influenced by coal and natural gas burning plants. The US national average is much higher at 3.315, mainly influenced by coal, and nuclear and natural gas burning plants. Canadian electricity site to source ratios were not made available other than for British Columbia, but literature suggests a value less than the United States due to the predominance of hydroelectricity in BC, Manitoba and Quebec.

The scope of this project was to analyze the site or billed energy consumption of MURBs within the Lower Mainland of BC. The Provincial site to source ratio for natural gas is 1.03 and the site to source ratio for electricity is 1.11, and therefore no conversions are made within this report to determine source energy. A simple conversion for any data presented here would be to multiply the gas energy by 1.03 and electricity by 1.11 to determine an annual estimate source energy for these MURBs. When extrapolating the results to other parts of the country, appropriate site to source factors could be applied to each of the buildings based on the % energy distribution.

2.6. Energy Modeling and Simulation

Energy modeling was performed to further understand how energy is consumed within MURBs, and to assess the impact of certain parameters. Of the 39 study buildings, 13 buildings were selected for detailed energy modeling. The buildings chosen for energy modeling were selected because they had sufficient, clean data and are representative of MURBs in the Lower Mainland.

An energy model was created for each of the 13 buildings selected for energy modeling. The buildings were modeled using a program called FAST (Facility Analysis and Simulation Tool). This program is an interface that uses the DOE2 engine to simulate annual energy consumption on an hourly basis. The program takes weather data for a typical year as well as inputs that describe the building dimensions, enclosure parameters, mechanical systems and electrical system. The program uses these inputs to calculate energy consumption for a typical year. FAST was developed by EnerSys Analytics and customized to model MURBs.

Architectural inputs for the energy model were obtained through the detailed quantity take-off process discussed previously. These included the floor area, exposed wall area, window to wall ratio, overall wall and roof R-values, window U-value and window solar heat gain coefficient. The infiltration rate was estimated based on research discussed previously. An average infiltration rate was chosen and used to model each of the 13 buildings since the actual infiltration rate of each building was not known.

Certain mechanical systems inputs were known such as the type of system (hydronic radiators versus electric baseboards) and the nominal make-up air flow rate; however, many of the mechanical and electrical inputs were not known. In cases where the required input parameters were not known, standard inputs were selected and used for each building model. This group of models was known as the un-calibrated models, and would be representative of a new building model where there is no existing metered data.

The initial (un-calibrated) output of the models was compared to the metered data for each building. The unknown mechanical and electrical input parameters were varied until the model output matched the metered data. Mechanical parameters that were varied to calibrate the model included make-up air supply temperature, nominal equipment efficiencies, domestic hot water flow rate, fireplace load, heating temperature set-point and baseboard heat output capacity. Electrical parameters that were varied to calibrate the model included light density, plug load density, elevators and miscellaneous common area electrical loads. The result of this process was a reliable, meter calibrated energy model for each building that reflects actual energy consumption.

The meter calibrated energy models are used to analyze the impact of various parameters on building energy consumption, particularly space heat consumption. The majority of the parameters studied were enclosure related; the impact of most mechanical system changes was beyond the scope of this study. However mechanical parameters related to ventilation were included in the study. The calibrated models are used to study the following items:

- Distribution of energy consumption in MURBs.
- The Impact of Individual Enclosure Upgrades on Energy Consumption.
  - Wall Thermal Performance: Increasing the overall effective wall R-value to R-10.0, R-15.6 (compliant with ASHRAE 90.1-2007 for steel frame construction) and R-18.2 (compliant with ASHRAE 189.1-2009 for steel frame construction).
  - Window Thermal Performance: Increasing the window U-value to meet the *BC Energy Efficiency Act* for metal frames, improving windows to double glazed non-metal frames and triple glazed non-metal frames. Also varying solar heat gain coefficient.

- Airtightness or Air leakage Rate: Increase or decrease enclosure airtightness.
- The Impact of Mechanical Improvements.
  - Make-Up Air Temperature Set-point: Varying the make-up air temperature set-point between 74°F (23°C) and 55°F (13°C).
  - Make-Up Air Flow Rate: Decreasing the make-up air flow rate to up to 60% of the nominal flow rate and increasing the make-up air flow rate to a rate typical in modern buildings.
  - Heat Recovery Ventilation: Adding central heat recovery ventilation to the existing make-up air system, or replacing with in-suite heat recovery ventilation.
- The Impact of Combining Energy Efficiency Measures.
  - “Good Practice”: Effective R-10 walls, double glazed non-metal frame windows, low airtightness, and a make-up air temperature set-point of 64°F.
  - “Best Practice”: Effective R-18.2 walls (ASHRAE 189.1-2009 compliant), triple glazed non-metal frame windows, very low airtightness, make-up air temperature set-point of 60°F, 80% central heat recovery.
- The Impact of Modeling Using Nominal Values: The nominal wall R-value and centre of glass window U-value were used in the meter calibrated energy model to view the energy impact (error) of using nominal values.

This analysis was completed for each of the thirteen study buildings selected for energy modeling. The results of the 13 buildings modeled were summarized in two ways. First, the percent savings of each simulation performed was averaged for the thirteen study buildings. Second, a typical building model was created by averaging certain input parameters from the thirteen buildings. The typical building model was used to determine the typical energy impact of each of the parameters analyzed, and to examine other parameters that were not studied for each of the 13 buildings.

3. ENERGY CONSUMPTION

3.1. Total Energy Consumption

Total energy consumption for 39 MURBs is presented in this section. Fig. 3.1.1 presents the total energy consumption for all of the buildings, normalized by gross floor area, sorted from low to high, with the overall electricity and gas energy portions indicated.

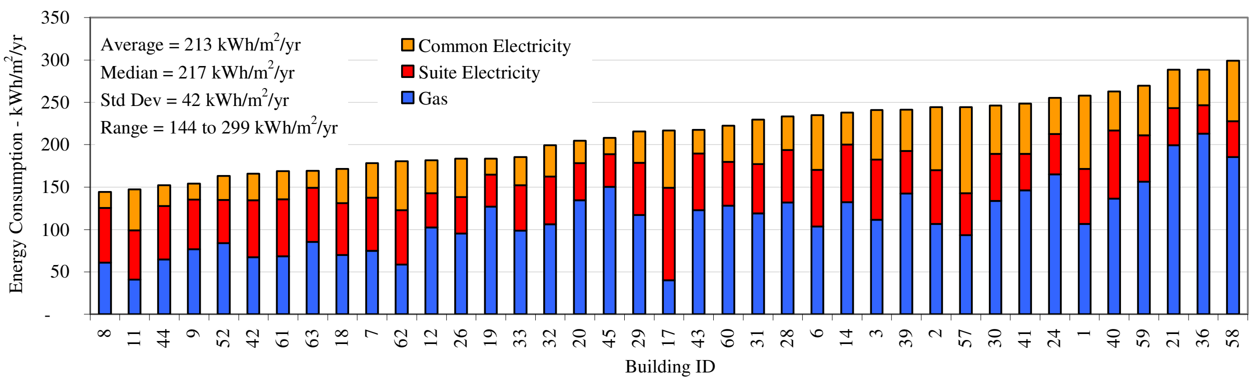


Fig. 3.1.1 Total Energy Usage per Gross Floor Area – Sorted Low to High, Split by Electricity (Common & Suite) and Gas.

Average energy use intensity for MURBs in the Lower Mainland and Victoria is 213 kWh/m²/yr for the 39 buildings analyzed in this study. A range from 144 to 299 kWh/m²/yr was observed in the well distributed sample set[2]. Of the 39 study buildings, 34 are in Metro Vancouver and five are in Victoria. The average for Vancouver is 220 kWh/m²/yr and Victoria is 166 kWh/m²/yr. Per heating degree day, the average energy consumption of the buildings is 0.080 kWh/m²/yr per HDD in Vancouver, where the average heating-degree day (18°C baseline) is 2741 for the study period. In Victoria, per heating degree day the average consumption is 0.061 kWh/m²/yr per HDD where the average heating degree day is 2712 for the study period. The 1971-2000 Environment Canada, 30 year annual average heating degree day value is 2750 for Vancouver and 3040 for Victoria, different than that seen over the past decade.

Comparing energy use normalized per suite, additional averages and trends for total building energy consumption are shown in Fig. 3.1.2, sorted from low to high and noted by study building ID.

[2] Compare the average intensity for MURBs of 213 kWh/m²/yr to 131 kWh/m²/yr for Single Family Dwellings (SFDs) in the Lower Mainland (2011 BC Hydro Estimate for post 1976 Gas and Electrically Heated Homes in Lower Mainland of BC). While MURBs are more densely occupied than SFDs (average floor suite area of 1117 ft² for MURBs [including common areas] versus approximately 1810 ft² for SFDs), MURBs have significantly less enclosure area and share common spaces. In addition, based on the national survey of household energy use, multi-family buildings use only on average 8-10% more energy than single-family dwellings (NRCan 2006). However, the MURBs here in this study are using approximately 63% more energy on a gross floor area than SFDs in the same climatic zone.

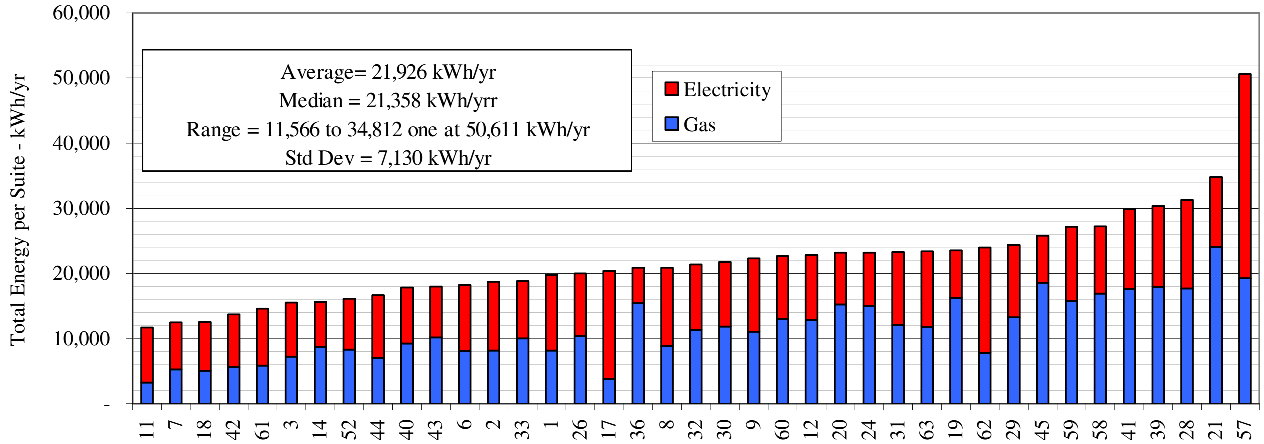


Fig. 3.1.2 Total Building Energy Consumption Normalized by Suite, divided between Total Electricity (Common & Suite) and Gas.

The energy use per suite is on average 21,926 kWh/yr within a range from 11,566 to 34,812 kWh/yr (with one building at 50,611 kWh/yr). Building 57, with the highest consumption at 50,611 kWh/yr is a high-end luxury condominium with suites in the 2000+ ft^2 range and is a building with full amenities including air conditioning, in-suite fireplaces, and common area recreation centre and pool.

From the average total energy use per suite, 10,443 kWh/yr is electricity, and 11,486 kWh/yr (41 GJ/yr) is gas. On average, 5,828 kWh/yr of electricity is typically used within the suite, and the remaining 4,615 kWh/yr is designated common electricity which is apportioned to each suite. Within each suite on average 2,196 kWh/yr of 5,828 kWh/yr (38%) of the suite electricity is used for space heat. On average 51% of the gas used within these buildings is for space heat, therefore, per suite 5,870 kWh/yr (21 GJ/yr) of energy is used for space heat.

From a 2010 BC Hydro internal analysis of 425 high-rise residential condominiums in the City of Vancouver, the average total electricity use per suite is 10,484 kWh/yr. This is distributed into 5,800 kWh/yr of electricity used within the suites and 4,684 kWh/yr of electricity used within the common areas apportioned to each suite. These numbers agree well with the 39 buildings in our study, with the total electricity within <1% and suite and common electricity within <1% per suite. The study buildings are included in the larger population of 425 condominium buildings.

From the same analysis, BC Hydro also analyzed data from 314 rental high-rise residential buildings, where much different totals were found. The total building electricity per suite was on average 4,673 kWh/yr (approximately 45% of the condominiums), with the suite consumption accounting for 2,826 kWh/yr and common area of 1,848 kWh/yr. The difference in electricity consumption between the condominium and rental unit buildings are significant and cannot be fully understood without analyzing the gas consumption, building characteristics, and occupant behaviour within the buildings. Unfortunately this information is not available at the current time. The results indicate that rental buildings may use less energy, but this cannot be concluded without an analysis of gas and other energy sources. As our energy study specifically analyzes data from condominium strata title buildings, the differences between rentals and condominiums is beyond the scope of this project.

Comparable gas consumption data for high-rise residential buildings is not available, nor can it accurately be determined for high-rise residential buildings from previous residential end-use studies.

3.1.2 Total Energy Consumption and Building Enclosure Area

Energy use per exterior enclosure wall area was also calculated for each of the buildings and is presented in Fig. 3.1.3, sorted from low to high and noted by study building ID.

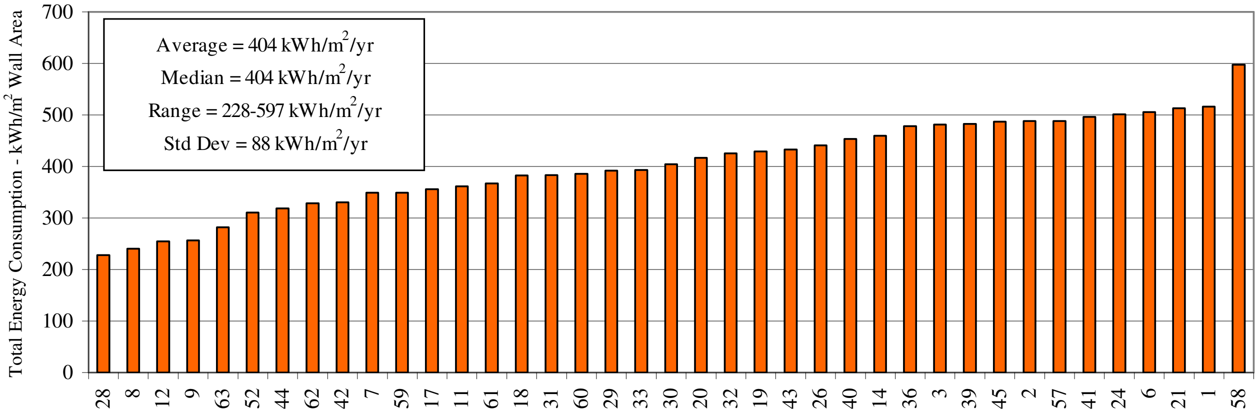


Fig. 3.1.3 Total Energy Consumption versus Gross Exterior Wall Area – Sorted from Low to High.

As the enclosure area is typically between 40% and 60% of the gross floor area for most MURB building forms, energy usage per wall area is accordingly higher. Values range from 220 kWh/m²/yr to 510 kWh/m²/yr in general, with the highest ratio of 597 kWh/m²/yr for Building 58 which is a fairly new building, and appears to be comparatively high.

3.1.3 Total Energy Consumption and Year of Construction

The energy consumption intensity per gross floor area for each of the buildings is plotted in Fig. 3.1.4 versus the year of construction.

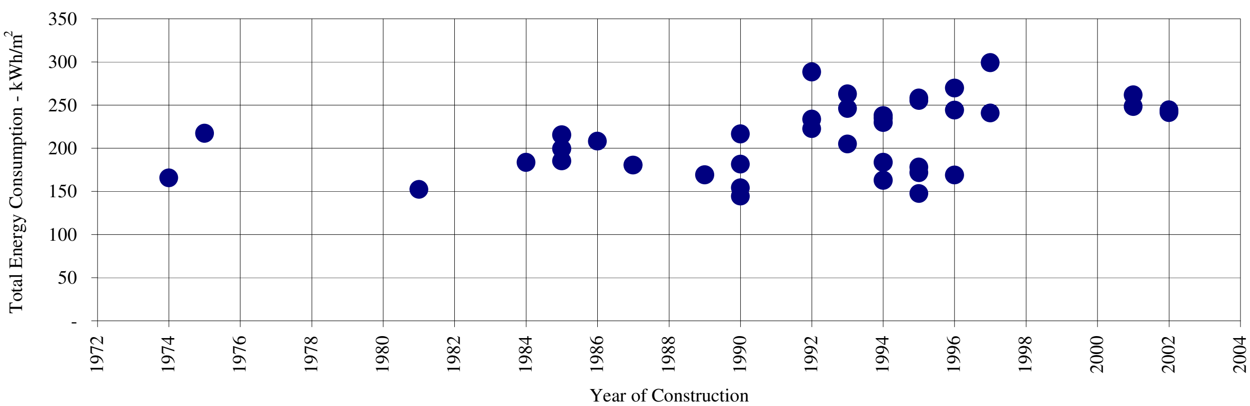


Fig. 3.1.4 Total Building Energy Intensity versus Year of Construction – Consumption in kWh/m²

As shown in the sample set of buildings, the total energy consumption intensity appears to have increased in newer buildings, particularly in buildings constructed from 1990 to 2000. The reason for the increase is likely a combination of factors, including amenities in newer buildings (pools, hot tubs, etc.), building size, and architectural expression (glazing areas, balconies etc.). The median year of construction for the buildings within the study is 1993.

The energy consumption is further broken down by the total space heat contribution within these buildings in Fig. 3.1.5.

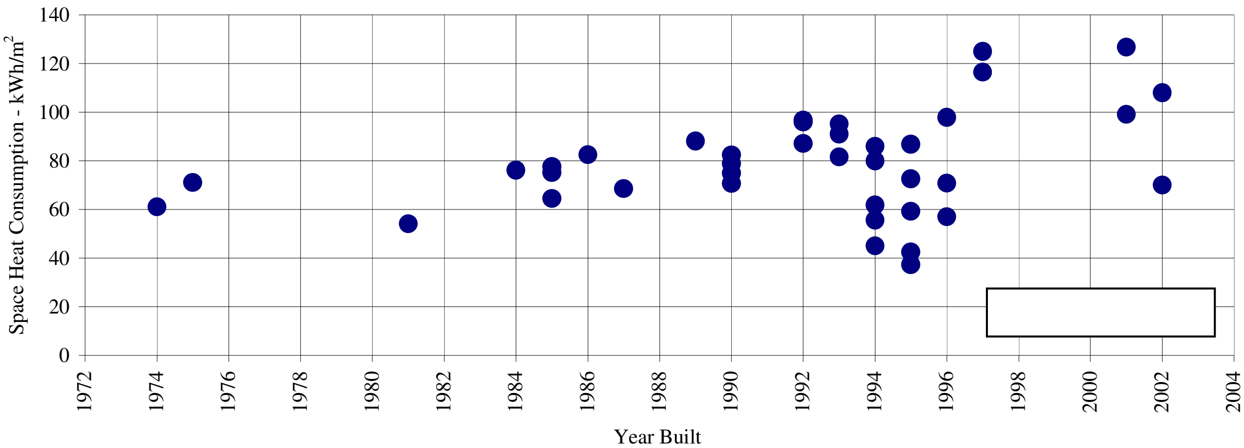


Fig. 3.1.5 Space Heat Intensity versus Year of Construction –Consumption in kWh/m^2.

Perhaps more apparent than the total energy consumption, space heating consumption appears to have increased in newer buildings (particularly those constructed after the mid-1990's). The reason for the increase in space heat cannot be concisely determined, but is likely due to a number of factors including building form, glazing area, insulation values, and mechanical systems. These factors will be further analyzed later in the study.

3.1.4 Total Energy Consumption and Glazing Area

Windows are typically the poorest thermally performing element of the building enclosure. Typical high-rise residential windows in the buildings in this study consist of thermally or even non-thermally broken aluminum frames (older buildings) with insulating glazing units with or without low-e coating and air fill. The overall thermal resistance (R-value) for such windows in these buildings is approximately R-1.5 to R-2.5 when accounting for the thermal bridging through frames. Non-combustible walls comparatively have overall R-values of R-4 to R-10, depending on the construction type. The higher the glazing percentage, the closer the overall R-value is to the low window R-value. Air leakage through older window frames also has a significant impact on energy consumption.

The ratio of window to wall area has increased with the architectural movement towards entirely glass clad high-rises in the Lower Mainland. Traditionally, punched windows were inserted into rough openings within exterior concrete or steel-stud infill walls and accounted for 20-40% of the wall area. Window-wall or curtain-wall systems which make-up the entire exterior wall area have become more popular with architects, developers and building owners wishing to maximize views with floor to ceiling glass. Typically in window-wall systems, glazing areas of up to 80% are common, with the remaining 20% made up of opaque spandrel panels at slab edges.

The glazing percentage for each of the buildings is plotted versus the year of construction in Fig. 3.1.6.

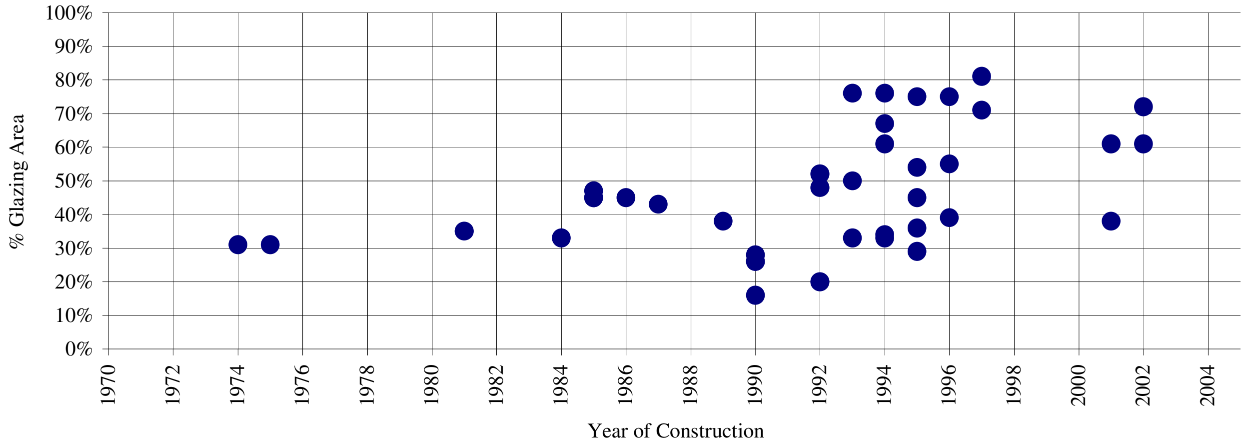


Fig. 3.1.6 Percent Glazing Area versus Year of Construction.

As shown, a movement towards higher glazing percentages occurred in the early 1990's, when glazing areas of up to 80% became relatively common with the new architectural styles. These higher glazing areas appear to have influenced the total energy consumption intensity as shown in Fig. 3.1.7 and specifically, the space heat consumption as shown in Fig. 3.1.8.

Fig. 3.1.7 Total Energy Intensity versus Percentage Window Area.

Fig. 3.1.8 Space Heat Energy Intensity versus Percentage Window Area.

There appears to be a trend between the glazing area (and subsequently reduced overall building R-value), and total energy and space heat energy consumption. The more detailed influence of overall enclosure R-value, including effects of glazing area on space heat consumption, are further analyzed later in this report.

3.2. Distribution of Space Heat Energy

The buildings in the study have similar mechanical systems, with centrally provided gas heated ventilation air to pressurized corridors, and electric baseboard heaters within suites. Buildings 19 and 45 have hydronic heat baseboard heaters in suites instead of electric baseboard heaters. Several of the buildings have in-suite gas fireplaces in some of the suites (i.e. at penthouse suites). Buildings 21, 36 and 58 have fireplaces within all of the suites, and based on the gas consumption data, appear to be providing much of the space conditioning heat to the suites. The distribution of energy which is used for space heat, for both electricity and gas, is shown in Fig. 3.2.1. Furthermore, the percentage of space heat which is from gas sources, is shown in Fig. 3.2.2.

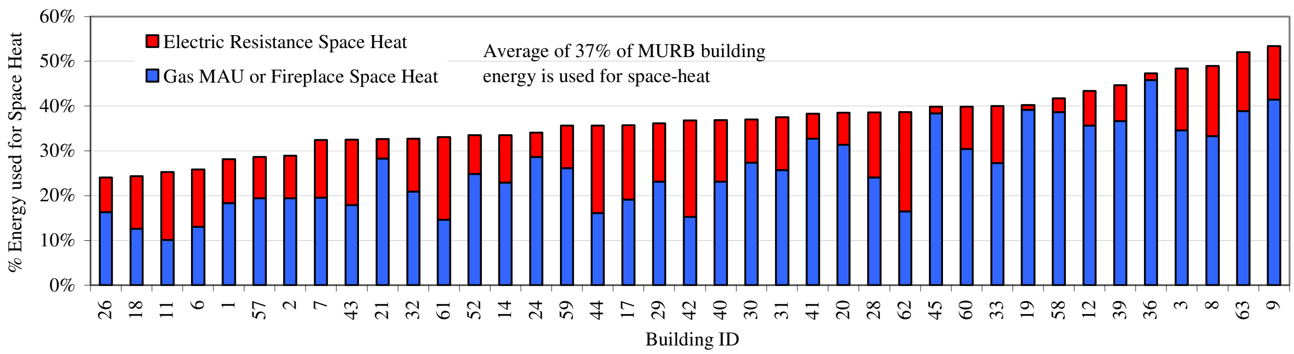


Fig. 3.2.1 Approximate Percentage of Total Energy which is used for Space Heat, Split by Portion of Gas and Electricity.

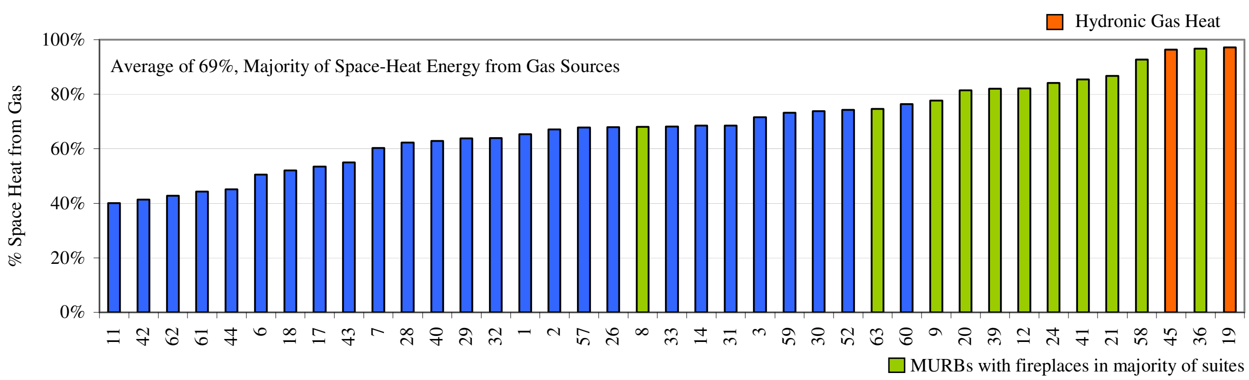


Fig. 3.2.2 Approximate Percentage of Total Building Space Heat which is from Gas Energy.

As shown, the predominant space heat energy source by analysis of the actual energy use of these MURBs is gas. Even in buildings without gas fireplaces, gas remains the predominant space heat source due to tempering of ventilation air. This space heat gas is that used to heat the air within the make-up air units for ventilation. Only five of the buildings have less than 50% of their space heat energy from gas heat (provided by make-up air unit), with none less than 40%.

Removing the hydronic heated buildings from the population data set has a negligible impact on the overall averages, and instead of 69% space heat from gas, the non-hydronic buildings use on average 67% of space heat from gas sources.

3.3. Influence of Predominant Energy Source on Consumption

The influence of predominant energy source and specifically the predominant space heat energy source is analyzed in an attempt to understand the differences in energy consumption within the buildings of the study.

Consider the total energy consumption for each building plotted against its gross floor area in Fig. 3.3.1. As shown, there are an equally distributed set of more and less efficient buildings than the average of 213 kWh/m²/yr. It is of interest to understand why these buildings are more or less energy efficient.

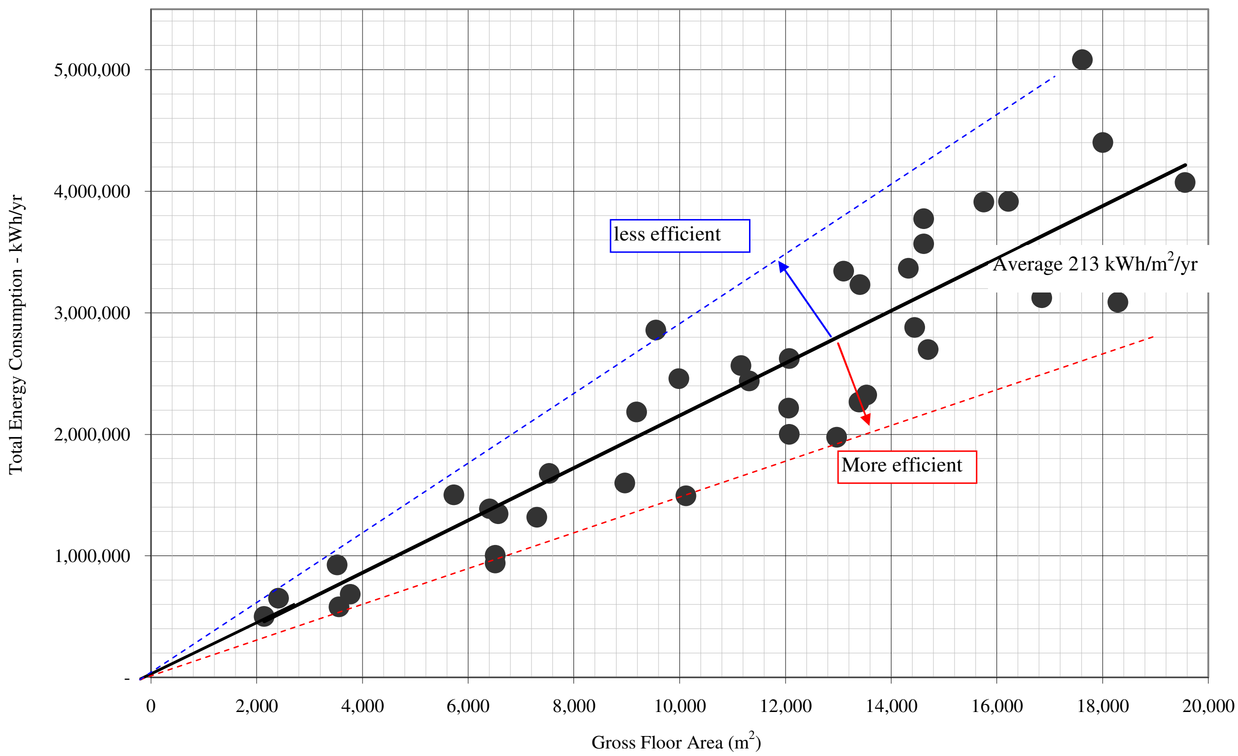


Fig. 3.3.1 Total Energy Usage versus Gross Floor Area.

To understand which buildings are more efficient, the buildings are grouped by predominant energy source. Four categories were developed for the analysis:

- gas dominant (>55% of total energy consumption is gas) – 13 of 39 buildings,
- electricity dominant (>55% of total energy consumption is electricity) – 13 of 39 buildings,
- no dominant consumption (gas/electric consumption is between 45 and 55%) – 11 of 39 buildings, and
- hydronic gas heat – two of 39 buildings.

Using the same data-points as in the previous figure, the categories are highlighted in Fig. 3.3.2. Trend lines have been approximated to indicate the differences in total energy consumption versus the dominant energy source. Not all buildings fit the correlation, and possible reasons for discrepancies are noted. While the population is statistically insignificant, the purpose is to highlight the relative differences in the study buildings.

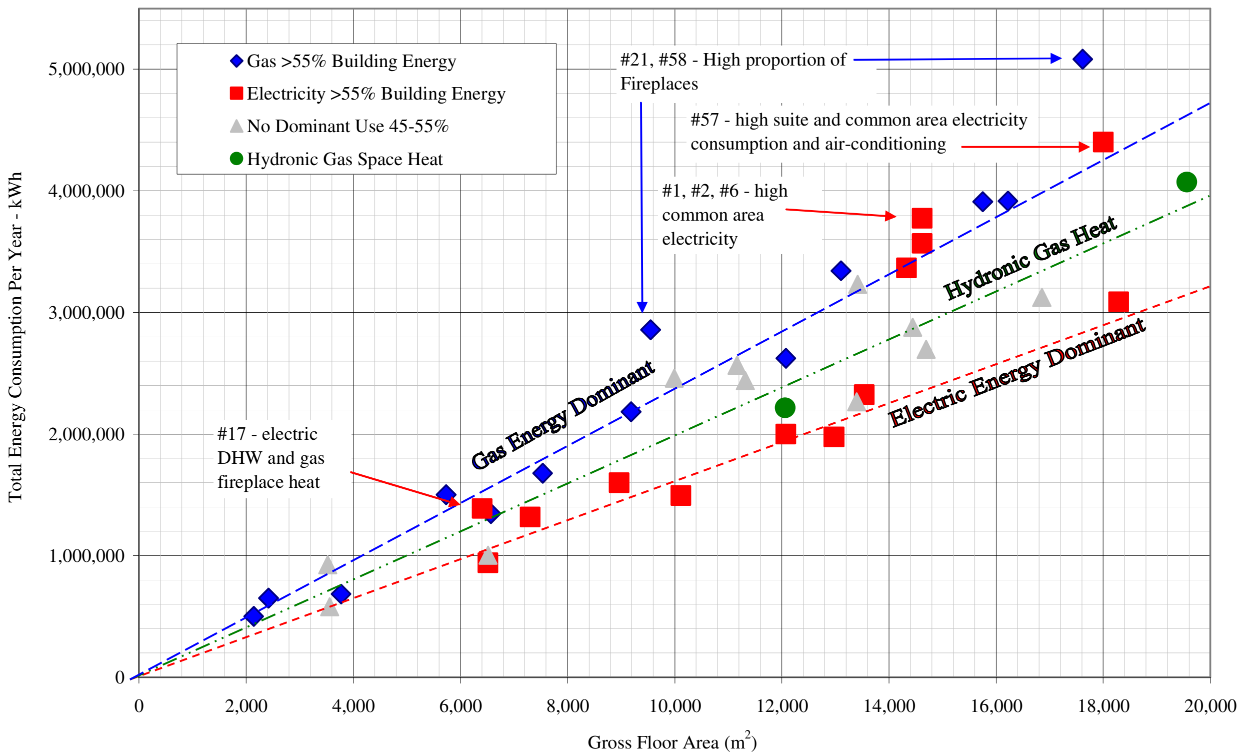


Fig. 3.3.2 Total Energy versus Gross Floor Area, Split between Gas and Electric Energy Dominated Buildings.

From the plot, it is shown that the gas energy dominated buildings use on average more energy than the electric dominated buildings. This is largely attributable to the efficiency losses of gas appliances. In the dataset above, the average consumption for all buildings is 213 kWh/m^2/yr, whereas the gas dominated buildings use on average 238 kWh/m^2/yr, the hydronic gas buildings 200 kWh/m^2/yr, and the electric dominated buildings 160 kWh/m^2/yr.

As it is apparent that the space heat energy is the driving contributor to the energy consumption between buildings, the total space heat portion of the buildings energy is analyzed in greater detail. Four slightly different categories were developed, specific to the space heat contribution:

- gas space heat >70% of the total space heat (lesser contribution of electric baseboards) – 15 of 39 buildings,
- gas space heat <55% of the total space heat (higher contribution of electric baseboards) – 9 of 39 buildings,
- gas space heat >55% and <70% - 13 of 39 buildings, and
- hydronic gas heat – two of 39 buildings.

The total space heat consumption intensity is plotted against gross floor area in Fig. 3.3.3. Trend lines again have been approximated to indicate the differences in space heat energy versus the dominant energy source.

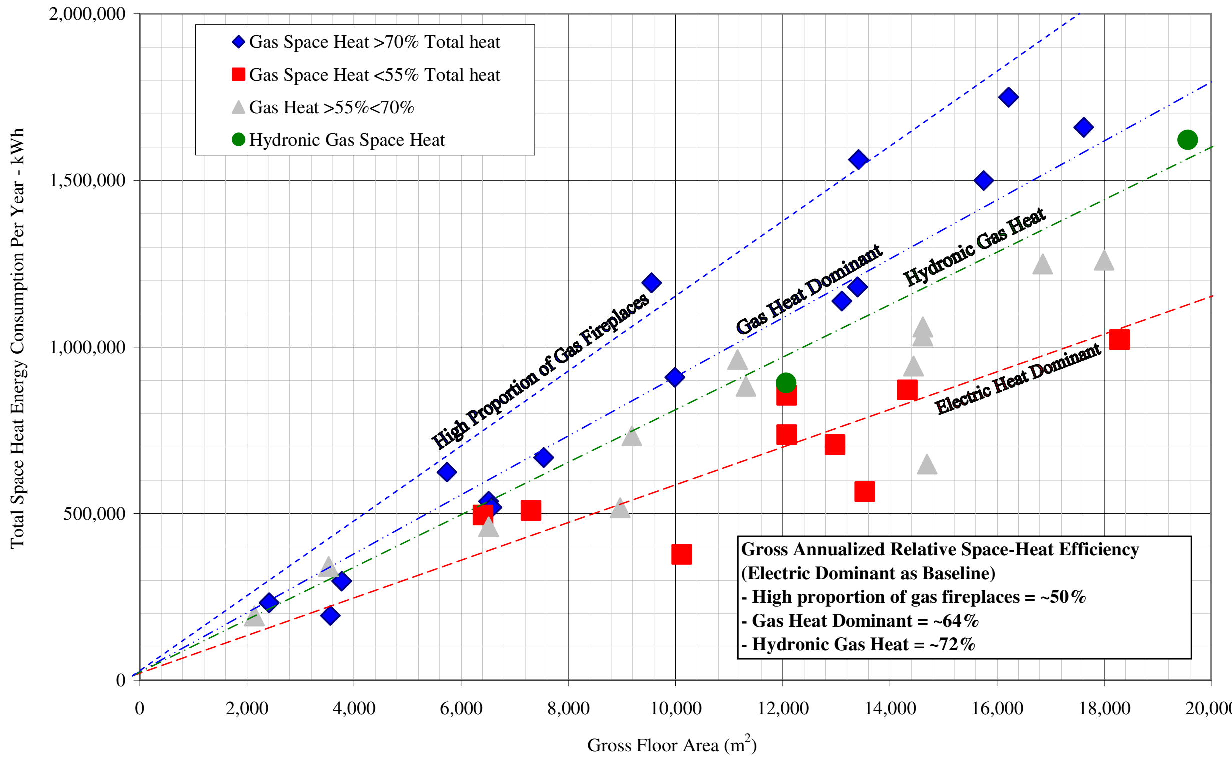


Fig. 3.3.3 Space Heat Energy versus Gross Floor Area, Split between Gas and Electric Space Heat Dominated Buildings.

Here, the differences in buildings become even more evident. A gross annualized relative space heat efficiency factor was determined for each of the building types compared to the electric baseline. Those buildings with a high proportion of gas fireplaces used for space heat have an efficiency factor of approximately 50% compared to the electric dominated buildings. Those buildings which are more gas dominant (i.e. higher contribution of make-up air ventilation to suites) have an efficiency factor of approximately 64%. The hydronic gas space heat buildings have an efficiency factor of 72%. These factors would be lower still compared to an entirely electric space heated building (100% site heat efficiency), however, the baseline "electric dominated" category of building still relies on gas for ‹55% of the space heat. The use of modeling in the later sections of the study further considers heating system efficiencies.

For comparison, equipment efficiencies of the gas space heating appliances are approximately 80% for the hydronic gas-heat boilers, 75-80% for the make-up air ventilation units, and much less for gas fireplaces. Therefore, the efficiency factors developed for the buildings as a whole are comparable, and expectedly less to account for distribution and other system energy losses. Energy modeling can assist with the determination of the space heat system efficiency factors.

The data in Fig. 3.3.3 is normalized using the gross building floor area and presented in Fig. 3.3.4 to further demonstrate the differences in space heat energy consumption efficiencies.

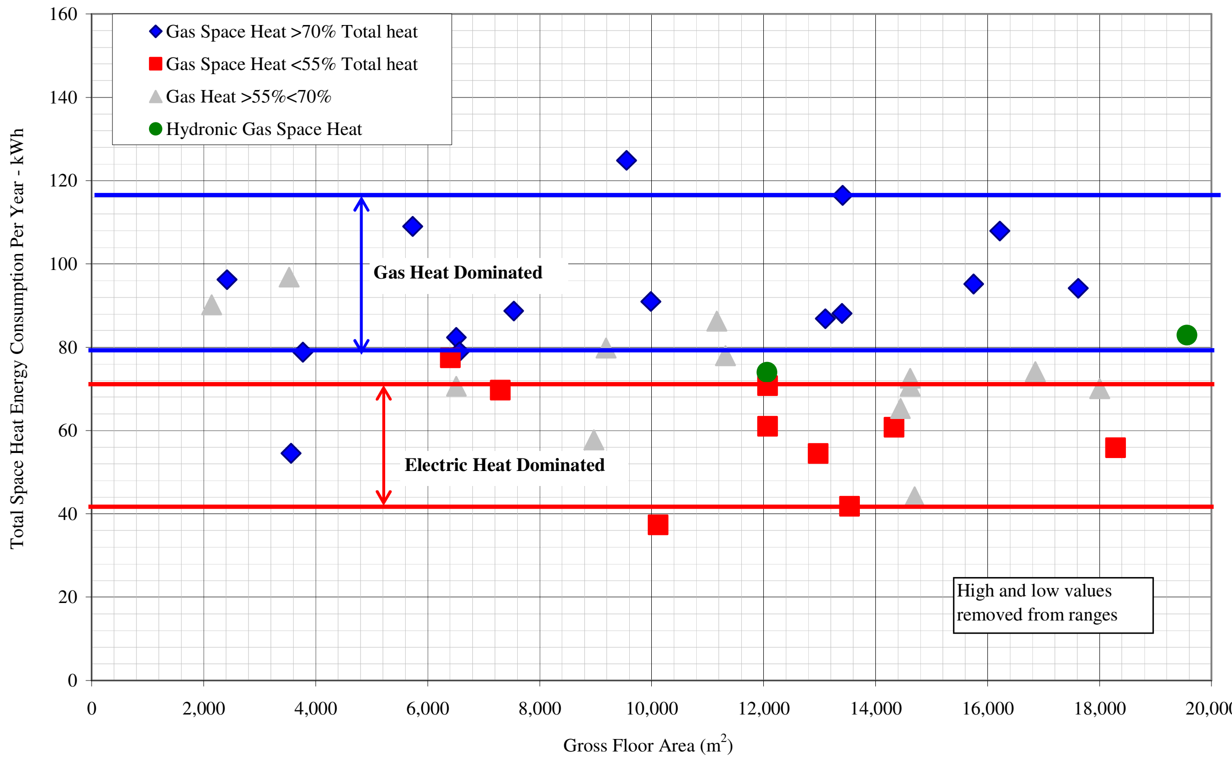


Fig. 3.3.4 Normalized Space Heat Energy plotted against gross floor area.

As shown, if the low and high values from each dataset are removed, distinct space heat intensity ranges are provided for gas heat and electric heat dominated buildings.

The data shows that while MURBs are being designed as electrically heated (with the exception of the two hydronic buildings) and have electric baseboards in suites, the majority of purchased space heat energy is from gas. This is apparent for buildings containing gas fireplaces; however, this trend is shown even in MURBs without fireplaces, where heated ventilation air is the majority of space heat energy consumed.

Fig. 3.3.5 plots the normalized gas and electric space heat energy versus the percentage of energy which is gas to demonstrate the impacts of inefficient gas fireplace consumption on electrical space heat, and total space heating consumption. The gas (blue diamonds) and electric (red circles) space heat consumption is plotted for each building and for each building lines up vertically. The total space heat consumption for a specific building is the sum of both, as indicated by the small black dashed lines above.

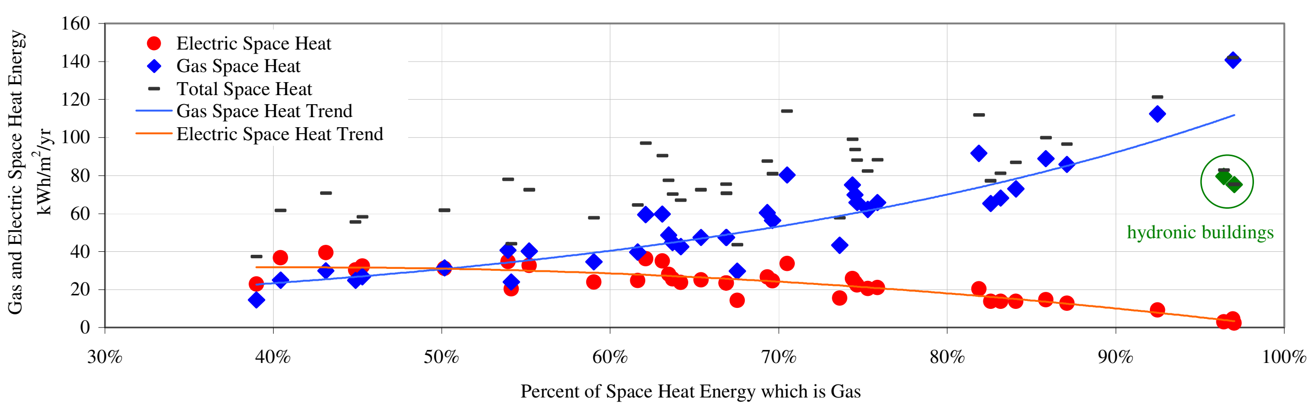


Fig. 3.3.5 Consumed Gas and Electric Space Heat Energy versus Percent of Space Heat with is Gas.

The data indicates that on average, MURBs which have 40-70% of the space heat from gas do not have gas fireplaces and that an increasing trend in gas consumption in those buildings can be attributed to higher ventilation rates or MAU system inefficiency. Electric baseboard heat in these buildings remains on average between 20 and 40 kWh/m^2/yr, but slightly decreases as more make-up air heat is provided. The MURBs which have greater than 70% of the space heat from gas typically contain fireplaces, and the fireplace use (while inefficient) results in less electrical space heat consumption (below 20 kWh/m^2/yr). The increase in gas space heat energy is higher than the reduction in electricity showing the effect of the lower fireplace efficiency. This is particularly apparent for Building 36 (newer building with gas fireplaces) on the far right where the gas space heat accounts for 140.7 kWh/m^2/yr (97%) and electrical 4.4 kWh/m^2/yr for a total space heat of 145.1 kWh/m^2/yr. Compare this to a building at 50% gas-heat without fireplaces where both the gas and electrical space heat accounts for 31.4 kWh/m^2/yr for a total space heat of 62.8 kWh/m^2/yr, 82.3 kWh/m^2/yr less than Building 36. Even the older hydronic buildings only consumed a total of 80 kWh/m^2/yr (both hydronic and MAU gas with ‹80% efficiencies). Considering the total average energy consumption is 213 kWh/m^2/yr for a MURB a space heat consumption of 145 kWh/m^2/yr appears to be excessively high.

The analysis demonstrates that gas fireplaces in MURBs are a hurdle in terms of energy efficiency both because of occupant behaviour in use and heating efficiency. Heating ventilation air using central make-up air units also contributes to a large portion of the space heat consumption of a MURB and higher ventilation rates as the result of design and building code changes between 1980 and 2000 have resulted in a significant increase in gas consumption. This is further discussed in the following section.

For the 39 study buildings, on average 69% of the purchased energy for space heat is for gas, with a range from 40% to 97%.The remaining 31% of the space heat is used by electric baseboard heaters (the design heating system) with a range from 3% to 60%. This electrical space heat accounts for 38% of the suite electricity consumption (range of 6 to 61%).

Gas fireplace heat partially offsets electric baseboard heat use; however, the inefficiency of gas fireplaces results in very high overall space heating loads for those buildings with gas fireplaces – which significant affects total building energy use and compared efficiency. It is likely that the gas for fireplaces could be reduced by sub-metering and charging occupants for use, however, inefficiencies with commercially available residential fireplaces indicates that they are a poor choice as a space heating appliance compared to alternate systems.

3.4. Additional Trends Affecting MURB Energy Consumption

Several trends became apparent in the analysis of the energy data. Firstly, the average energy consumption intensity (both natural gas and common electricity) within mid- to high-rise condominium MURBs appears to have increased over the past 20 to 40 years. This is illustrated in Fig. 3.4.1 which plots the year of construction with each building's space heat and total energy consumption intensity.

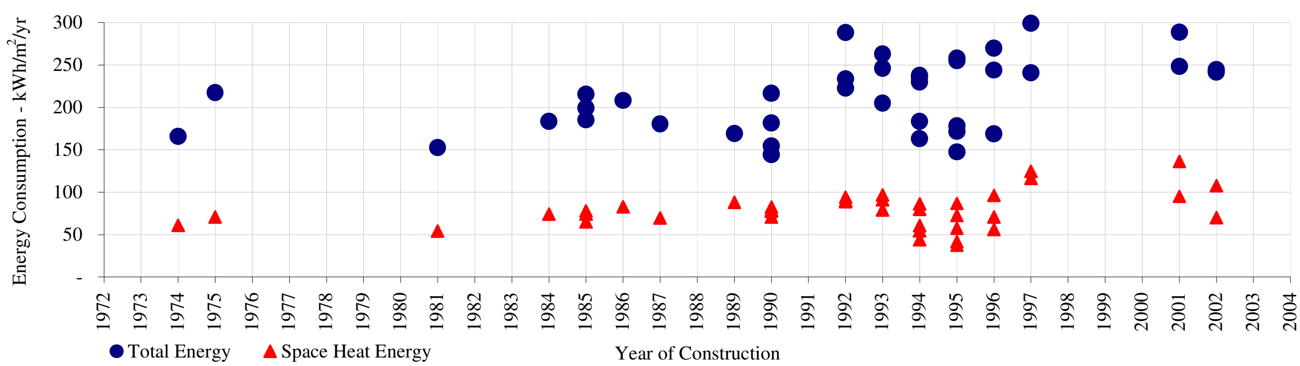


Fig. 3.4.1 Total and Space Heat Energy Consumption of study MURBs by Year of Construction.

The largest influence in the increase in total energy consumption appears to be an increase in energy for space heat. Interestingly, the average electricity consumption and electrical space heat has not significantly changed based on the age of building. In fact, the data would suggest a slight decrease in electrical space heat with the inclusion of gas fireplaces in newer buildings and higher MAU flow rates as previously demonstrated. This indicates that the gas space heat for ventilation and fireplaces (and the efficiencies thereof) is one of the largest influences on the increase in MURB energy consumption and as shown in Fig. 3.4.2.

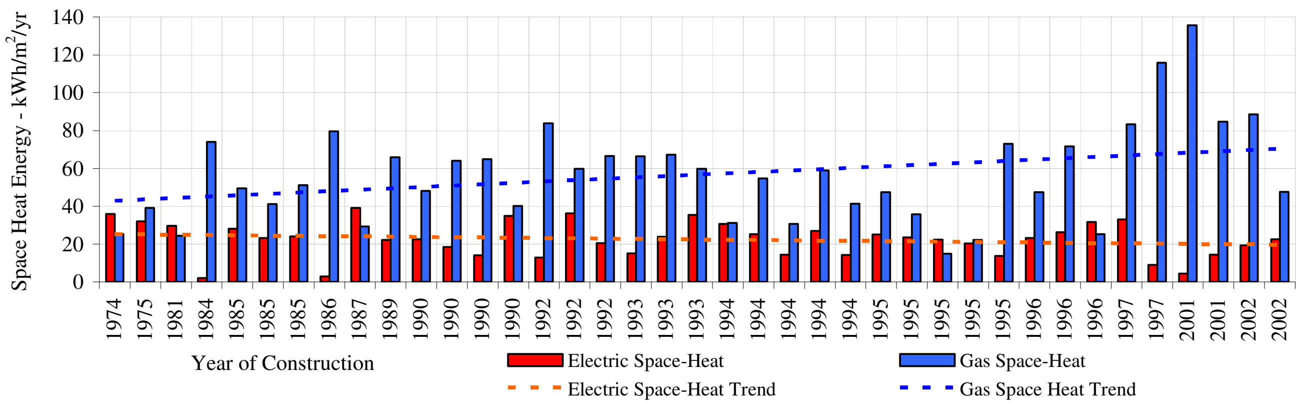


Fig. 3.4.2 Gas and Electric Space Heat Energy by Year of Construction.

The two hydronic buildings (19 and 45) that were originally constructed in 1984 and 1986 consume minimal electric space heat. Buildings with gas fireplaces are also anomalous since the ratio of gas to electric space heat is disproportionate. For example, the two buildings constructed in 1997 and 2001 include gas fireplaces and electric baseboard heaters; however, the data indicates the electric heat is rarely used compared to the fireplaces.

Other factors influencing higher energy consumption intensities in newer MURBs include increased common electricity from amenities such as larger lobbies, gyms and so on in newer buildings and increased mechanical loads from fans, pumps, elevators and so forth in more complex and taller buildings.

The effective thermal performance of the study buildings has not significantly improved over the past 40 years. While the older buildings have lower glazing areas and less insulation within the walls, the newer buildings have higher glazing percentages and comparable effective insulation levels within the walls. Window to wall ratios range up to 80% in the study buildings. Effective overall R-values are discussed later in this report.

Increased natural gas consumption from increases in provided ventilation air (i.e. greater cfm per suite, translated to cfm/ft² of gross floor area) which requires larger make-up air units burning more gas. Mechanical audits of the study buildings identified a range in designed and provided make-up air ventilation rates from 30 cfm/suite (0.025 cfm/ft²) in buildings constructed in the 1980s to over 150 cfm/suite (0.140 cfm/ft²) in buildings constructed post-2000. Fig. 3.4.3 plots the total energy and total space heat energy consumption within 13 of the study buildings versus the make-up air ventilation flow rate normalized to cfm/ft² of floor area.

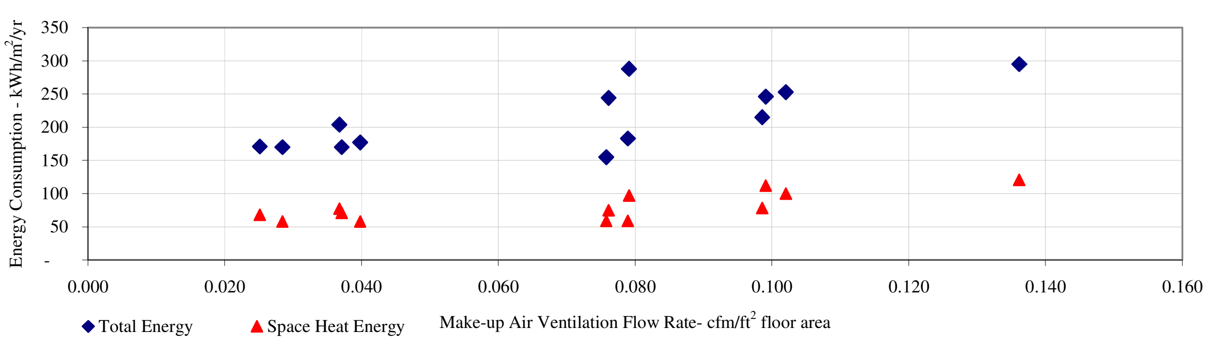


Fig. 3.4.3 Total and Space heat Energy Consumption versus Designed Make-up Air Ventilation Flow Rate.

Ventilation is provided for occupant health and ventilation equipment is sized to provide a minimum cfm/person or cfm/ft^2 of floor area depending on the code requirement. In a MURB, ventilation supply is provided by the make-up air unit and a pressurized corridor to distribute to suites. In the past 40 years, minimum ventilation rates have increased in MURBs resulting in larger MAUs and greater gas consumption proportional to the higher flow rates. This is the result of a design shift from using a pressurized corridor approach for only smoke and odour control to using the same system to intentionally provide ventilation to suites in-line with ASHRAE 62 requirements (in some jurisdictions of North America this is not allowed by building code). However, experience with MURBs has also shown that the pressurized corridor approach is less than 100% effective at providing sufficient ventilation air to suites even in newer buildings. As a result, occupants often find it necessary to open windows for sufficient fresh-air. This suggests that even higher pressurized corridor ventilation rates are required in some MURBs which in turn would consume even more gas per suite.

Heated make-up air already constitutes a significant portion of a building's energy consumption and the data would suggest that even more natural gas for ventilation heat if the industry continues to rely on a pressurized corridor approach for ventilation. In terms of energy efficiency, ventilation strategies should be de-coupled from heating or at the very least recover the heat from ventilation air through a centralized system or in-suite systems.

As a more energy efficient and effective ventilation strategy, it makes sense to compartmentalize suites and provide heating and ventilation directly to each suite. This can be done with either centralized mechanical equipment or in-suite mechanical equipment. Typically the in-suite approach is more economical, as the cost for duct work, fire-dampers, odour control for a whole building ventilation approach (similar to a commercial building) is more expensive. In a temperate climate such as Vancouver, the use of in-suite balanced continuous supply and exhaust systems with option heat recovery ventilators (HRVs) can help provide ventilation air directly to the suites at a temperature which is acceptable for comfort year round. In colder climates, the use of small duct-mounted electric heaters may be necessary to temper ventilation air during the coldest months.

The impact of ventilation flow rate on space heating and total building energy consumption is demonstrated further through calibrated energy simulation later within this report.

3.5. Energy Consumption End Use Summary

For the 39 MURBs in the study, a summary of average energy consumption and distribution of energy sources is determined. As each building is unique, a range of values are provided.

- Average high-rise MURB consumes 213 kWh/m^2/yr (range of 144 to 299 kWh/m^2/yr).
- Average size of the MURBs within the study is 18 floors (5 to 33 floors), 11,023 m^2 (range of 2,142 to 19,563 m^2) and contains 113 suites (range of 16 to 212 suites).
- 49% of the energy is electricity, 102 kWh/m^2/yr (range of 28 to 82% electricity).
  - 57% of electricity is used in suites (range of 33 to 77%):
    - 38% of suite electricity is used for electric baseboard heating (range of 6 to 61%).
    - 62% is used for appliances, lighting, electronics, etc. (range of 39 to 94%).
  - 43% of electricity is used in common areas (range of 23 to 67%):
    - 100% is used for operation of elevators, lighting, HVAC distribution, ventilation, plumbing, fans, pumps, parking garage etc. Also within pools, hot tubs and other amenity areas. A very small portion is used for electric baseboard heat in lobby or other common areas.
  - 22% of the total electricity (suites and common) is used for space heat (range of 4 to 36%).
- 51% of the energy is gas, 111 kWh/m^2/yr (range of 18 to 72% gas):
  - 51% is used for space heat within make-up air units and fireplaces (where provided) (range of 30 to 83%, or 100% where electric hot water).
  - 49% is used for domestic hot water or considered baseline use (i.e. some gas pilot lights etc.) (range 17% to 60%, or 0% where electric-hot water).
- 37% of the total building energy is used for space heat (range of 24 to 53%):
  - 69% of space heat is from gas (range of 40 to 97%).
  - 31% of the remaining space heat is from the in-suite electric baseboard heaters (range of 3% to 60%).

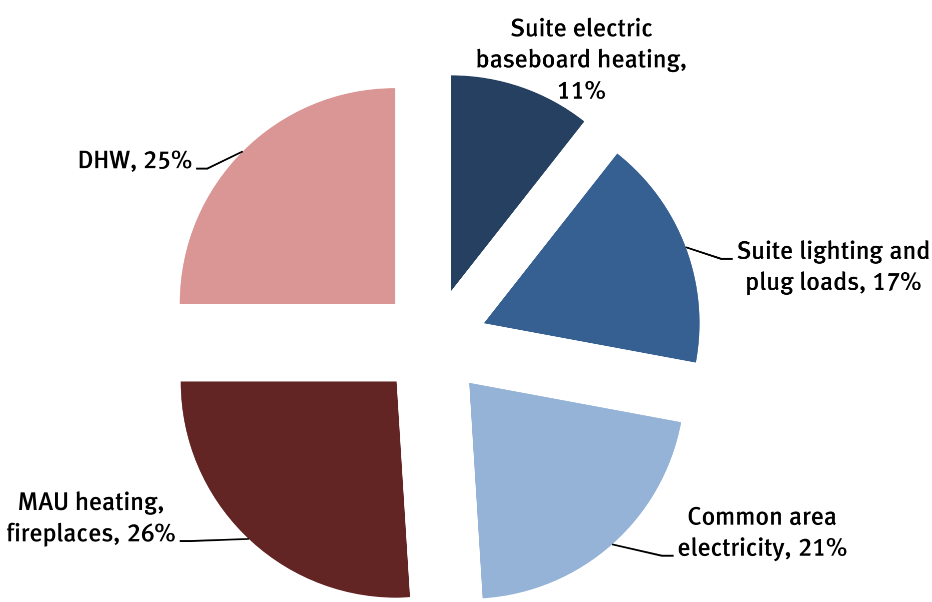


Fig. 3.5.1 Summary of Bill Determined Energy Consumption End-Use – Average of Study MURBs.

4. GREENHOUSE GAS EMISSIONS

Greenhouse gas emissions were calculated for each of the study buildings. Conversion factors to determine the tons of CO2 per unit of electrical energy were taken from 2007 NRCan published values in Retscreen software version 4.1. The burning of natural gas producing one MWh of energy releases 0.179 tons of CO2, and is the standard emission factor for natural gas.

British Columbia is fortunate to have “clean” electricity where the majority of power is produced by hydroelectric dams. The CO2 emission factors are determined by the power authorities depending on the make-up of provincial electrical power plants and purchase of power sources, whether it is from CO2 clean hydro and nuclear sources to CO2 intensive coal and natural gas. The influence of power trading between clean and other power sources particularly between BC and Alberta or the US may not fully be accounted for in these factors.

Based on the mix of electricity sources within British Columbia, one MWh of electricity consumed releases 0.055 tons of CO2 (NRCan 2007). BC Hydro publishes a lower conversion factor of 0.022 tons CO2/MWh electricity in their 2008 EN8 (2) Greenhouse Gas Intensities report as part of their Global Reporting Initiative (GRI). The Ministry of Energy, Mines and Petroleum Resources (MEMPR) suggested a much higher conversion factor of 0.360 tCO2/MWh, up until 2016 at which time will drop to 0, to account for the current use of “dirty” electricity (i.e. from coal or gas-fired power plants) purchased from other North American jurisdictions including Alberta. Within this report, the higher NRCan number of 0.055 tCO2/MWh is used, with some additional analysis on the much higher 0.360 tCO2/MWh.

Other provinces rely on coal and natural gas power plants which release significantly more CO2. For example, in Alberta, one MWh of electricity releases 0.874 tons of CO2 (1600% higher than BC), and in Ontario, 0.260 tons of CO2 (475% higher than BC).

The end result is that buildings within BC will automatically have lower CO2 and other greenhouse gas emissions than most other provinces. The data is subjective when comparing to other provinces and localities, and the CO2 conversion factors must be kept in mind. However, comparisons between buildings are relatively useful for this study. It should be reinforced that the energy used within the study buildings consists of approximately 50% gas, fixed at 0.179 tons CO2/MWh, and 50% electricity with a 70% lower emission factor of 0.055 tons CO2/MWh, therefore natural gas is the more significant contributor here.

Fig. 4.1.1 presents the total CO2 emissions for each of the study buildings. Fig. 4.1.2 provides a comparison between buildings, dividing the total building emissions by the number of suites to determine the total CO2 emissions per individual suite.

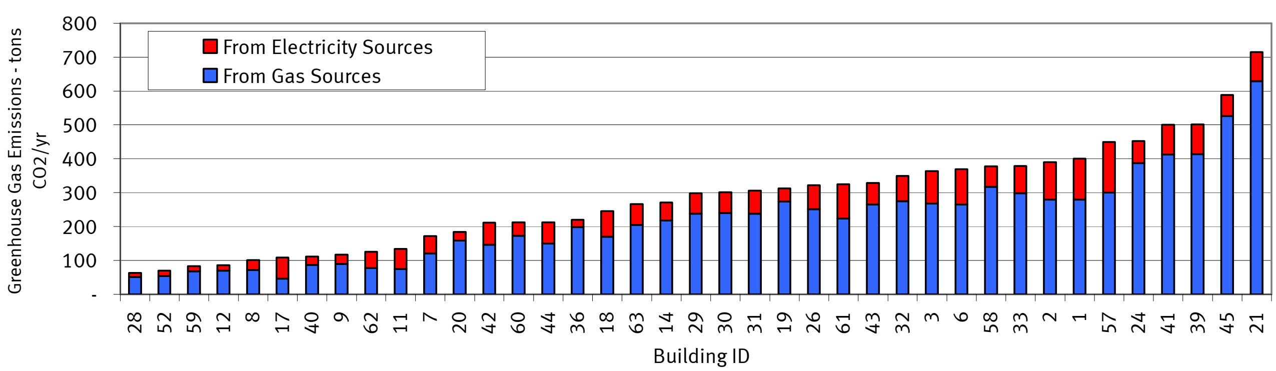


Fig. 4.1.1 Annual Greenhouse Gas Emissions from Energy Consumption – Tons of CO2 per building.

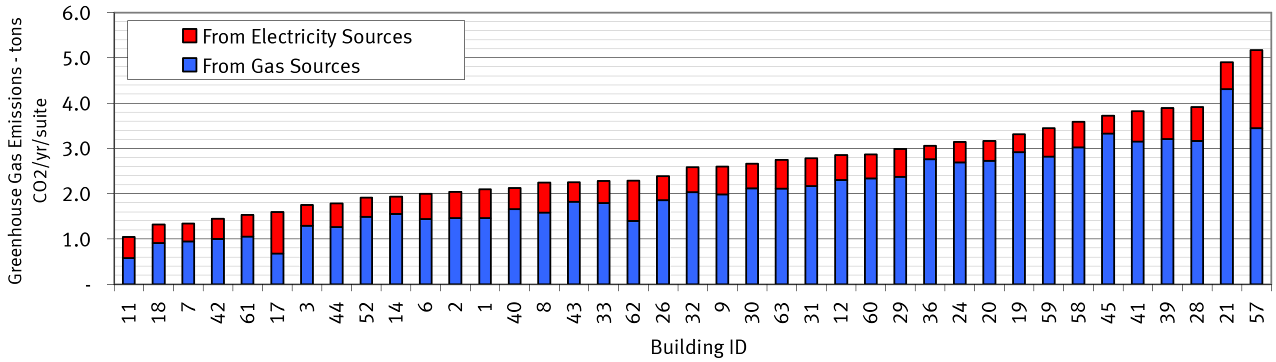


Fig. 4.1.2 Annual Greenhouse Gas Emissions from Energy Consumption – Tons of CO2 per suite.

On average, 279 tons of CO_2 (2.6 tons/suite) are produced through energy consumption each year. This is a relatively low number (cars release 3 to 10 tons/year), but can potentially be significantly reduced, and as shown by some of the buildings in the study, to less than 1.5 tons/ year/suite.

A breakdown of further end-use energy consumption and CO_2 emissions is further demonstrated using the typical MURB energy model developed in Section 8 of this report. The typical building model is represented here using BC and Alberta CO_2 emissions factors. Using BC CO_2 emissions factors, the total emissions for the typical MURB is 284 tons of CO_2 equivalent (2.6 tons/suite) and is represented in Fig. 4.1.3. Using Alberta CO_2 emissions factors, the total emissions for the typical BC MURB would be 1175 tons of CO_2 equivalent (10.7 tons/suite) and is represented in Fig. 4.1.4.

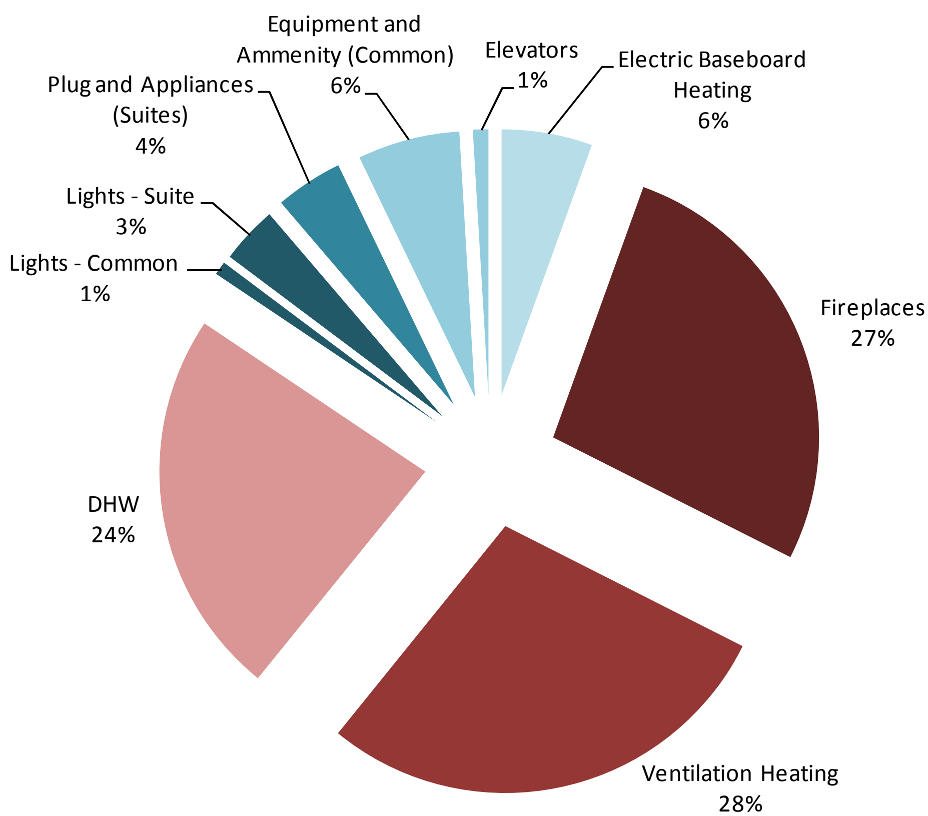


Fig. 4.1.3 Annual Greenhouse Gas Emission Distribution – Typical Study Building – BC CO2 emissions.

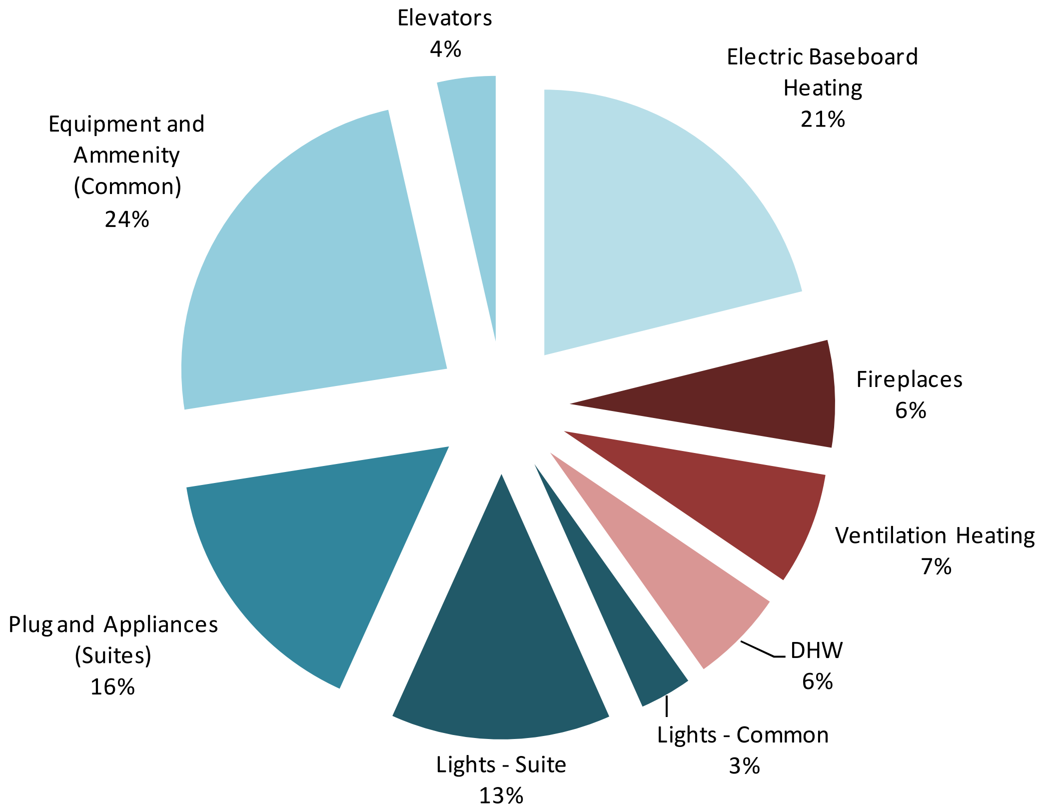


Fig. 4.1.4 Annual Greenhouse Gas Emission Distribution – Typical Study Building – Alberta CO2 emissions.

5. BUILDING OPERATING ENERGY COSTS AND THE DISCONNECT BETWEEN CONSUMPTION AND BILLING

Assuming 7¢/kWh for electricity and $11/GJ for natural gas, average 2007 through 2010 BC Hydro and Terasen utility rates, the operating costs of the 39 MURBs can be compared without allowing for inflation and rate changes. Historical utility rates from 1994 through 2010 are presented in Fig. 5.1.1 for both natural gas and electricity in units of GJ and kWh, and in Fig. 5.1.2 for both energy sources in equivalent kWh.

For the 39 buildings in the study, the average total energy cost ranges from $27,000 to $260,000 and the mean of all buildings is $128,000 per year. Of this, $49,000 is spent on gas, and $79,000 on electricity. For the building as a whole this represents a significant amount of money (in the order of $1.07 per square foot of floor area per year). Per suite the total energy cost ranges from $700 to $3,000 per suite per year, for an average of $1186.

Individual occupants typically pay directly for the suite electricity, and are invoiced on a monthly basis. On the other hand, the monthly invoices for gas and the common area electricity are paid directly by the collective owner group (Strata Corporation). The monthly fee paid by the individual owners to the Strata Corporation includes for the cost of this energy, but also includes a number of non-energy costs and the occupants typically never see these energy bills. Therefore, the average energy distribution and associated costs per suite in a typical MURB are as follows:

- 28% of the energy consumed is for suite electricity, which is equal to $408/suite/yr or 36% of the total energy cost, paid by the suite owner or occupant.
- 21% of the energy consumed is for common area electricity, which is equal to $323/suite/yr or 27% of the total energy cost, paid by Strata Corporation.
- 51% of the energy consumption is for gas (make-up air heat, fireplaces and domestic hot water), which is equal to $455/suite/year or 38% of the total energy cost, paid by Strata Corporation.
- In buildings where fireplaces are present, approximately $200/suite/year may be used, paid by the Strata Corporation.

Of the per suite total of $1186 paid per year, 36% ($34 per month) is paid by the owner or occupant, and 64% ($65 per month) is paid by the Strata Corporation. Clearly, the actual amount paid by the occupant is small and this disconnects the owner or occupant from the relative size of the total annual energy bill which on average is $128,000. This disconnect is a hurdle which must be overcome in order to effectively reduce energy consumption. It also shows that the central HVAC and electrical systems have the largest impact on total energy usage. Therefore energy efficiency improvements made to central shared systems likely has the greatest potential benefit.

A breakdown of further end-use energy consumption and a highlight of this disconnect is further demonstrated in the energy simulation section for a typical MURB.

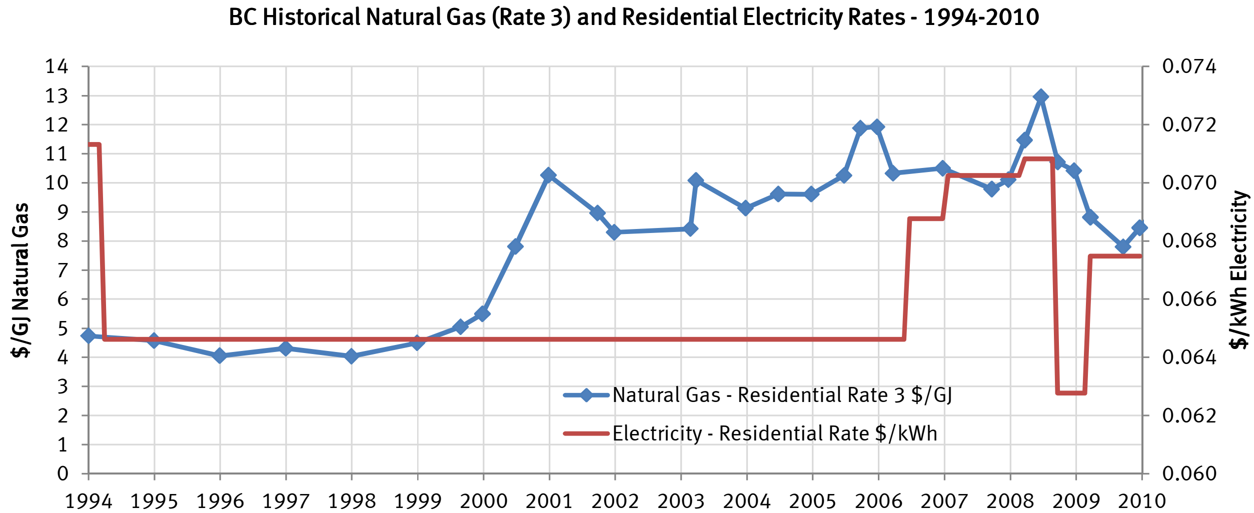


Fig. 5.1.1 Historical Fortis BC (Terasen Gas) Residential Rate 3 and BC Hydro Residential Electrical Rate between 1994 and 2010, Units of GJ and kWh.

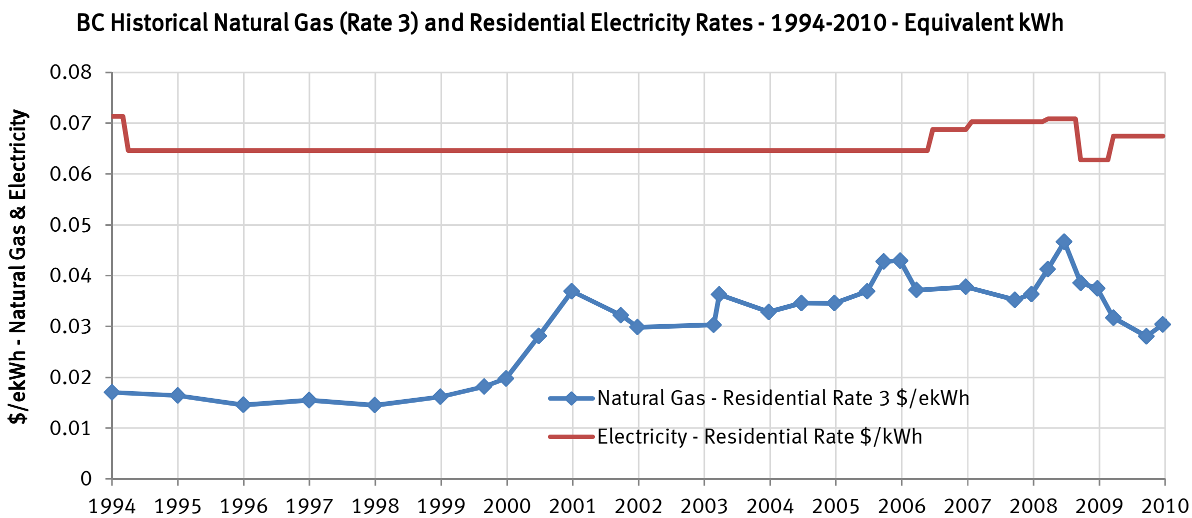


Fig. 5.1.2 Historical Fortis BC (Terasen Gas) Residential Rate 3 and BC Hydro Residential Electrical Rate between 1994 and 2010, Units of Equivalent kWh (ekWh).

6. PRE- AND POST-REHABILITATION – INDIVIDUAL BUILDING CASE STUDIES

Of the 39 study buildings with sufficient data for analysis, 19 buildings underwent building enclosure rehabilitation to address moisture damage within the past decade. Of these 19 buildings, 11 of the buildings were selected for a detailed pre- and post-rehabilitation analysis, where sufficient clean data existed to perform an analysis. The selected buildings are representative of rehabilitated MURBs in the Lower Mainland. As RDH was involved with rehabilitation of each of the 11 buildings, detailed drawings, specifications, construction information, and photographs of the pre- and post-rehabilitated assemblies were available and made use of in the following sections. In addition, two other buildings were selected for analysis which represents newer construction practices common to the Lower Mainland to bring the total to 13 buildings.

For each of the 13 selected buildings, the following was performed to assess the energy consumption (including pre- and post-rehabilitation energy savings for the 11 buildings) and to further understand energy consumption behaviour:

- Visit to each building to review the as-built conditions and perform an inventory and an overview mechanical audit of the space heating and ventilation systems.
- Preparation of a graphical 3D building model to aid with the detailed quantity take-offs required for the energy and thermal analyses. Graphics from the model are used throughout the building reports.
- Compilation of a building description complete with floor plans, elevations and relevant quantities.
- Preparation of a description and photographs of the pre- and post-rehabilitation wall, roof, and window enclosure assemblies (where applicable).
- Detailed thermal modeling of the building enclosure using THERM to determine the component and overall effective thermal resistances (R-values). Comparison and discussion of thermal improvements (where applicable).
- Discussion of the pre- and post-rehabilitation air barrier assemblies.
- Discussion of mechanical systems within the building included the following:
  - Estimation of make-up air gas consumption based on equipment design load.
  - Estimation of the domestic hot water consumption based on baseline energy consumption.
  - Estimation of fireplace gas consumption (where relevant).
  - Estimation of hydronic space heat gas consumption (where relevant).
- Review and compare the gas and electrical energy consumption for all years and specifically for the pre- and post-rehabilitation years.
- Determination of the gas and electric baseline consumption and space heat energy by performing both a weather normalized regression analysis and supporting visual review of the un-normalized billing data.
- Weather normalized regression to compare pre- and post- rehabilitation gas and electrical consumption and estimate energy savings as the result of the rehabilitation (where applicable).
- Preparation of weather normalized pre- and post-rehabilitation monthly data set for comparison of savings and use for energy modeling (where applicable).
- Summarize estimated energy savings from the rehabilitation work (where applicable).
- Summarize gas and electric distribution.

- Performing energy modeling using the pre- and post-rehabilitation energy consumption (where applicable) to calibrate the model, including the following:
  - Compare predicted versus actual energy savings.
  - Assess the impact of airtightness, natural air leakage and mechanical ventilation conductive heat-loss on space heating energy requirements.
  - Estimate the distribution of space heat loss considering ventilation and estimated air leakage rates.
  - Assess the impact of the thermal performance of the walls, windows/doors and roof on space heating energy requirements. Comparing pre and post-rehabilitation R-values (where applicable) as well as potential upgrades.
  - Assess the impact of mechanical system efficiencies, and potential improvements which could be made to the heating and ventilation systems to reduce energy consumption.
- Summarize energy cost savings from rehabilitation.
- Summarize greenhouse gas emission savings from rehabilitation.

An additional analysis of energy consumption by floor and by suite orientation was performed for the pre- and post-rehabilitation condition of Building 18.

6.1. Typical Building Analysis – Building 19

The individual building write-up for Building 19 is provided within the body of this report as an example analysis performed on the 13 buildings. Building summaries are provided for the other 12 buildings within Section 6.2.

6.1.1 Building 19: Energy Savings Summary

Building 19 was rehabilitated to address moisture related deterioration between March 2004 and February 2005. As part of the rehabilitation, the following key changes were made to the building enclosure assemblies:

- Original fibreglass batt insulation within the steel stud wall assemblies was removed, and replaced with semi-rigid mineral wool exterior insulated assemblies.
- Non-thermally broken aluminum glazing assemblies were replaced with thermally broken aluminum glazing assemblies, complete with a moderate performance low-e coating within the new insulated sealed units.
- Reduced thermal bridging at details.

R-values of the pre- and post- rehabilitation building enclosure components were modeled in detail and corresponding area calculations were used to determine the overall effective R-value of the building enclosure. The overall effective R-value for Building 19 improved from R-2.92 to R-4.26 (+46%) as a result of the building enclosure rehabilitation work. This improvement was not intentional as the repair was designed to minimize the rehabilitation costs to address moisture damage; however, incidental improvements were realized as a result of the detail changes including an exterior insulated wall assembly, the new thermally improved window and door assemblies and increased airtightness. The energy consumption at the building was reduced by a total of 8.1% (13.9% of the space heat energy) as a result of the building enclosure rehabilitation work. The overall improvements are summarized in Table 6.1.1 and Table 6.1.2 and for a standard weather year.

Table 6.1.1 Summary of Overall R-value and Energy Consumption Changes as the Result of the Building Enclosure Rehabilitation Work.			
Enclosure Thermal Performance	**Pre-Rehabilitation R-value**	**Post-Rehabilitation R-value**	**Improvement**
	hr ft² F/Btu ***(m² K/W)***	**hr ft² F/Btu** ***(m² K/W)***	
Effective Window R-value	1.37 *(0.24)*	2.16 *(0.38)*	+57%
Effective Wall Area R-value	3.94 *(0.69)*	5.25 *(0.93)*	+33%
Effective Roof R-value	14.26 *(2.51)*	18.28 *(3.22)*	+28%
Overall Effective Building Enclosure R-value	**2.92** ***(0.51)***	**4.26** ***(0.75)***	**+46%**

Table 6.1.2 Summary of Overall R-value and Energy Consumption Changes as the Result of the Building Enclosure Rehabilitation Work.						
Energy Consumption		**Pre-Rehabilitation kWh/m²/yr**	**Post-Rehabilitation kWh/m²/yr**	**Energy Savings kWh/m²/yr**	**% of Space Heat Savings**	**% of Total Energy Savings**
Gas	Space heat: Hydronic Baseboard and MAU ventilation	72.7	63.3	9.4	12.5%	5.3%
	Baseline : Estimated Domestic Hot water	51.3	51.3	0	-	0%
Electricity	Suite: Space heat	2.6	1.8	0.8	1.0%	0.4%
	Suite: All Other	33.6	31.9	1.6	-	0.9%
	Common: Space heat	0.4	0.1	0.3	0.5%	0.2%
	Common: All Other	18.0	15.6	2.4	-	1.3%
Total Space Heat – kWh/m²/yr		**75.7**	**65.1**	**10.5**	**13.9%**	**-**
Total Energy – kWh/m²/yr		**178.5**	**164.0**	**14.5**	**-**	**8.1%**
Total Energy – kWh/suite		**24,552**	**22,551**	**2,001**		
Greenhouse Gas Emissions, tCO_2		**326**	**300**			**7.8%**

6.1.2 Building Description

Building 19 is located in Greater Vancouver within a neighbourhood of similar sized buildings. The building is oriented with the long dimension along the northeast-southwest direction. The building is 10 storeys tall and contains 94 suites. The gross floor area is approximately 139,140 ft² and the gross wall and roof enclosure area is 72,260 ft². Glazed window and door area makes up 34% of the 56,610 ft² vertical wall area. Buildings 19 and 45 in the study are of similar form and construction. Fig. 6.1.1.1 shows the typical suite layout floor plan and Fig. 6.1.2.3 shows a 3D view of the building. Elevations are shown in Fig. 6.1.2.4 through Fig. 6.1.2.7.

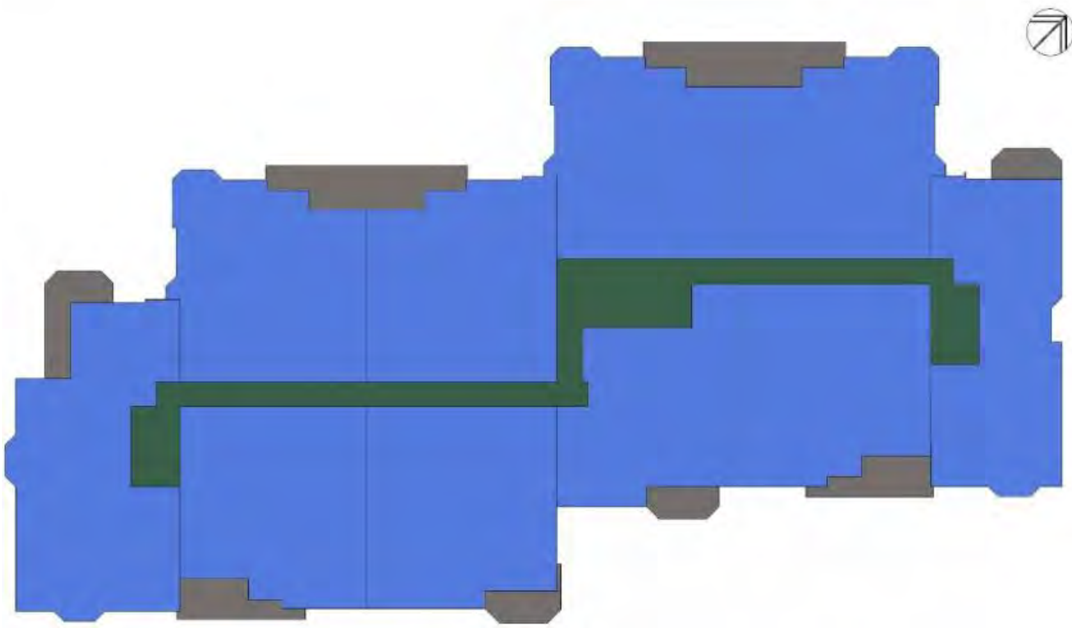


Fig. 6.1.2.1 Typical Suite Floor Plan.

Fig. 6.1.2.2 Northwest elevation of building from 3D model.

Fig. 6.1.2.3 Southeast elevation of building from 3D model.

Fig. 6.1.2.4 North-west Elevation.

Fig. 6.1.2.5 East Elevation.

Fig. 6.1.2.6 South-east Elevation.

Fig. 6.1.2.7 West Elevation.

6.1.3 Building Enclosure

The building was originally constructed between 1983 and 1984. As a result of water related damage, rehabilitation of the building enclosure was required to address structural deterioration of the building enclosure.

The rehabilitation work took place between March 2004 and February 2005. This work included new exterior wall, roof, window and sliding door assemblies.

Pre-Rehabilitation

Exterior Walls and Roofs

The original exterior walls consisted of an insulated steel stud wall assembly with stucco cladding at floors two through 10, and brick tile cladding at the ground floor. The walls were insulated fibreglass insulation between 4" (true depth) steel studs spaced at 16" o.c. with a nominal insulation R-value of R-13.7. The steel studs, un-insulated slab edges and balconies that project through the exterior walls reduce the effective R-value of the walls and are accounted for in the thermal modeling. Fig. 6.1.3.1 and Fig. 6.1.3.2 show typical details of the exterior wall assemblies pre-rehabilitation and Fig. 6.1.3.3 shows an overview of the rehabilitated wall assembly.

Fig. 6.1.3.1 Typical pre-rehabilitated insulated wall (exterior cladding and sheathing removed). Note thermal bridging occurs at studs, around windows and slab edges. Portions of the studs were severely corroded.

Fig. 6.1.3.2 Typical pre-rehabilitation insulated wall conditions (exterior cladding, sheathing and insulation removed). Electrical conduit, 4x corner studs, less than typical stud spacing, sill and head tracks, exposed concrete slab edge, in-slab ducts all reduce the thermal resistance of the batt insulation in the steel stud wall assembly.

Fig. 6.1.3.3 Exterior wall during rehabilitation with exposed exterior wall assemblies.

The original stucco contained expanded polystyrene beads in the stucco mix (referred to as 'Thermo-Stucco' cladding); however, the thermal improvement that this provided was negligible compared to normal cement stucco due to the saturation of the polystyrene beads with water.

The original roofs consisted of inverted insulated assemblies constructed with extruded polystyrene insulation on top of a waterproofing membrane. A few small decks at the building were constructed in a similar manner. A thickness of 3" of XPS was typically used to insulate the assemblies.

Thermal modeling was used to calculate effective U- and R-values of each wall and roof assembly arrangement on the building. Fig. 6.1.3.4 plots the R-values for each of the components versus the area that the assembly detail occupies to provide a sense of which assembly insulating characteristics have the greatest influence on the overall R-values. In the figure, higher R-values typically represent center of wall conditions, away from thermal bridges such as balconies, corners, slab edges etc.

Overall effective U- and R-values for the wall and roof were calculated using area-weighted U- values from the detailed area calculations. These overall effective wall and roof R-values were calculated to be R-3.94 and R-14.26 respectively.

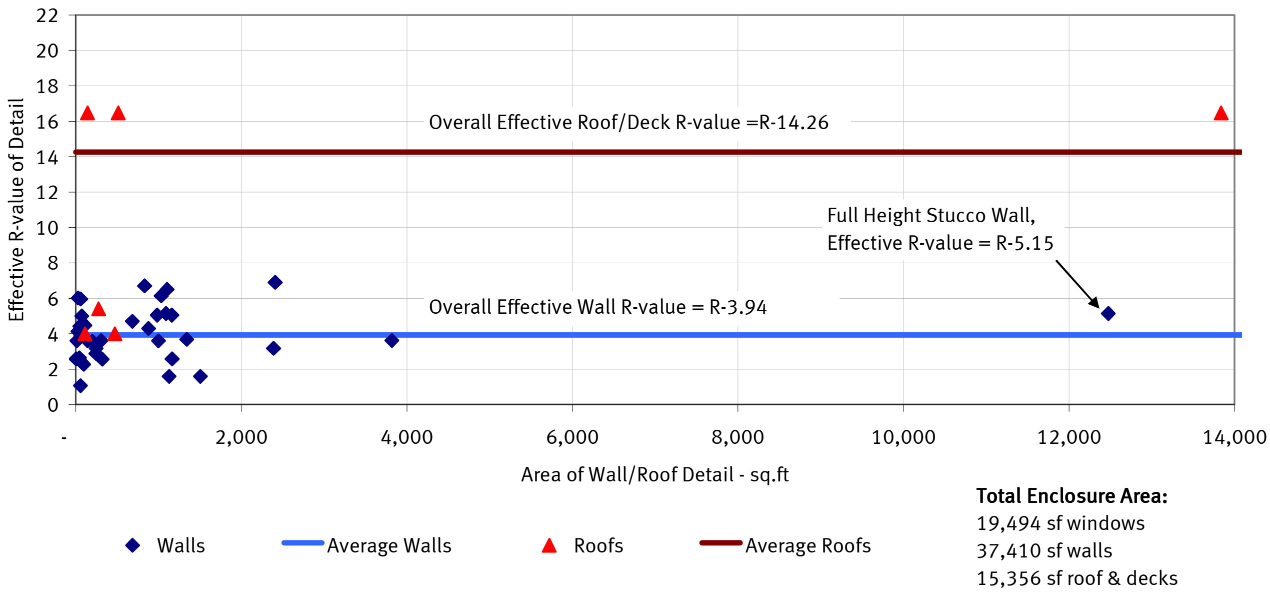


Fig. 6.1.3.4 Modeled Pre-Rehabilitation Overall Effective R-values of Wall and Roof Assembly Arrangements.

Windows

The original windows and sliding doors consisted of clear (non low-e) air-filled IGUs in non-thermally broken aluminum window and door frames. Windows and doors occupy 34% of the exterior wall area. The center of IGU thermal performance is U-0.48/R-2.1. Aluminum edge spacer bars reduce the edge of glazing thermal performance.

Effective window and door R-values were calculated for all of the window configurations in the building using THERM and WINDOW and are presented in Fig. 6.1.3.5. Smaller windows have lower overall R-values due to a higher frame to glazing ratios (frames have a lower R-value, ‹R-0.5 to R-1.0 than the IGUs, ~R-2). The overall effective R-value for all of the windows/doors in the building was calculated to be R-1.37 (including the fixed/operable windows and sliding doors).

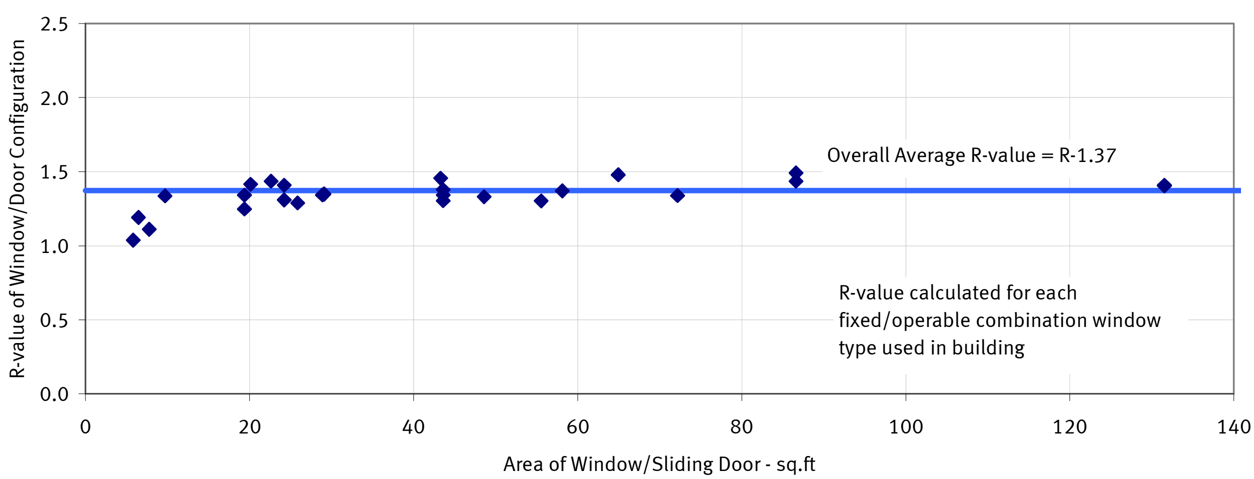


Fig. 6.1.3.5 Modeled Pre-Rehabilitation Effective R-values of Window Configurations, by Area of Window Unit.

Airtightness

The air barrier of the original building enclosure consisted of loosely sealed polyethylene installed on the exterior side of the drywall and the face-sealed stucco cladding. During rehabilitation, relatively poor air-sealing details were found in the polyethylene around penetrations and interfaces. Fig. 6.1.3.6 and Fig. 6.1.3.7 show the condition of the original polyethylene air barrier and deteriorated steel stud wall assemblies.

Fig. 6.1.3.6 Original air barrier consisted of poorly detailed and typically unsealed and loose 2mil polyethylene as shown around this electrical penetration at a party wall during rehabilitation. The face-sealed stucco and sealant likely formed the most airtight element of the original exterior wall assemblies.

Fig. 6.1.3.7 Severely corroded condition of steel studs and sill plate. The corrosion of the studs was so severe, from being in contact with wet gypsum sheathing that the sill plates were completely corroded to iron oxide and portions of the studs were detached resulting in slightly reduced thermal bridging and improved thermal performance at the affected areas compared to the originally constructed wall assemblies.

Pre-Rehabilitation R-value Summary

Table 6.1.3.1 provides a summary of the pre-rehabilitation overall effective building enclosure U- and R-values.

Table 6.1.3.1 Pre-Rehabilitation Wall, Roof and Window Overall Effective U- and R-values.

Pre-Rehabilitation R-values	**Area, sq.ft – % of enclosure**	**U-effective – Btu/hr ft² F *(W/m² K)***	**R-effective – hr ft² F/Btu *(m² K/W)***
Roofs and Decks	19,494 – 27%	0.070 *(0.40)*	14.26 *(2.51)*
Opaque Wall Components	37,410 – 52%	0.254 *(1.44)*	3.94 *(0.69)*
Windows and Doors	15,356 – 21% (34% of wall area)	0.728 *(4.13)*	1.37 *(0.24)*
Overall Building	**72,260**	**0.343 *(1.95)***	**2.92 *(0.51)***

Post-Rehabilitation

Walls and Roofs

The rehabilitated walls typically consist of an exterior insulated stucco clad wall assembly at floors two through 10, and an exterior insulated brick tile wall assembly at the ground floor. The walls are insulated with 2 ¼” semi-rigid mineral wool insulation between vertical girts typically spaced at 16” o.c. with a nominal insulation R-value of R-9.5. Insulation is continuous over steel-stud framing and slab edges; however, the vertical steel girts, balconies and other penetrations through the insulation reduce the effective R-value of the walls and are accounted for in the thermal modeling. Fig. 6.1.3.8 and Fig. 6.1.3.9 show typical exterior insulation wall assembly details at Building 19.

Fig. 6.1.3.8 Semi-Rigid Insulation between the z-girts on the exterior of the self-adhered membrane and gypsum sheathing.

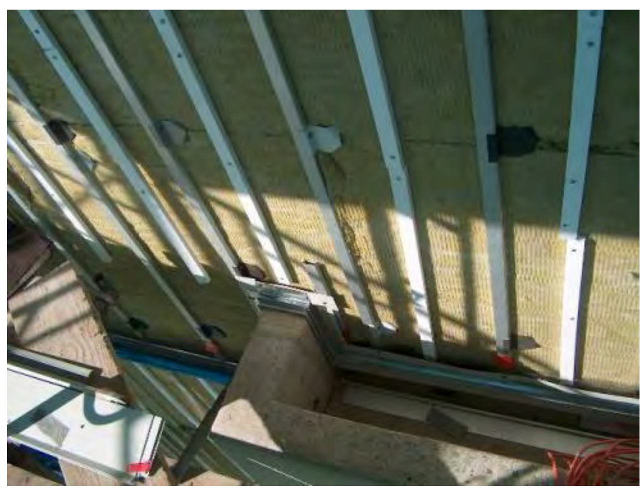


Fig. 6.1.3.9 Z-girts between semi-rigid insulation at 16” o.c. Styrofoam spacers are installed between girts on the outside of the insulation for a more rigid stucco backer board support during base-coat application.

The rehabilitated roofs consist of inverted insulated assemblies, constructed with 3” of XPS on top of a waterproofing membrane. A few small decks at the building were re-constructed in a similar manner.

Thermal modeling was used to calculate effective U- and R-values of each wall and roof assembly at each arrangement on the building. Fig. 6.1.3.10 plots the R-values for each of the components versus the area the assembly detail occupies to provide a sense of which assembly insulating characteristics have the greatest influence on the overall R-values.

The overall effective U- and R-values for the wall and roof were calculated using area-weighted U- values from the detailed area calculations. The overall effective wall and roof R-values were calculated to be R-5.25 and R-18.28 respectively, improvements of 33% and 28% over the pre-rehabilitation conditions.

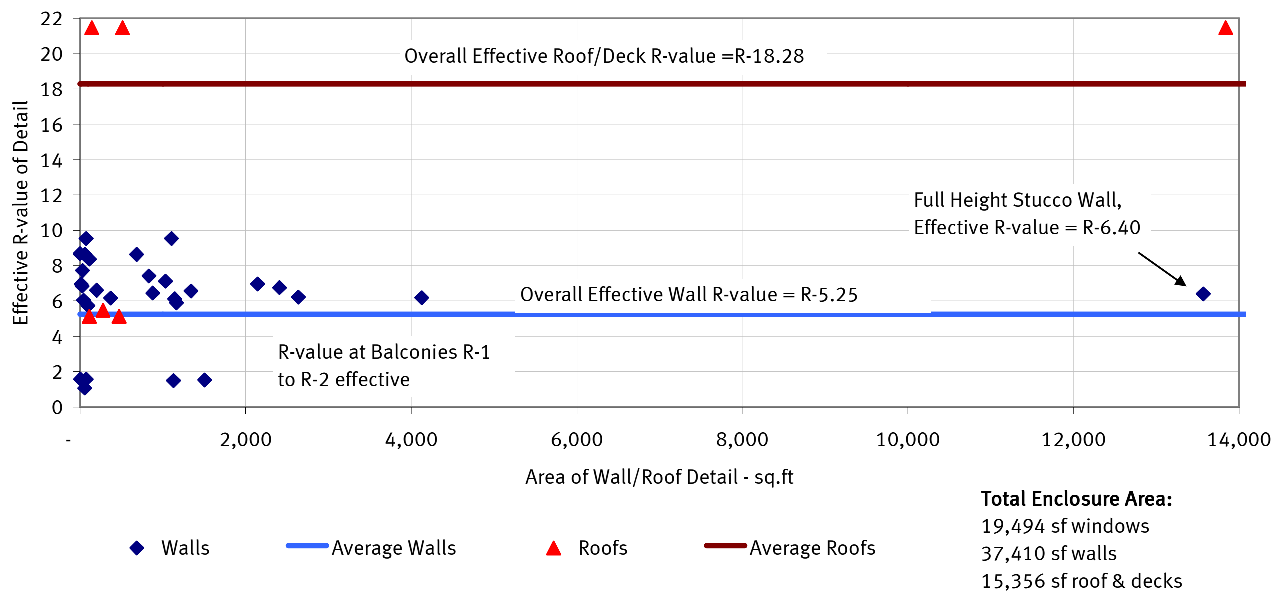


Fig. 6.1.3.10 Modeled Post-Rehabilitation Effective R-values of Wall and Roof Assembly Details.

Windows

The replacement windows and sliding doors consisted of air-filled low-e IGUs in thermally broken aluminum window and door frames occupying 34% of the exterior wall area. The center of IGU thermal performance is U-0.30/R-3.4. Aluminum edge spacer bars reduce the edge of glazing thermal performance. Effective window and door R-values were calculated for all of the window configurations in the building using THERM and WINDOW and are presented in Fig. 6.1.3.11. The overall effective R-value for all of the new windows/doors in the building was calculated to be R-2.16, an improvement of 58% over the original arrangements.

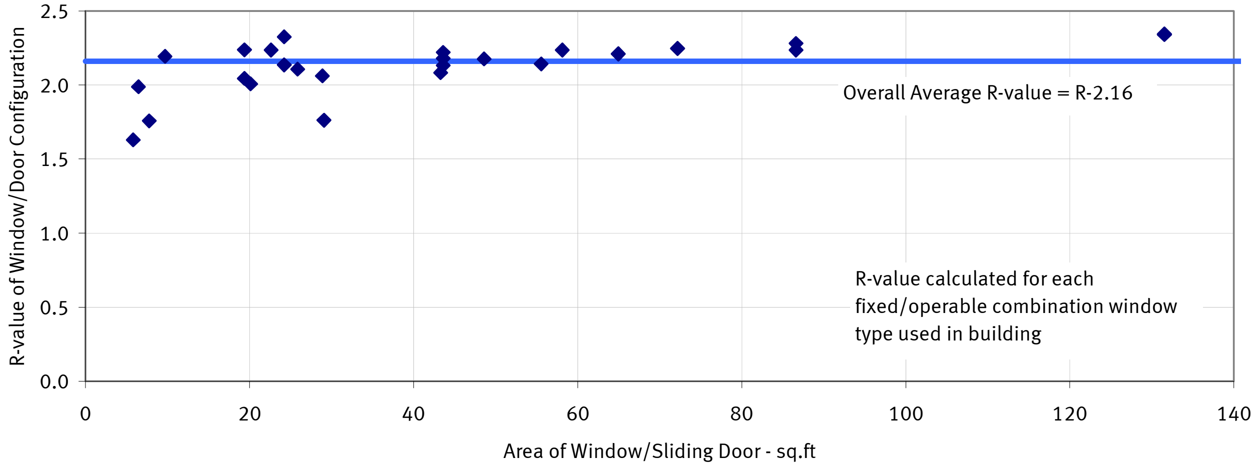


Fig. 6.1.3.11 Modeled Post-Rehabilitation Effective R-values of Window Configurations, by Area of Window Unit.

Airtightness

The air barrier of the upgraded building enclosure included the use of a self-adhered waterproofing membrane applied to the exterior gypsum sheathing complete with improved transition details. Figures Fig. 6.1.3.12 and Fig. 6.1.3.13 show some typical details of the air barrier membrane over the gypsum sheathing.

Fig. 6.1.3.12 Post-Air barrier Installation – Sealed Self-Adhered Membrane applied to rigid gypsum sheathing with tie-ins to all interfaces.

Fig. 6.1.3.13 Post-Air barrier Installation – Continuous Sealed Self-Adhered Membrane from wall to balcony slabs/curbs and sliding doors.

Summary of Enclosure Thermal Performance Pre- and Post-Rehabilitation

Table 6.1.3.2 provides a summary of the pre-and post-rehabilitation overall effective component U- and R-values. Fig. 6.1.3.14 graphically demonstrates the individual component R-values using a color gradient R-value scale, similar to how an infrared scan would appear (red/warm areas as low R-values, blue-green cold areas as high R-values).

Table 6.1.3.2 Pre- and Post-Rehabilitation Wall, Roof and Window Overall Effective U- and R-values.

Pre-Rehabilitation R-values	**Area, sq.ft – % of enclosure**	**Pre-Rehabilitation**		**Post-Rehabilitation**	
		U-effective – Btu/hr ft² F ***(W/m² K)***	**R-effective – hr ft² F/Btu** ***(m² K/W)***	**U-effective – Btu/hr ft² F** ***(W/m² K)***	**R-effective – hr ft² F/Btu** ***(m² K/W)***
Roofs and Decks	19,494 – 27%	0.070 *(0.40)*	14.26 *(2.51)*	0.058 *(0.33)*	18.28 *(3.22)* **+28%**
Opaque Wall Components	37,410 – 52%	0.254 *(1.44)*	3.94 *(0.69)*	0.190 *(1.08)*	5.25 *(0.93)* **+33%**
Windows and Doors	15,356 – 21% (34% of wall area)	0.728 *(4.13)*	1.37 *(0.24)*	0.463 *(2.63)*	2.16 *(0.38)* **+58%**
Overall Building Effective	**72,260**	**0.343 *(1.95)***	**2.92 *(0.51)***	**0.236 *(1.34)*** *31% reduction*	**4.26 *(0.75)*** **+46%**

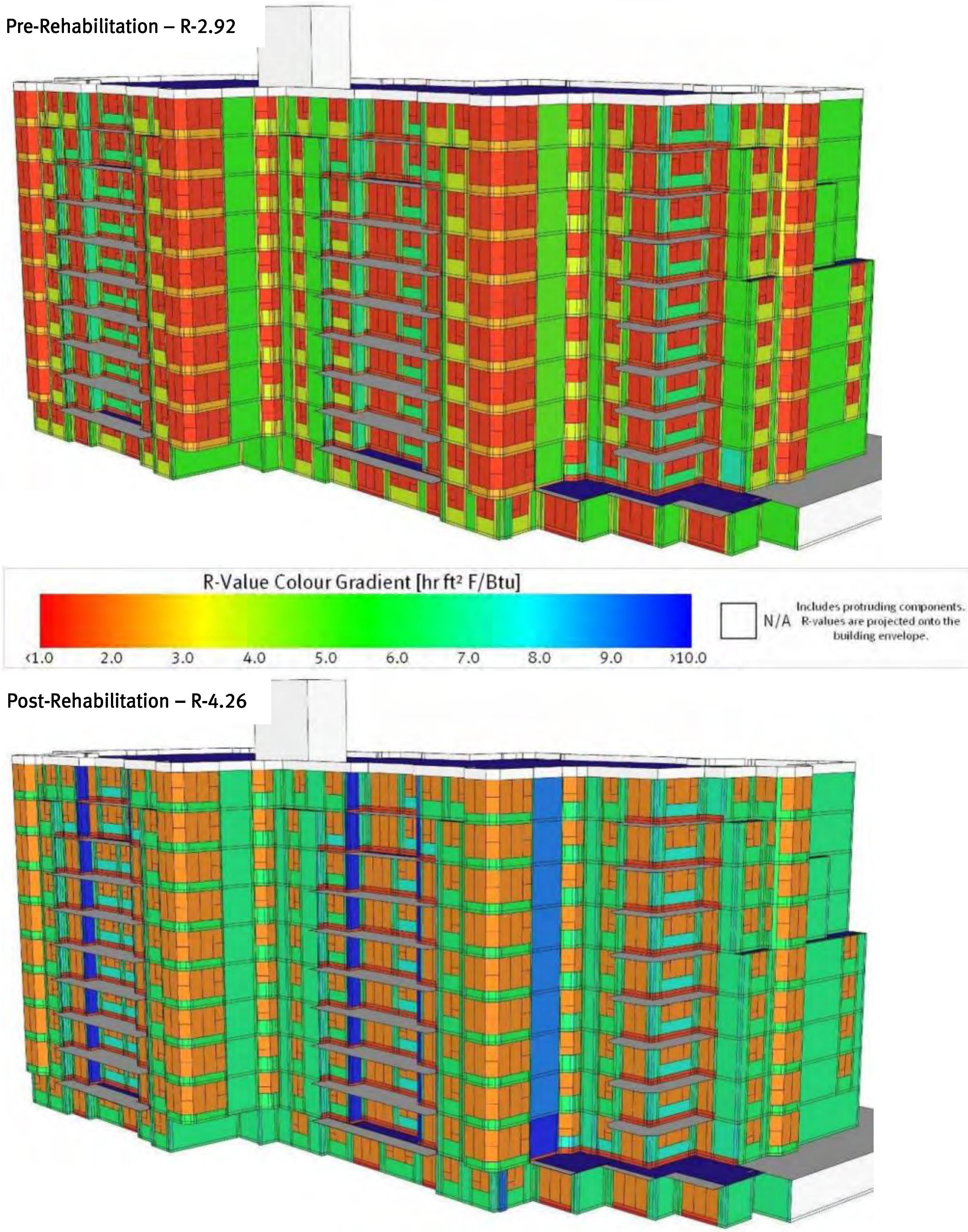


Fig. 6.1.3.14 Color Coded Calculated R-value for Building 19 – Pre- and Post-Rehabilitation.

6.1.4 Mechanical Systems

A mechanical audit of the building was performed in November 2008 by RDH and a mechanical consultant. The following information was collected during the visit and from discussions with property maintenance personnel.

Space Heating and Ventilation

Space heat at Building 19 is provided by gas-fired hydronic baseboard heaters within the suites and at the amenity spaces at the ground level lobby. Ventilation air is heated at a gas-fired rooftop make-up air unit and provided to the central corridors prior to flowing into the suites.

Hot water for the hydronic system is heated using a gas fired boiler with a continuous pumped recirculation system to distribute 160-180°F hot water through central lines into the suites. The gas boiler was installed in 1983 at the time of original construction and has a nameplate efficiency of 80%. Because of potential issues with thermal shrinkage of the plumbing couplings in the main hot water lines throughout the building, the system continuously re-circulates hot water through the main lines of the building even during the summer months (except in those suites where the thermostat is off). Several leaks have occurred in the past when the hot water system was shut-off accidentally or the boiler was shut-down for maintenance. Complaints from building occupants of overheating are reportedly common during the summer months during which the heat cannot be completely shut-off.

Some occupants reportedly use supplementary plug-in electric resistance heaters or electric fireplaces which would account for the low level of electric space heating observed in the utility meters.

No gas fireplaces are present in this building.

The mechanical ventilation strategy at Building 19 is typical of other MURBs in the study and consists of a continuous supply of tempered fresh air to the corridors with intermittent point exhaust within bathrooms and kitchens of the suites. Bathroom and kitchen exhaust fans are not continuously operated and are occupant controlled. Because of the age of the building, humidistats or timers are not present. Windows are typically opened by occupants to provide adequate fresh outdoor air instead.

The make-up air unit (MAU) is located on the roof to the east side of the elevator room. The unit was installed in 1984, at the time of construction. The unit is an Engineered Air indirect gas-fired make-up air unit (Eng Air S-350) with maximum heat input of 350 Mbtu, with a burner efficiency of 76% and flow capacity of 3500 cfm at an external static pressure of 0.5" w.c .(125 Pa). This is equal to approximately 0.025 cfm/ft^2 or an average of 37.2 cfm/suite. Because the unknown effectiveness of this ventilation to be supplied to the suites, it is unknown whether this meets a minimum of 15 cfm/per person. The temperature set-point of the MAU at the time of the visit was 21°C (70°F) and reports from the property maintenance personnel indicate that it is not typically adjusted.

A review of gas energy consumption from other buildings in the study indicates that the gas used for make-up air, makes up a significant portion of the gas used at the building, and contributes to the space heating energy. Tempering of outdoor air to a constant 21°C year-round offsets the required amount of space heat input from heating appliances within the suites for the make-up air. The gas consumption specifically for the MAU at this building is estimated later in this report.

The ventilation system is designed so that air flows into the suites through suite door undercuts as the corridor is intended to be positively pressurized with respect to the suites. However, this corridor pressurization is not always positive and significant amounts of fresh air flows through unsealed hallway doors into stairwells, shafts and the elevator shafts, resulting in less make-up air to the suites, particularly considering some of the door undercuts are reduced by the occupants. Moreover, the effect of wind and building stack effect results in negative pressures and associated reverse flow of suite air into the corridor space. Because of these noted issues with building flows and corridor pressurization, the in-situ efficiency of supplying tempered ventilation air from the corridors to each of the suites is questionable in terms of both ventilation and heating effectiveness.

Domestic Hot Water

The domestic hot water (DHW) system consists of a newer gas fired boiler with a nameplate efficiency of 81% supplying 160°F (71°C) to three hot water storage tanks. Hot water typically leaves the tanks at 140°F (60°C) and is pumped through central lines feeding the suites.

There is no heat exchanger between the domestic hot water system and hydronic boiler; however, it is likely that savings could be achieved by incorporating a heat-exchanger, particularly considering the loses from the continuously running hydronic system boiler.

Lighting

Lighting for the building is typical of a multi-unit residential building constructed in 1983. Parking garage lighting is minimal but consists of less efficient T12 bulbs. Corridor lighting is also predominantly T12 bulbs. Suite lighting consists of typical residential incandescent fixtures with a limited number of florescent fixtures/bulbs where installed by owners.

Elevators

Two cable run elevators service the building. All components including the AC to DC converters, DC motors, controls and elevator cabs are original from 1983. Based on a review of the components, elevator usage is estimated to be typical for a multi-unit residential building of this age.

Mechanical Upgrades

No significant mechanical upgrades have been performed in the past eight years at this building. The majority of the mechanical equipment is original; however, the domestic hot water plumbing, tanks and boiler were replaced in 2001-2002 prior to the building enclosure rehabilitation work. An upgrade of the hydronic boiler and piping system is planned by the owners in the near term.

6.1.5 Energy Consumption – All Years

The section presents the energy analysis for the building for all years where utility data was provided and the following section discusses the changes observed pre- and post-rehabilitation. The total building energy use and gas/electrical distribution is the focus of this section, whereas the pre-post analysis focuses on space heat consumption, affected by the building enclosure in the following section.

Gas and electric utility data for this building was provided by Terasen Gas and BC Hydro from January 1st, 1998 through January 31st, 2009. The metering typically appears to be accurate; however, for a few months the gas metering data appears to be erroneous or was corrected to address a broken or malfunctioning gas meter. A review of the energy consumption over the 11 year period was performed as part of the analysis.

The utility metering date does not typically fall on the first day of the month; therefore, the provided metering data is sorted into actual calendar month (1st to 30th or 31st) consumption for analysis (calendarized).

Monthly gas consumption from January 1st 1998 through January 1st 2009 is provided in Fig. 6.1.5.1 in units of Gigajoules (GJ). Monthly electrical consumption for the same time period is provided in Fig. 6.1.5.2 in units of kilowatt hours (kWh). Electrical consumption is provided by BC Hydro for all suites combined, referred to as "suites" and all common usage referred to as "common." The total gas and electrical energy consumption is provided in Fig. 6.1.5.3 in common energy equivalent units of kWh, as one GJ of energy is equal to 277.78 kWh.

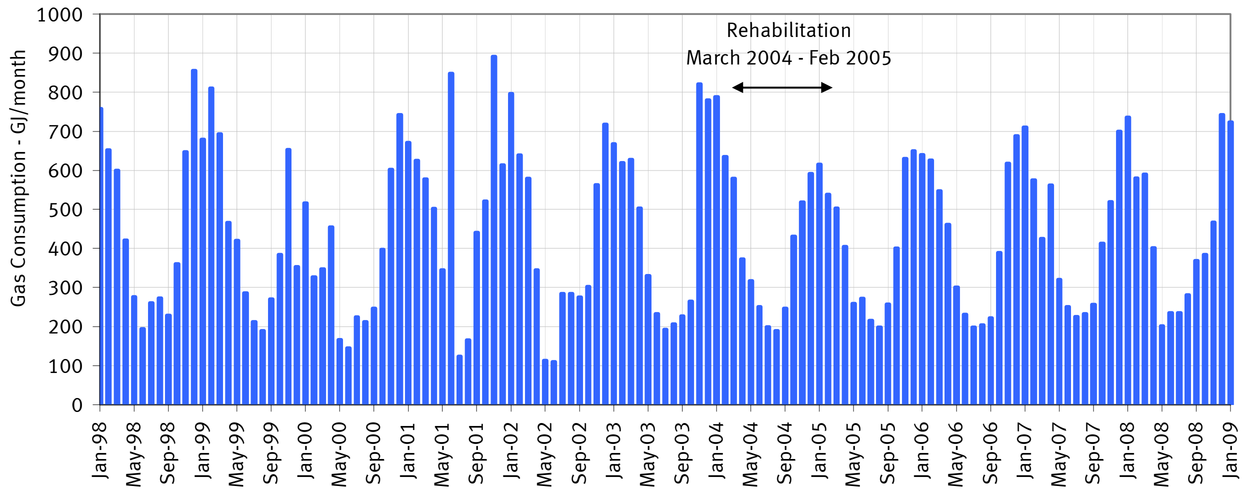


Fig. 6.1.5.1 Gas Consumption, January 1st 1998 through January 1st, 2009.

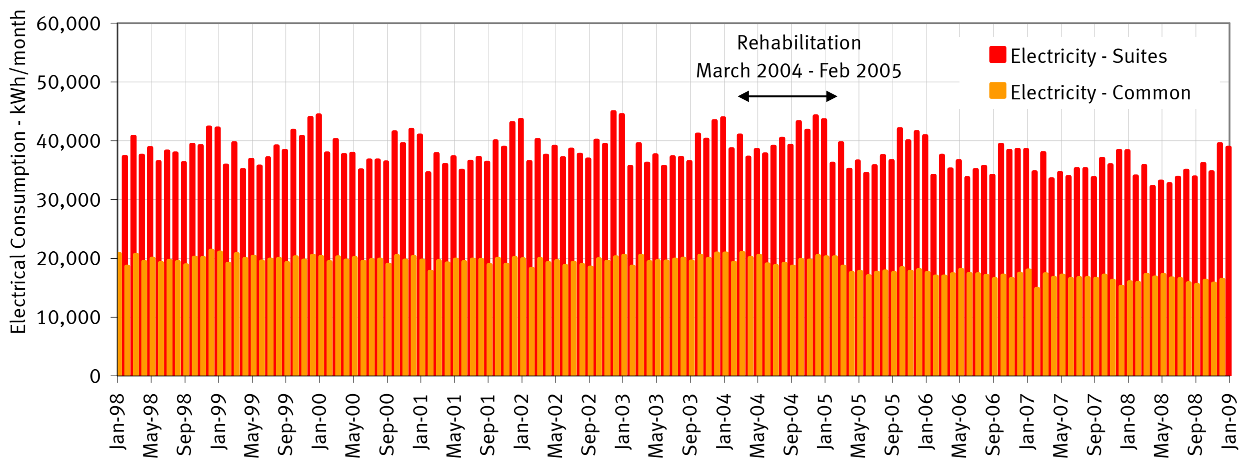


Fig. 6.1.5.2 Suite and Common Electrical Consumption, January 1st 1998 through January 1st, 2009.

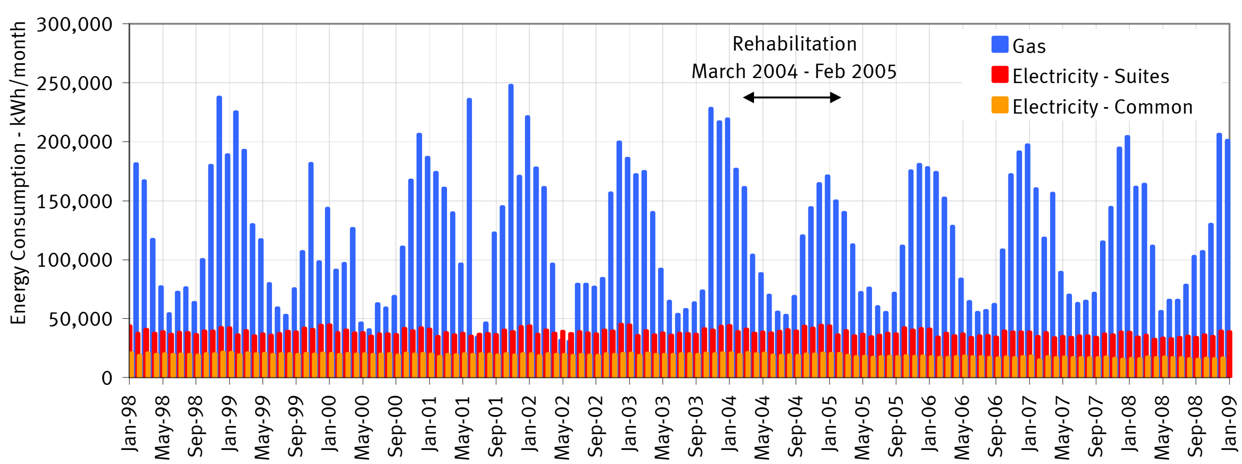


Fig. 6.1.5.3 Total Energy Consumption, January 1st 1998 through January 1st, 2009.

Analysis of all 11 years of data indicates that gas energy accounts for the majority of energy used at the building (69% of the total or approximately 1,530,000 kWh/yr of the 2,210,000 kWh/yr used on average). As shown in the preceding figures, seasonal trends are observed in both the gas and electrical energy consumption at the building. The trends are expectedly greater for the gas, which is used to heat hot water for the hydronic baseboards, the primary method of space heat within the building, and for the gas heated make-up air. Supplemental electric heaters in suites and common areas and seasonal variances in lighting account for the small wintertime seasonal increases in electrical consumption.

On an annual average basis for the past 11 years, the total energy consumption within the building is summarized as follows.

- The total energy consumed consists of approximately 685,000 kWh of electricity (31%) and approximately 5,500 GJ (1,529,000 kWh) of gas (69%) for a total of 2,214,000 kWh (7970 GJ). The total energy consumption was reduced following the rehabilitation as discussed in the following section.
- Normalized energy consumption per unit of floor area is 171 kWh/m^2/yr for all years combined. The normalized consumption has varied from 157 to 182 kWh/m^2/yr. The lesser consumption occurring in recent years post-rehabilitation and highest consumption year pre-rehabilitation. This is further discussed in the next section.
- Normalized energy consumption is approximately 23,554 kWh per suite from all energy sources. Of this, only 4,865 kWh/suite (or 21% is actually paid directly by the suite owners) is from electricity used within the suite. The remainder, 2,426 kWh/suite (10%) is used for common area electricity and 16,263 kWh/suite (69%) is for gas.

6.1.6 Energy Consumption – Pre and Post Building Enclosure Rehabilitation

The rehabilitation of Building 19 took place between March 2004 and February 2005. Utility data was provided from January 1998 through January 2009. As the rehabilitation was substantially completed during the 11-month period between March 2004 and February 2005, only data for the 75 months pre-rehabilitation and 46 months post-rehabilitation was used for the analysis.

To assess the impact of the building enclosure, the total energy consumption and specifically the space heat energy consumption before and after the rehabilitation were assessed. The two methods discussed in the methodology were utilized to estimate the realized energy savings directly as the result of the building enclosure rehabilitation.

Of the total energy consumption in the building, the space heat portion is of greatest interest for the building enclosure upgrade analysis. The thermal performance of the building enclosure and air leakage are directly related to the space heat energy consumption. Rehabilitation of the building enclosure typically improves the thermal performance of the enclosure components, including a reduction in the amount of air leakage through the enclosure.

The portion of energy used for space heat can be determined by analyzing the monthly gas or electrical consumption versus a baseline value. The non-space heat baseline is determined from lowest of the July and August consumption when typically the space heat system operates at a minimum depending on thermostat set-point or is turned off. This baseline value can be determined by statistical analysis or visually, and is equal to the average lowest monthly consumption each year. For this building it is assumed that for gas consumption, this baseline is primarily associated with domestic hot water use, and the electrical consumption is all of the non-space heat electricity.

6.1.7 Gas Baseline and Space Heat Determination

Gas metering data for Building 19 is plotted in Fig. 6.1.7.1 from January 1998 through January 2009. The jagged data suggests gas metering errors occurred a few times, primarily during the pre-rehabilitation time period. A visual review and average of the lowest yearly summertime values determines a baseline monthly value of 180 GJ (50,000 ekWh) for both the pre- and post- rehabilitation period.

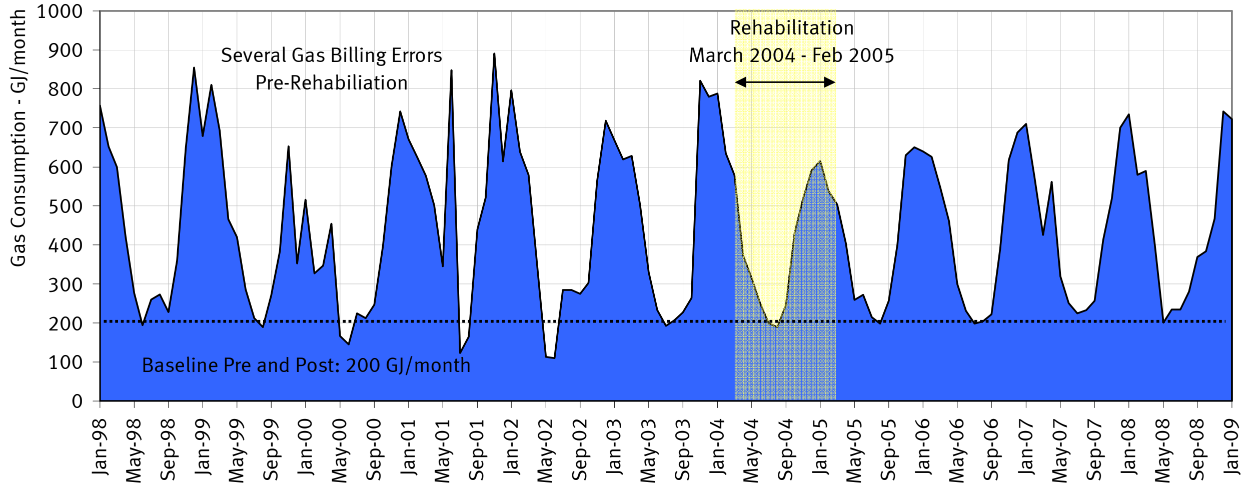


Fig. 6.1.7.1 Monthly Gas Consumption Metering Data, January 1998 to January 2009.

To determine the weather normalized baseline value, the monthly gas consumption data is plotted versus the monthly heating degree day (HDD) value (Fig. 6.1.7.2). Various regression techniques were performed; however, for the gas consumption, a 2nd order polynomial regression best predicts the monthly gas use for a given HDD. While a linear regression provides acceptable correlation, the non-linear polynomial relationship better represents the monthly space heating trends. This is consistent across all of the analyzed buildings: linear correlation where occupants have no control over space heat (i.e. make-up air gas or common area electricity) and polynomial correlation where occupants have control over the thermostat and space heat system.

From this analysis a baseline gas consumption of approximately 199 GJ (55,560 ekWh/month) is also determined. A visual non-weather normalized analysis also supports this baseline of 200 GJ/month.

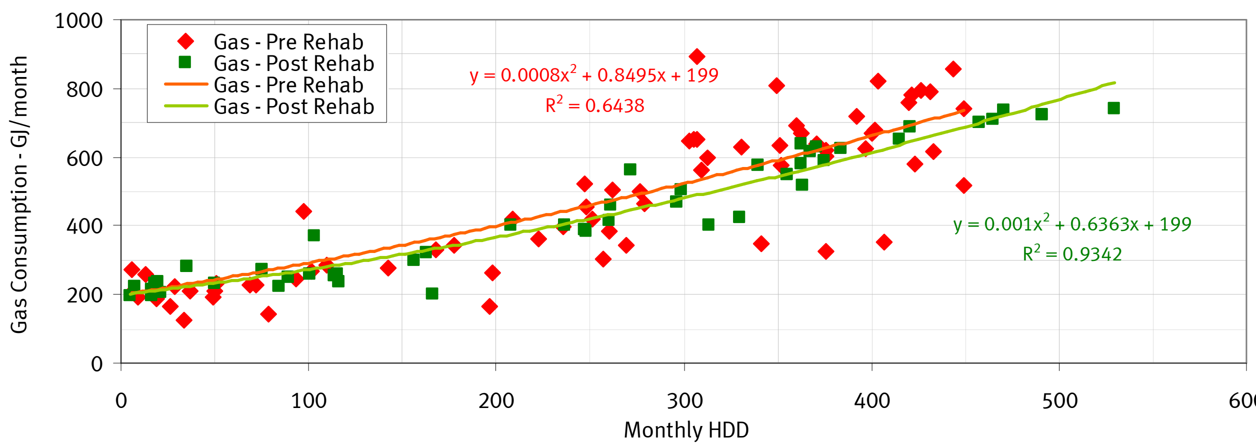


Fig. 6.1.7.2 Monthly Gas Consumption versus Heating Degree Days.

Using the relationships developed for heating degree days versus gas consumption, the monthly pre- and post-rehabilitation gas consumption can be determined for a Vancouver weather normal year (CWEC data, 3019 HDD) and is plotted in Fig. 6.1.7.3 and Fig. 6.1.7.3.

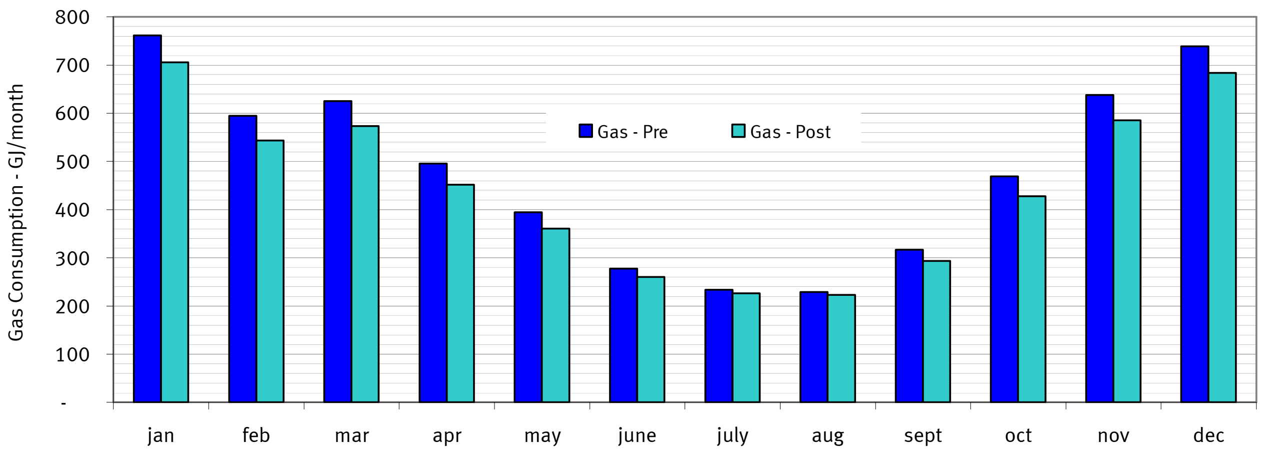


Fig. 6.1.7.3 Weather Normalized Pre- and Post- Rehabilitation Monthly Gas Consumption.

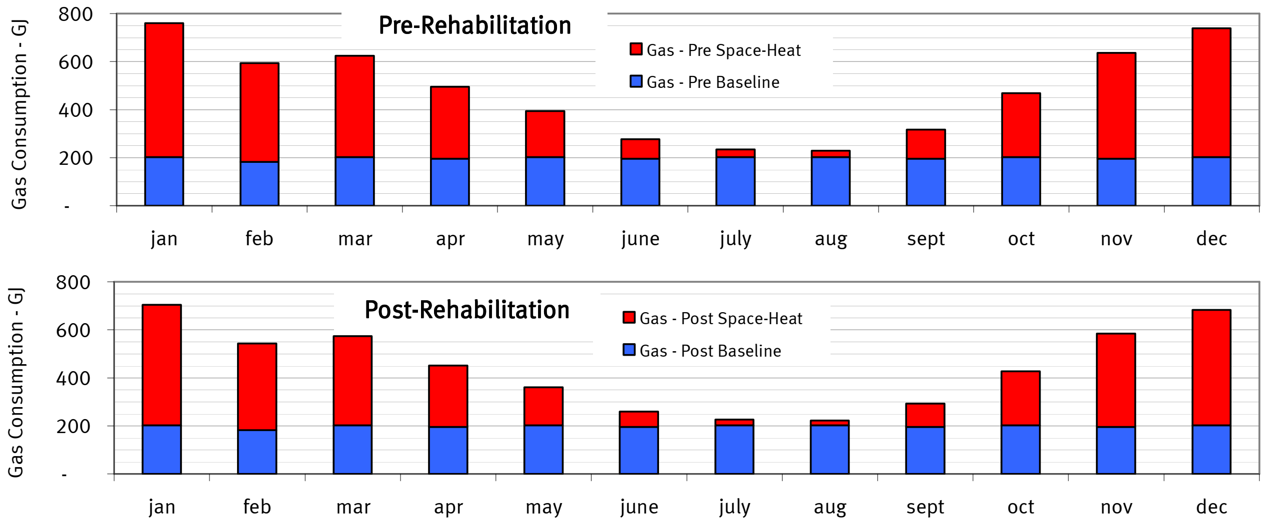


Fig. 6.1.7.4 Weather Normalized Pre- and Post-Rehabilitation Monthly Gas Consumption – Space heat and Baseline.

From the weather normalized gas data, the following conclusions can be made about the impacts of the rehabilitation:

- Annual gas consumption from pre- to post- rehabilitation dropped from 5,773 GJ to 5,334 GJ, a savings of 439 GJ/yr or a reduction of 7.6% of the overall gas usage. The non-weather normalized visual analysis estimated a reduction of 5%. Normalized to the building floor area, this is a reduction of 124.1 kWh/m^2/yr to 114.6 kWh/m^2/yr for a total of 9.4 kWh/ m^2/yr.
- Pre- and post-rehabilitation baseline DHW gas consumption is 2,388 GJ/yr or 25.4 GJ/suite, normalized to 51.3 kWh/m^2/yr.
- Gas used for space heating was reduced from 3,385 GJ/yr to 2,946 GJ/yr for a reduction of 13.0% in the space heating requirement. The non-weather normalized visual analysis also estimated a reduction of 9%. Pre-rehabilitation gas used for space heating accounts for 59% of the total gas consumption, and 55% post-rehabilitation. When normalized, the gas space heat consumption is reduced from 72.7 kWh/m^2/yr to 63.3 kWh/m^2/yr or by 9.4 kWh/ m^2/yr.

Gas Consumption for Make-up Air Ventilation

Based on the make-up air unit (MAU) specifications, set-point temperature, estimates of seasonal efficiency and heating degree days for the normalized weather year, the MAU gas use can be estimated. The gas energy consumption of the MAU unit for ventilation can then be separated from that used by the hydronic heat. Table 6.1.7.1 summarizes the specifications and assumptions for the make-up air unit.

Table 6.1.7.1 Building 19 Make-up Air Unit Specifications

Model	Eng Air S-350
Age	1984
Fuel Type	Natural Gas
Input	350 Mbtuh (Max), 175 Mbtuh (Min)
Output	266 Mbtuh
Combustion Efficiency	76%
Set-point Temperature of Supply Air	70°F (21°C)
Supply Air Flow	3500 cfm
Flow Rate/Suite	37 cfm/suite
Fan Motor Power	1 HP
Fan Electricity Use/Year	6535 kWh, running 24/7
Assumptions	
Seasonal Efficiency Calculation from DOE Model	61.5% (Range from 66.4% in winter to 29.1 % in summer)
Fan temperature increase	2°F
Temperature to which gas will heat air	68°F
Heating Degree Hours	162,780 °F-hr at 68°F (6783 °F-day, 3768 °C-day)

The gas consumed by the MAU for ventilation air heat can be estimated using the following formula:

$$Q(Btu) = \frac{1.08(\frac{Btu}{^\circ F \cdot hr \cdot cfm}) \cdot FanFlow(cfm) \cdot HeatingDegreeHours(\frac{^\circ F \cdot hr}{yr})}{SeasonalEfficiency}$$

where the heating degree hours are calculated for the set-point temperature minus the fan temperature rise (i.e. at a balance point of 68°F).

Based on this calculation, the annual gas consumption by the make-up air unit would be in the order of 1,116 GJ (normalized to 24.0 kWh/m^2/yr) pre- and post-rehabilitation unless flow rates were to change as the result of the rehabilitation. Considering the total gas consumption for space heating (MAU and hydronic) at Building 19 is 3,385 GJ pre- and 2,946 post-rehabilitation, this accounts for 33% of the pre- or 38% of the post-rehabilitation gas consumption.

The monthly gas consumption showing the distribution of the make-up air and hydronic gas heat for the pre- and post-rehabilitation weather normalized consumption is estimated in Fig. 6.1.7.5. Further refinement of this analysis and baseline domestic hot water energy is performed in the energy modeling section.

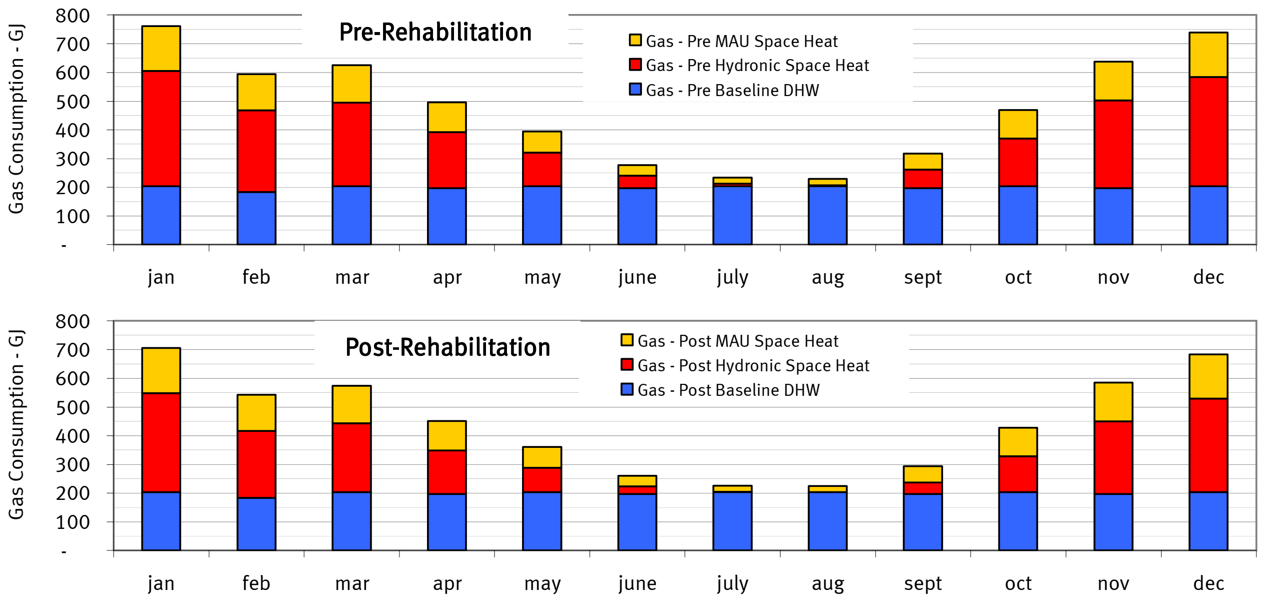


Fig. 6.1.7.5 Weather Normalized Pre and Post Rehabilitation Gas Consumption for DHW, MAU and Hydronic Space Heat.

As shown, the heated ventilation air provides a significant portion of the space heat in Building 19. The effectiveness of this means to supply this ventilation is questionable and therefore affects the effectiveness of the heat provided by this air to the suites. As a large portion of this air will leak out of the building through elevator and stairwell shafts prior to reaching the suites, the effective ventilation heating efficiency is unknown without further research. It should also be noted that the summer-time consumption provides little comfort benefit between the months of June through September and accounts for approximately 136 GJ or 12% of the annual use which could be saved by controls or manual shut-off of the gas heat during those months. For comparison hydronic space heat is in the same order in the summer, however, typically wasted due to mechanical issues previously discussed and suite thermostat settings. An analysis of the impact of the make-up air set-point on energy consumption is presented in the energy modeling section of this report.

6.1.8 Electricity Baseline and Space Heat Determination

Electricity metering data for Building 19 is plotted in Fig. 6.1.8.1 from January 1998 through January 2009. A visual review and average of the lowest yearly summertime values determines a baseline monthly value for both the suites and common areas of the building. Small reductions in the monthly baseline are evident in both the suites and common areas post-rehabilitation as shown in the figure. As the building is primarily heated using gas, only small seasonal variations result due to the use of supplemental electrical heaters.

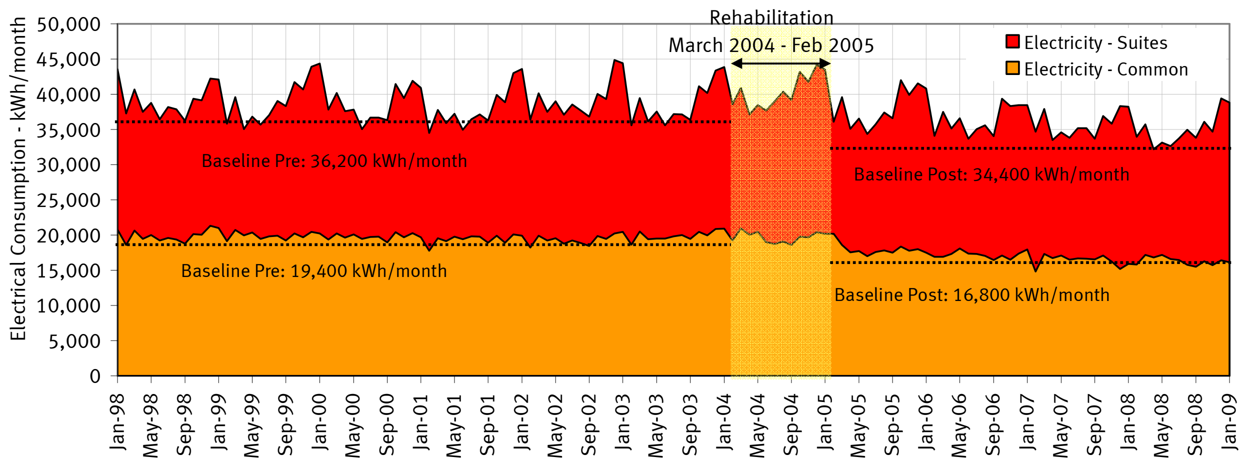


Fig. 6.1.8.1 Monthly Suite and Common Electricity Consumption Metering Data, January 1998 to January 2009.

To determine the weather normalized baseline values, the monthly suite and common electrical consumption data is plotted versus the monthly heating degree day (HDD) value (Fig. 6.1.8.2 and Fig. 6.1.8.3). Various regression techniques were performed; however, for the suite or common electrical consumption at Building 19 linear regression best predicted the electrical use for a given HDD. This is likely because the electrical load has a minimal space heating component. From this analysis, the monthly baseline pre- and post-rehabilitation electrical consumption is determined.

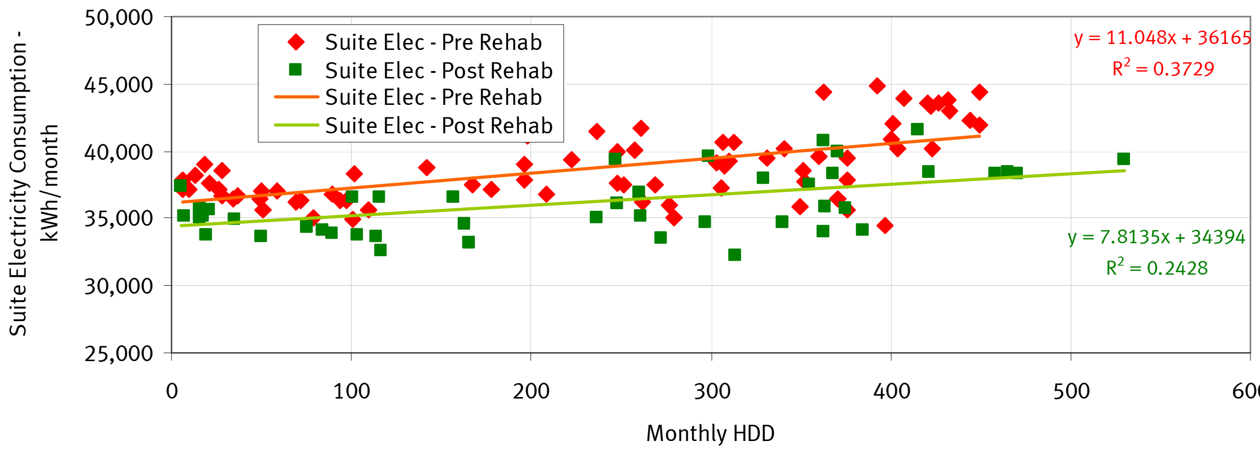


Fig. 6.1.8.2 Monthly Suite Electrical Consumption versus Heating Degree Days.

The suite electrical consumption shows a small monthly reduction in the baseline energy use from pre- to post-rehabilitation. Regression suggests that the monthly baseline drops by 5% from 36,165 kWh to 34,394 kWh/month. The visual assessment estimated a non-weather normalize drop of 35,500 kWh to 34,200 kWh/month (4%) which confirms the linear regression analysis.

Space heating from supplemental electric heaters appears to be reduced as a result of the upgrade.

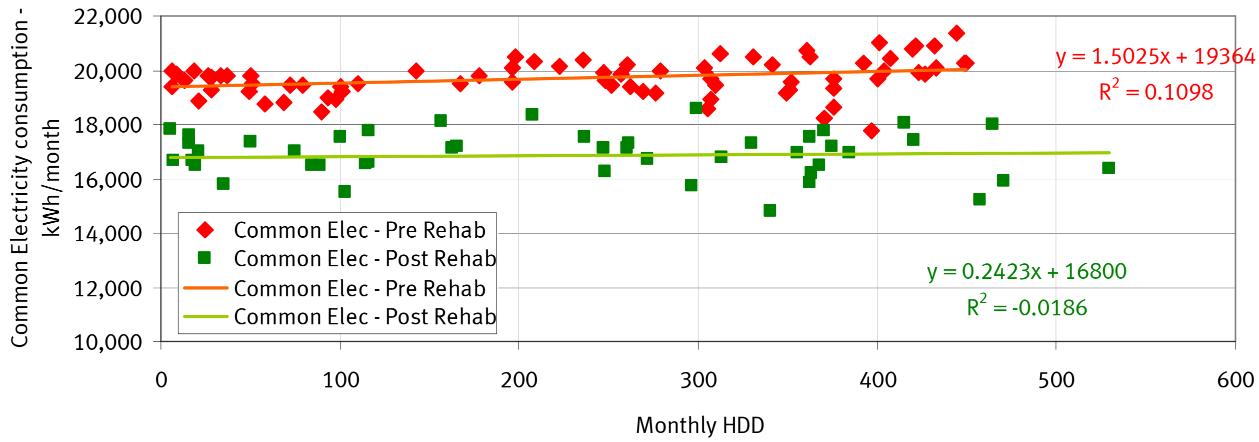


Fig. 6.1.8.3 Monthly Common Electrical Consumption versus Heating Degree Days.

The common electrical consumption shows a distinct reduction in the baseline energy pre- and post-rehabilitation. Regression suggests that the monthly baseline drops from 19,364 kWh to 16,800 kWh/month or by 13%. The visual assessment estimated a drop of 19,200 to 16,200 (16%), which confirms the regression analysis. The monthly heating degree day to energy consumption correlation relationship is poor due to the limited amount of electrical space heat dependent equipment.

While it appears that there is a small amount of common electric space heat used prior to the rehabilitation, this seems to have been eliminated post-rehabilitation. Common area electricity associated with space heating includes any electric baseboard heaters, pump electricity to circulate water for the hydronic system, and the MAU fan (which should be constant year-round).

Using the linear relationship developed for heating degree days versus electricity consumption, the monthly pre- and post-rehabilitation suite and common area electricity consumption can be determined for a Vancouver weather normal year and is plotted in Fig. 6.1.8.4.

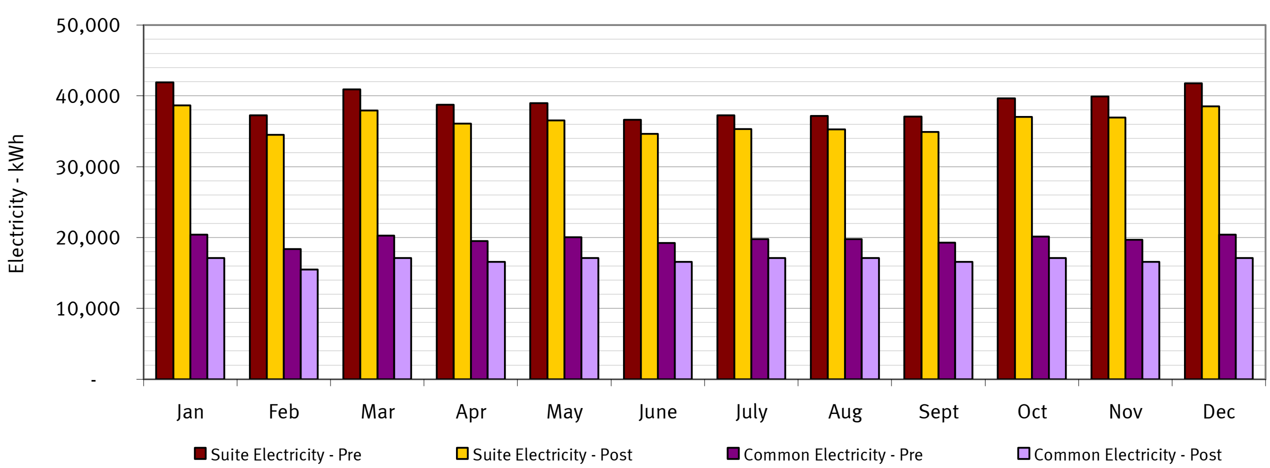


Fig. 6.1.8.4 Weather Normalized Pre- and Post-Rehabilitation Monthly Electrical Consumption.

From the weather normalized electricity data the following conclusions can be made about the impacts of the rehabilitation:

- Total suite electrical consumption from pre- to post-rehabilitation dropped from 4,972 to 4,652 kWh/suite, a savings of 330 kWh/suite/yr and a reduction of 7% of the suite electrical usage. The non-weather normalized visual analysis also estimated a reduction of 7%. Normalized to the building floor area, this is a reduction of 36.2 to 33.8 kWh/m^2/yr or by 2.4 kWh/ m^2/yr.

- The baseline suite electrical consumption was reduced from 4,617 to 4,317 kWh/suite or 5% of the total suite electricity. The non-weather normalized visual analysis estimated a reduction of 4%. Space heat makes up the remaining energy with a reduction from 355 to 251 kWh/suite which is a reduction of 29% of the space heat energy (a large percentage but small absolute reduction). The non-weather normalized visual analysis estimated a larger reduction of 43%; however, the absolute reduction in energy is minimal, so small changes in the estimated kWh result in large percentage differences.
- Total common electrical consumption from pre- to post-rehabilitation dropped from 2,520 to 2,146 kWh/suite, a savings of 375 kWh/suite/yr which is a reduction of 15% of the common electrical usage. The non-weather normalized visual analysis confirmed a reduction of 16%. Normalized to the building floor area, this is a reduction of 18.3 to 15.6 kWh/m^2/yr or by 2.7 kWh/ m^2/yr.
- The baseline common electrical consumption was reduced by 13% from 2,472 to 2,145 kWh/suite. The non-weather normalized visual analysis confirmed a reduction of 14%. Space heat makes up the remaining energy with a reduction of 84% from 51 to 8 kWh/suite (again a negligible absolute reduction).

6.1.9 Space Heat Energy Summary

The purchased space heat energy input for the building can be determined by summing the gas and electrical space heat consumption from the metering data. This does not account for the baseline heating provided by lights, appliances, solar radiation, people, equipment and other items in the building which provide heat but are not considered space heating appliances. Table 6.1.9.1 summarizes the pre- and post-rehabilitation space heat loads.

Table 6.1.9.1 Space Heat Energy Summary for Building 19

Space Heat Energy Source		Pre-Rehabilitation	Post-Rehabilitation
		Energy kWh/m^2/yr, %	Energy kWh/m^2/yr, %
Gas	**TOTAL**	**72.7, 96.1%**	**63.3, 97.2%**
	Hydronic Baseboard System*	48.7, 64.3%	39.3, 60.4%
	Make-up Air*	24.0, 31.7%	24.0, 36.9%
Electricity	**TOTAL**	**2.9, 3.7%**	**1.8, 2.8%**
	Suite: Space heat	2.7, 3.2%	1.8, 2.8%
	Common: Space heat	0.4, 0.5%	0.0, 0.0%
	Total Space Heat Energy	**75.7**	**65.1**

* - The distribution of hydronic space heat to MAU ventilation heat is estimated based on load calculations for the make-up air unit subtracted from the metering data.

As shown, the majority of space heat at Building 19 is from gas as it is a hydronic heated building. The hydronic system accounts for approximately 60% to 65% of the space heat energy with the remainder coming from the gas used to heat the ventilation air. A small amount of electrical energy (supplemental heaters) is also used for space heating within some suites.

The efficiency of the ventilation air delivered to the corridors is poor for several reasons including air leakage through shafts, stairwells, wind and stack-effect and blocked suite door undercuts – this results in poor heating efficiency of this gas space heat. However, the heated air that does get into the suite does reduce the amount of heat input from suite sources. For these reasons, it is likely that the useful space heat from the ventilation air is less than what the metering analysis indicates, but cannot be determined accurately without further information of the actual air flow distribution throughout this building.

6.1.10 Total Energy Consumption and Savings Summary

The energy consumption distribution and energy savings for Building 19 pre- and post-rehabilitation is summarized in Table 6.1.10.1. Fig. 6.1.10.2 and Fig. 6.1.10.3 plots the energy consumption on a monthly basis and Fig. 6.1.10.4 compares energy pre- and post-rehabilitation on an annual basis. The presented data summarizes the above weather-normalized analysis from the metering data.

Table 6.1.10.1 Summary of Pre- and Post- Rehabilitation Energy Consumption for Building 19

		Pre-Rehabilitation	Post-Rehabilitation	Savings		
Energy Source		Energy $kWh/m^2/yr$, %	Energy $kWh/m^2/yr$, %	Energy $kWh/m^2/yr$	% of Space Heat	% of Total Energy
Gas	Space heat: Hydronic Baseboard and MAU ventilation	72.7	63.3	9.4	12.5%	5.3%
	Baseline: Estimated Domestic Hot water	51.3	51.3	0	-	0%
Electricity	Suite: Space heat	2.6	1.8	0.8	1.0%	0.4%
	Suite: All Other	33.6	31.9	1.6	-	0.9%
	Common: Space heat	0.4	0.0	0.3	0.5%	0.2%
	Common: All Other	18.0	15.6	2.4	-	1.3%
Total Space Heat – $kWh/m^2/yr$		**75.7**	**65.1**	**10.5**	**13.9%**	
Total Energy – $kWh/m^2/yr$		**178.5**	**164.0**	**14.5**		**8.1%**
Total Energy – kWh/suite		**24,552**	**22,551**	**2,001**		

Overall, the space heat energy consumption was reduced by 13.9% from 75.7 to 65.1 $kWh/m^2/yr$ as a result of the building enclosure rehabilitation. The majority of this energy is from a reduction in the gas space heat from the hydronic baseboard system and partially suite and common area supplemental electric space heaters. It is possible that a portion of the gas space heat could also have been caused by a change in the pressure regime within the building and a subsequent reduction in the make-up air flow rate (as discussed in the following section).

The total building energy consumption was reduced by 8.1% from 178.5 to 164.0 $kWh/m^2/yr$ as a result of the building enclosure rehabilitation.

During a more typical year in the past decade of 2745 HDD (average of 1998 through 2008 for Vancouver) instead of the weather normalized year of 3019 HDD, the post-rehabilitation energy consumption would be reduced from 164.0 to 157.0 $kWh/m^2/yr$ (with the relative savings remaining the same).

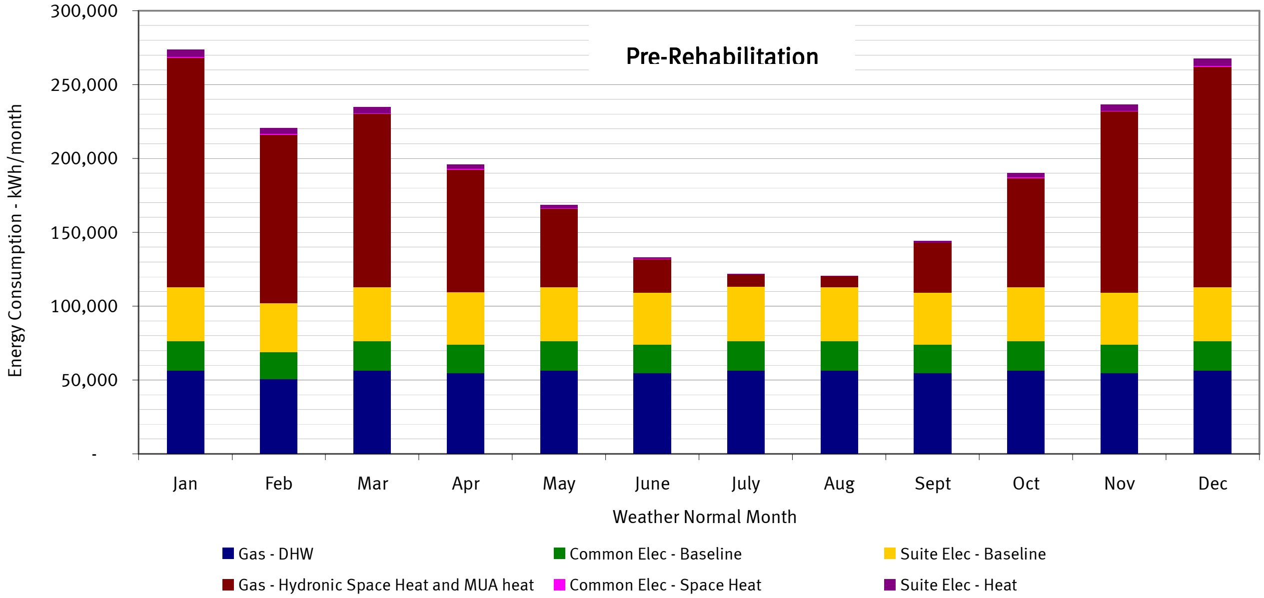


Fig. 6.1.10.2 Pre-Rehabilitation Monthly Energy Consumption, kWh.

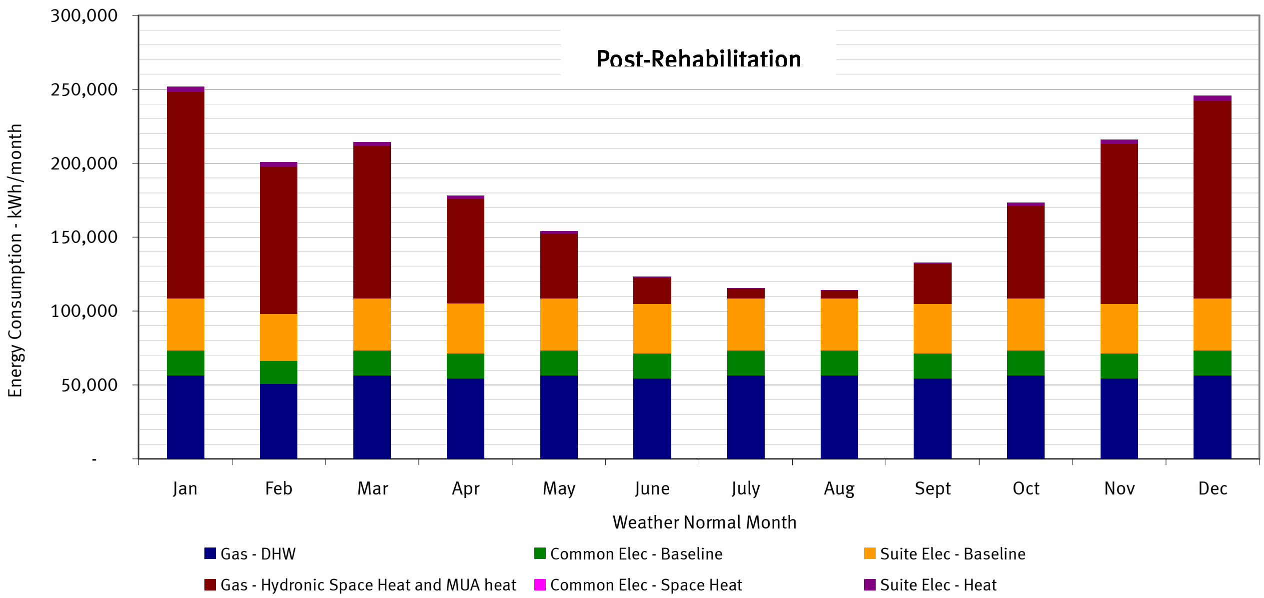


Fig. 6.1.10.3 Post-Rehabilitation Monthly Energy Consumption, kWh.

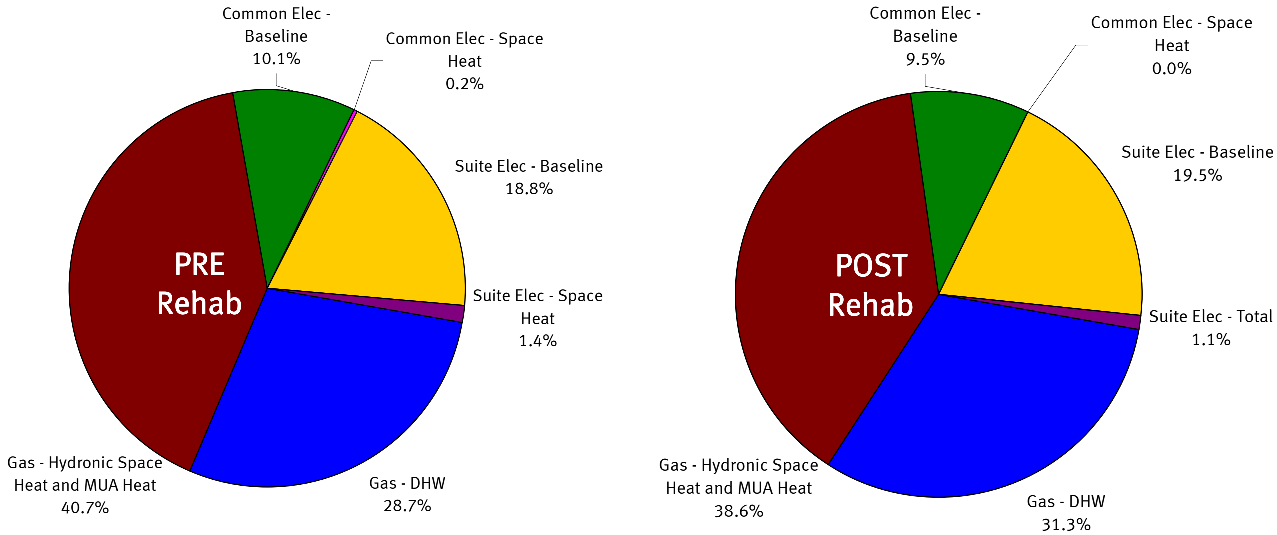


Fig. 6.1.10.4 Pre- and Post-Rehabilitation Annual Energy Consumption Distribution.

While the ventilation MAU gas and hydronic gas is not separated in the plot as was done in the analysis in the previous section, the gas use can further be broken down to show the relative contribution to overall energy use. Pre-rehabilitation, it is estimated that ventilation air heat accounted for 33% of the gas heat consumption, therefore the 40.7% could be broken down into 13.4% MAU ventilation heat and 27.3% hydronic heat. Post-rehabilitation, it was estimated that ventilation air heat accounted for 38% of the gas heat consumption (because the hydronic heat was reduced), therefore the 38.6% could be broken down into 14.7% MAU ventilation heat and 23.9% hydronic heat. Within Building 19 make-up air ventilation gas heat accounts for approximately 13-15% of the buildings entire energy consumption, greater than common electricity at 9-10%, and close to suite electricity of 18-19%.

Of note, supply ventilation rates for this building are 37 cfm/suite provided by the pressurized corridor, which are considered low by current practice, where newer buildings are designed with ventilation air flow rates of up to and exceeding 100 cfm/suite. The higher flow rates in these newer buildings with similar make-up air units of efficiency will result in significantly greater gas energy consumption and is demonstrated in the following section.

6.1.11 Whole Building Energy Modeling and Simulation

Energy simulation was performed for Building 19 to assess the pre- and post-rehabilitation energy savings and to perform further analyses on the energy impact of various design parameters which cannot be performed using the metering data alone. Energy simulation was performed using the software program FAST (Facility Analysis and Simulation Tool), a DOE compliant software package developed by Enersys Analytics. The program has the advantage over many other software packages in that the actual metering data (weather normalized in previous section) can be input into the energy model to improve the accuracy of the energy savings estimates and distribution (i.e. to estimate contribution of DHW, space heat, lights elevators etc.). FAST also allows for modification of the DOE engine code, which was necessary to meter-calibrate the models.

6.1.12 Energy Model Inputs

Energy simulation was performed using the pre- and post-rehabilitation building enclosure parameters as inputs. Two models were prepared for each building, one without metering data (non-meter calibrated) and one with metering data input into the program (meter calibrated). A non-meter calibrated energy simulation would be similar to that performed for a new building prior to construction, and calculates energy consumption based on design assumptions and pre-determined load calculations. In operation, buildings rarely consume the same amount of energy that they were designed to, largely due to occupant behaviour and operation, mechanical system performance and seasonal efficiency (i.e. ventilation and space-conditioning), enclosure assumptions, air leakage, etc. Meter calibrated energy modeling corrects for these initial assumptions and uses monthly weather normalized climate data and monthly gas and electric metering data to improve estimates of space heat energy consumption, and building energy distribution. Meter-calibration factors in how the building is actually operated and is better suited to analyze the impact of various parameters such as air leakage, and to assess the influence of energy saving measures.

Table 6.1.12.1 shows the architectural inputs for the Building 19 energy model. Floor areas, enclosure areas and window percentages were determined from the detailed quantity take-offs. Overall effective wall, roof and window R- and U-values were calculated for the building. The infiltration rate was estimated at an average of 0.15 cfm per square foot of enclosure area at 5 Pa. The effective overall R-values for the wall, roof and window components including thermal bridging are known with a relatively high degree of certainty as shown (Section 6.1.3); however, the change in pre- and post-rehabilitation whole building airtightness is unknown. Rather than estimating the possible pre- and post-rehabilitation air leakage rates for the model input, a constant air leakage rate for both the pre- and post-rehabilitation models was assumed. Parametric analyses were then performed to determine the contribution of the unknown enclosure airtightness and air leakage rate on the space heat and total energy consumption.

Table 6.1.12.1 Architectural Inputs for Building 19

Total Floor Area	139,138		ft²
Percent Area for Common Space	11%		
Number of Suites	94		
Number of Storeys (above grade)	10		
Height of Average Storey	8.7		ft
Orientation from North	315°		
Gross Exposed Wall Area, Wall 1	18,808		ft²
Gross Exposed Wall Area, Wall 2	8,942		ft²
Gross Exposed Wall Area, Wall 3	19,558		ft²
Gross Exposed Wall Area, Wall 4	9,306		ft²
Window Percentage, Wall 1	43%		
Window Percentage, Wall 2	17%		
Window Percentage, Wall 3	34%		
Window Percentage, Wall 4	35%		
Average Infiltration Rate (0.15 cfm/sf)	0.428		ACH @ 5 Pa
	Pre	*Post*	
Overall Roof R-value	14.3	18.3	°F-ft²-hr/Btu
Overall Wall R-value	3.9	5.3	°F-ft²-hr/Btu
Overall Window U-value	0.73	0.46	Btu/°F-ft²-hr
Window Shading Coefficient	0.78	0.37	

Table 6.1.12.2 shows the mechanical inputs for the Building 19 energy model. Of the mechanical inputs required to model the building, some could be determined from the available mechanical information while others were unknown. Inputs in the table that are marked with an asterisk are parameters that could not be determined. For these inputs a standard, typical value was selected for the initial un-calibrated model for all of the buildings. These parameters were varied as necessary for each individual building to achieve meter calibration. Table 6.1.12.2 shows the starting, un-calibrated input assumptions as well as the calibration changes made so that model-predicted energy performance aligned with the meter data. A discussion of the calibrations specific to Building 19 follows presentation of the electrical inputs.

Table 6.1.12.2 Mechanical Inputs for Building 19.

	Un-Calibrated	*Calibration Changes*		
System Type	No Direct Mechanical Ventilation / Central MAU			
Ventilation				
Minimum Outside Air	0.025		cfm/ft² floor area	
Overall Static Pressure	1.30		in. of water	*
Make-up Air Supply Temperature	68	70	°F	*
MAU / Central Air Handler	Gas Heated			
Furnace Heating Efficiency	76%			
Furnace Type	Single Stage			
In-Suite Space Heating				
Space Heating Equipment	Hydronic			
Hydronic Heating Fuel Source	Fossil Fuel			
Boiler Heating Efficiency	75.0%			
Boiler Type	Single Staged			
Baseboard Capacity	None (blank)	3.8	Btu/ft²	*
Baseboards in Common Space?	Yes			
Fireplaces	No			
Auxiliaries				
Fan Efficiency	50%			*
Pump Efficiency	65%			*
Domestic Hot Water (DHW)				
Source	Fossil Fuel			
Heater Type	Single Staged			
Supply Temperature	140		°F	*
Equipment Efficiency	75%	70%		*
Avg. Daily Peak Flow Rate	10.0	11.0	gpm	*
Electric Contribution to DHW (Heat Trace)	0%			
Space Conditions				
Heating Temperature Set-point (Day)	70	72	°F	*
Heating Temperature Setback (Night)	64	70	°F	*

Table 6.1.12.3 shows the electrical inputs for the Building 19 energy model. Standard typical values were selected for the un-calibrated model for all buildings, and these parameters were varied for each building individually such that model output matched the building energy meters. Table 6.1.12.3 shows the typical assumed values used in the un-calibrated model for all buildings, and the changes made to calibrate the Building 19 model. It should be noted that some suites will have supplemental electrical space heaters. This will appear as part of suite electrical consumption in the metered data, and as part of plug load power in the modeled data.

Table 6.1.12.3 Electrical Inputs for Building 19.

	Un-Calibrated	*Calibration Changes*	
Common Area Lighting Power Density	0.32		W/ft²
Suite Lighting Power Density	0.8		W/ft²
Plug Load Power Density	0.55		W/ft²
Peak Average Hourly Elevator Load	32		kW
Exterior Lighting & Miscellaneous Loads	15	16	kW

6.1.13 **Pre-Rehabilitation Calibrations**

The energy model for Building 19 was calibrated to match the metered data by varying the unknown mechanical and electrical input parameters. Model output was compared to energy meters in three divisions, suite electrical consumption, common area electrical consumption and total gas consumption.

Fig. 6.1.13.1 and Fig. 6.1.13.2 show the metered and modeled suite electrical energy consumption for the un-calibrated and calibrated models, respectively. Since Building 19 is heated with hydronic radiators and a gas-fired boiler, the only loads that contribute to space electrical consumption are lights, plug loads and fans, the latter of which is negligible compared to lights and plug loads. The initial assumptions for lighting and plug load densities were quite good for this building, and calibration was not required.

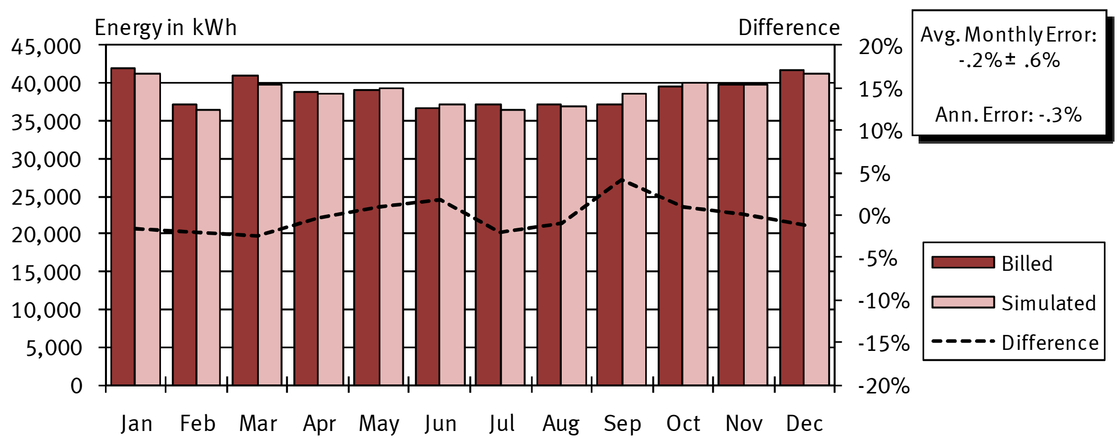


Fig. 6.1.13.1 Un-calibrated metered and modeled suite electrical consumption.

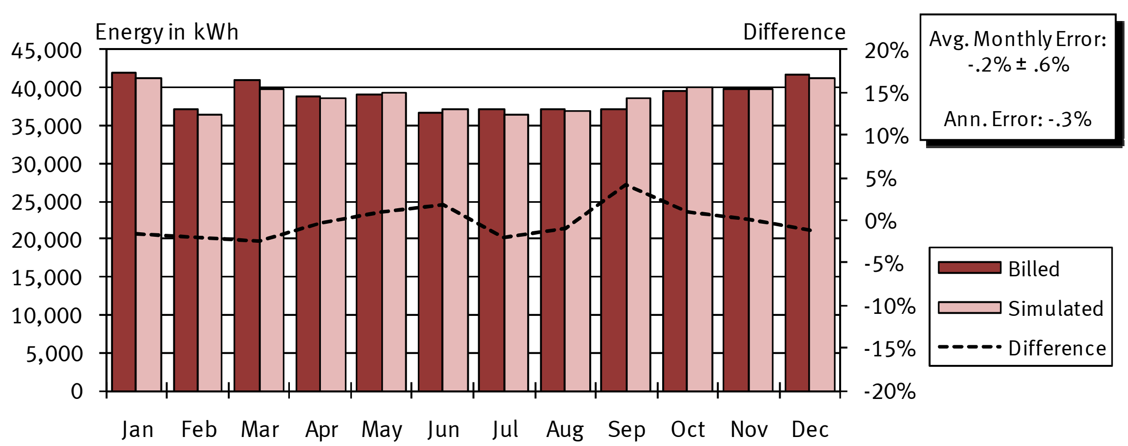


Fig. 6.1.13.2 Calibrated metered and modeled suite electrical consumption.

Fig. 6.1.13.3 and Fig. 6.1.13.4 show the metered and modeled common electrical energy consumption for the un-calibrated and calibrated models, respectively. Common area electricity consists of lighting in lobbies, corridors, stairwells and other common spaces, make-up air fans, exterior lighting, elevators, and any other miscellaneous loads. Most of the model inputs for common loads are unknown and so the un-calibrated model was based primarily on the initial assumptions. The un-calibrated modeled annual electrical energy consumption was 3% lower than the actual metered consumption. The miscellaneous loads were increased from 15 kW to 16 kW to improve the calibration.

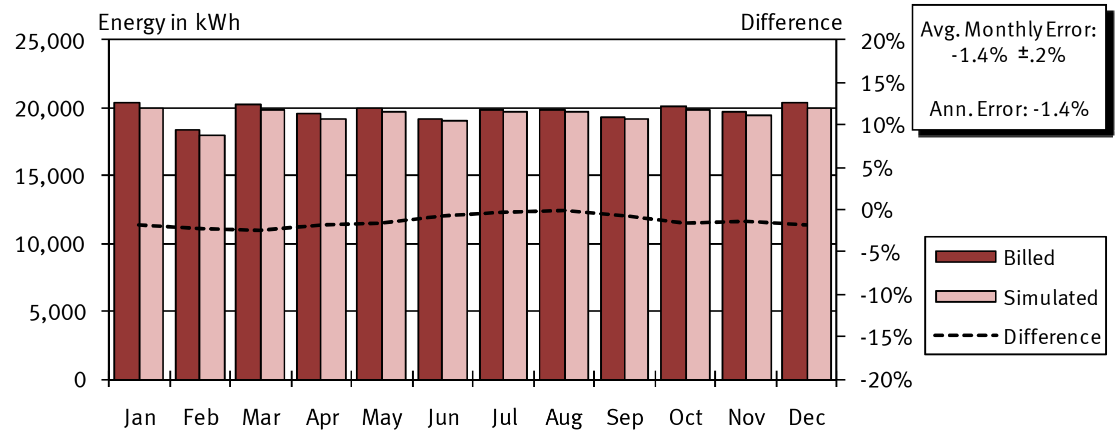


Fig. 6.1.13.3 Un-calibrated metered and modeled common electrical consumption.

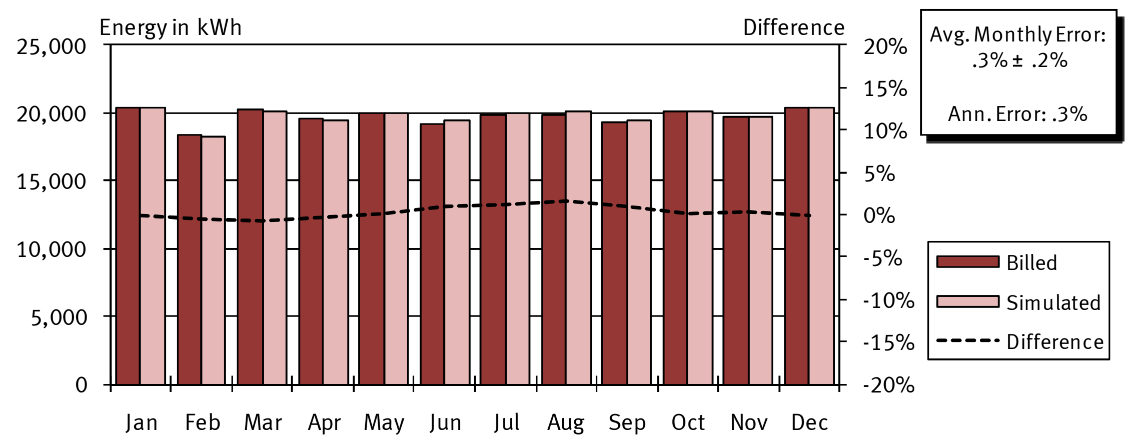


Fig. 6.1.13.4 Calibrated metered and modeled common electrical consumption.

Fig. 6.1.13.5 and Fig. 6.1.13.6 show the metered and modeled gas energy consumption for the un-calibrated and calibrated models, respectively. The un-calibrated model showed 18% less gas consumption than the metered data over the course of a year. Gas energy consumption for Building 19 consists of domestic hot water (DHW) heating, make-up air heating and space heating. The July and August gas load shows the DHW load as there is little or no space and make-up air heating in these months. To calibrate DHW, the DHW equipment efficiency was reduced and the flow rate was increased. A greater increase in gas consumption was required in heating months. To calibrate the model, make-up air supply temperature was raised, baseboard capacity was increased and heating temperature set-point and setback were increased.

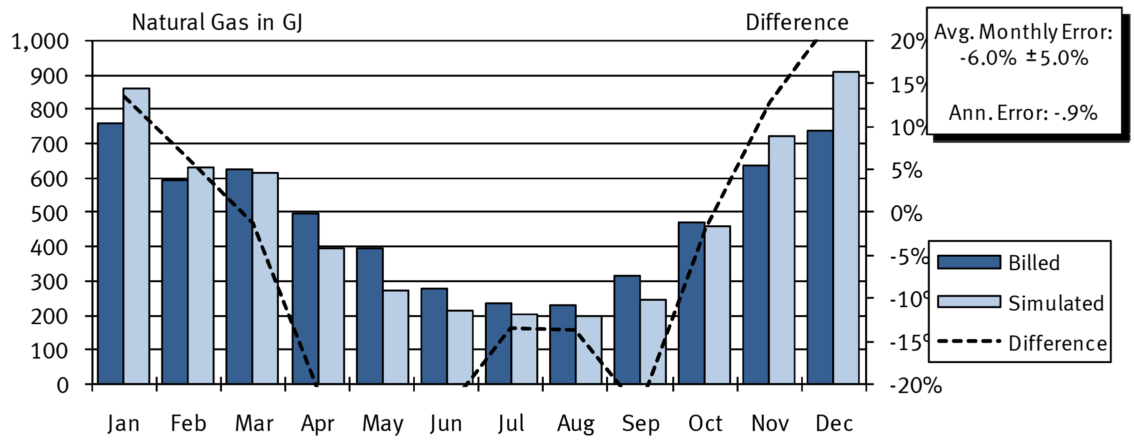


Fig. 6.1.13.5 Un-calibrated metered and modeled gas consumption.

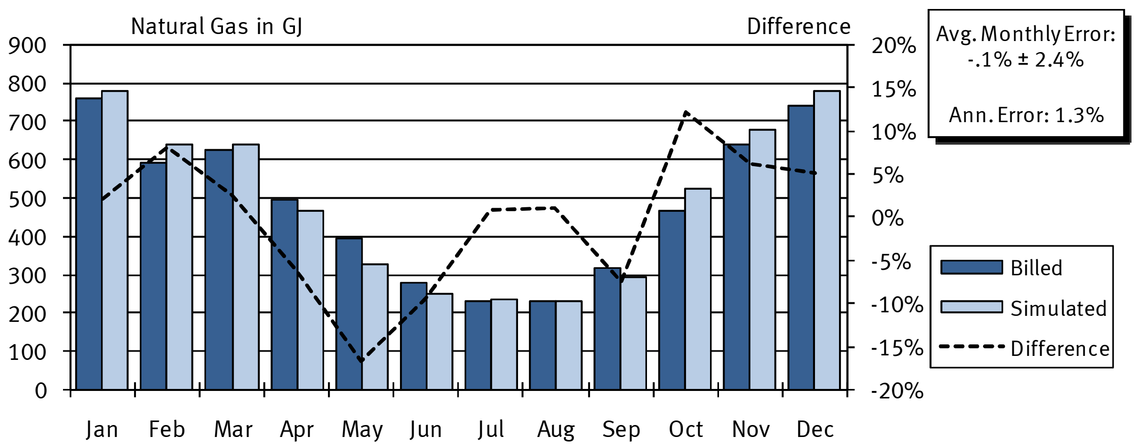


Fig. 6.1.13.6 Calibrated metered and modeled gas consumption.

6.1.14 Post-Rehabilitation Calibrations

Once the pre-rehabilitation models had been calibrated, the post-rehabilitation wall enclosure changes were entered into the model and the resulting post model results were compared to the post metered energy data.

Fig. 6.1.14.1 shows the metered and simulated suite electrical energy consumption. Annual metered suite electrical consumption was 7% lower than the simulated energy consumption. Since Building 19 does not have electrical space heating and suite electricity consists only of lighting and plug loads, the reason for the pre-post drop in suite electricity is unknown. Occupants could be using supplemental electric space heaters less often due to the thermally improved enclosure. There may have been some other change, such as higher efficiency lighting may have been installed, or the reduction may be attributed to a change in occupant behaviour.

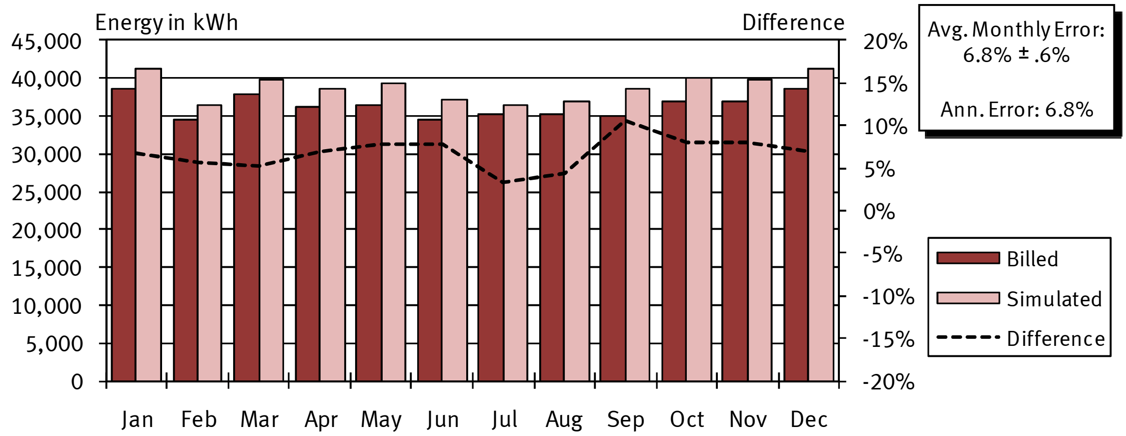


Fig. 6.1.14.1 Post-rehabilitation metered and modeled suite electrical consumption.

Fig. 6.1.14.2 shows the metered and simulated common electrical energy consumption. Annual metered common electrical consumption was 18% lower than simulated electrical consumption. The reason for the significant drop from pre- to post-metered electrical energy consumption is unknown.

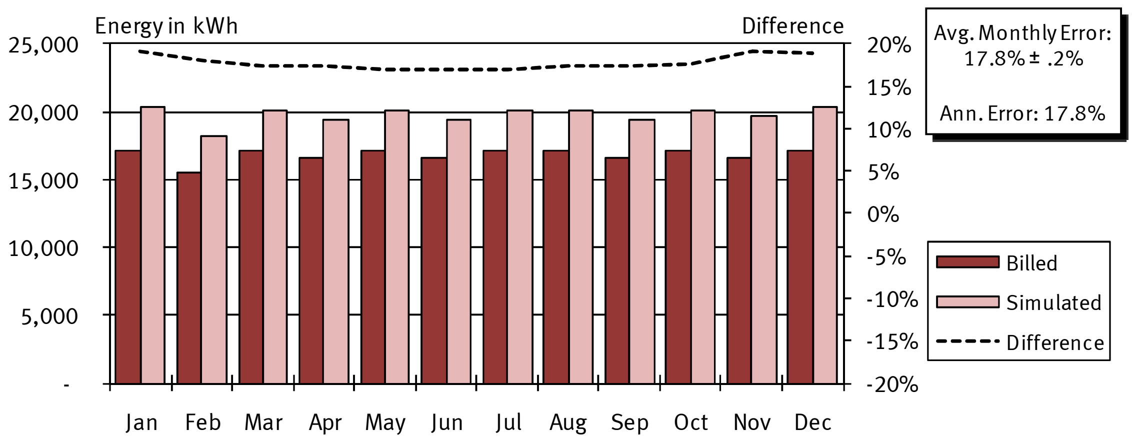


Fig. 6.1.14.2 Post-rehabilitation metered and modeled common area electrical consumption.

Fig. 6.1.14.3 shows the metered and simulated gas energy consumption. The modeled results are very close to the metered data, with only 0.1% difference over the course of the year.

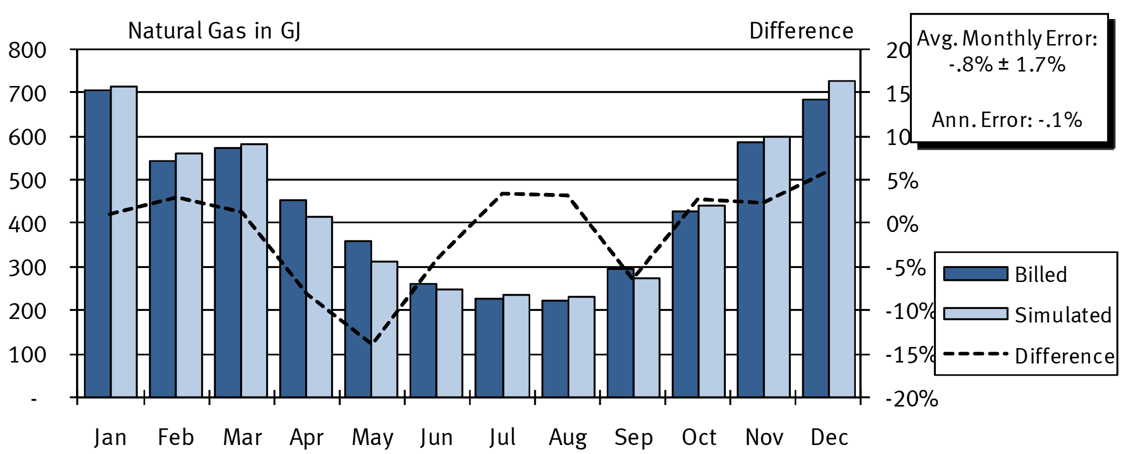


Fig. 6.1.14.3 Post-rehabilitation metered and modeled gas consumption.

6.1.15 Predicting Annual Energy Consumption and Potential Rehabilitation Savings using Energy Modeling

Table 6.1.15.1 presents the normalized energy consumption from the metering data presented in the previous sections, and estimated by the two energy models (un-calibrated and calibrated) for both the pre- and post-rehabilitation building cases. The only differences between the pre- and post-rehabilitation cases are the change in wall, roof, and window R-values and the window glazing solar-heat gain coefficient (as a result of the low-e coating).

It should be noted that the energy model is not set up to account for the small supplemental electric resistance heaters as used in some of the suites. The energy consumed by this source is low (3.1 reduced to 2.0 kWh/m^2/yr) and is not included in the meter calibrated analysis as space heat, but is included in the total energy consumption value.

Table 6.1.15.1 Comparison of Actual and Modeled Annual Energy Consumption.

Case	**Pre-Rehabilitation Energy Consumption**				**Post-Rehabilitation Energy Consumption**			
	Gas Space Heat	Gas DHW	Electricity – All	Total	Gas Space Heat	Gas DHW	Electricity – All	Total
	Normalized to kWh/m^2/yr of floor area				Normalized to kWh/m^2/yr of floor area			
Metering Consumption Analysis – Estimated Distribution	**72.7**	**51.3**	**54.5**	**178.5**	**63.3**	**51.3**	**49.3**	**163.9**
Post % savings					**13%**	**0%**	**9.4%**	**8.1%**
Modeled – **Non-Meter Calibrated,** Default Output	85.4	37.5	54.1	177.0	66.4	37.5	54.1	158.0
% Difference to Meter Data	17.4%	-26.8%	-0.7%	-0.8%	4.9%	-26.8%	9.6%	-3.6%
Comments	Over-estimated space heat, under-estimated gas DHW.							
Post % Savings					**22.2%**	**0%**	**0%**	**10.7%**
Comments					Over-estimated gas space heat savings.			
Modeled – **Meter calibrated,** Corrected Output	81.3	44.3	54.4	180.0	70.3	44.3	54.4	168.9
% Difference To Meter Data	11.8%	-13.7%	-0.1%	0.9%	11.0%	-13.7%	10.3%	3.1%
Comments	Total energy consumption very close. Gas consumption better but distribution still different from metering estimates; DHW underestimated in metering since analysis did not account for summer space heat consumption.							
Post % Savings					**13.6%**	**0%**	**0%**	**6.1%**
Comments					Total savings prediction closer to actual.			

The modeling exercise demonstrates the benefit of meter calibrating the pre- and post-rehabilitation energy consumption. Both the un-calibrated and calibrated models showed low percent difference in total energy consumption; however, the un-calibrated model has incorrect distribution between space heating and DHW. The calibrated model distribution is closer to the metered data. The remaining difference is because DHW consumption was under-estimated in the metered analysis. The model results indicate there is some space heating gas consumption in the summer months, and this could not be accounted for in the meter analysis.

By using the meter calibrated pre- and post-rehabilitation energy models further parametric analyses can be performed to assess the impacts of various parameters on energy consumption. The enclosure upgrades studied are wall R-value, window U-value, and enclosure airtightness. The mechanical upgrades studied are make-up air temperature set-point, make-up air flow rate, and heat recovery ventilation.

6.1.16 Distribution of Energy Consumption

The calibrated energy model can be used to determine the distribution of total building energy consumption at Building 19. Fig. 6.1.16.1 shows the annual building energy consumption by component in kWh/m^2 and percentage of total. Overall, 45% of energy is used for space heating, 25% is used for DHW heating, and 30% is electricity for lighting, plug loads, appliances and other equipment.

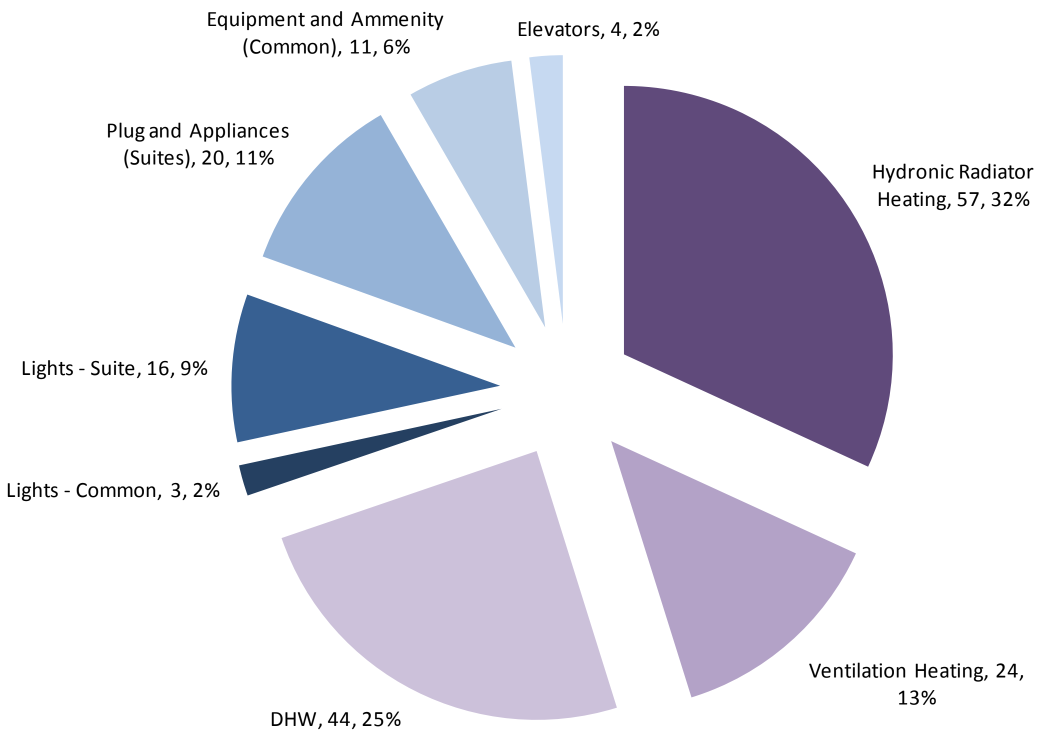


Fig. 6.1.16.1 Distribution of total building energy consumption, kWh/m^2 and percentage of total.

6.1.17 The Impact of Individual Enclosure Upgrades on Energy Consumption

Energy modeling was performed on post-rehabilitation building cases to determine the relative incremental impact of the thermal improvements made to the exterior walls, roof and windows. Additional parametric simulations were also performed to show the potential for better insulated exterior walls and higher performance windows up-to and beyond current practice and building code requirements.

Incremental building enclosure thermal improvements are not additive for energy reductions (i.e. one cannot simply add the individual energy savings from a window upgrade to the savings from wall upgrade together), because of depreciating returns on the additional insulating value. Upgrades must be considered in a package. This complicates the assessment returns to doing only a wall or only a window upgrade. The simulations here assume a fixed baseline configuration and present the relative change from that baseline.

The Impact of Wall Thermal Performance

Energy simulations were performed to assess the impact of modifying only the wall R-value on space heat energy consumption. Table 6.1.17.1 shows the R-values that were modeled by changing only the R-value in the calibrated pre- and post-rehabilitation models. The difference between the pre- and post- models are that the post scenarios include the upgraded roof R-value, window U-value and window SHGC.

Table 6.1.17.1 Summary of scenarios modeled for wall thermal performance.

	Pre R-Value [hr-ft^2-F/Btu]	Post R-Value [hr-ft^2-F/Btu]
Baseline	3.9	5.3
Excluding Balconies	4.4	6.5
Effective R10	10.0	10.0
ASHRAE Standard 90.1	15.6	15.6
ASHRAE Standard 189	18.2	18.2

Table 6.1.17.2 and Fig. 6.1.17.2 show the annual space heating energy consumption of each scenario that was modeled. Dollar savings shown in Table 6.1.17.2 are based on a gas cost of $11/GJ. The baseline pre- and post-space heat consumption is 81.3 kWh/m^2 and 70.3 kWh/m^2, respectively. The rehabilitation enclosure upgrade alone would have reduced space heat energy consumption by 11.0 kWh/m^2. The scenario results show that an enclosure that meets the ASHRAE Standard 189 requirement of R-18.2 effective walls would reduce space heat energy consumption by 20%.

The scenarios show the importance of accounting for thermal bridging in the energy model. Thermal bridging reduces the effective R-value of exterior walls. Had balconies been neglected in the model, annual space heat energy consumption would be under-predicted by 2.4% in the pre-rehabilitation model and 5.2% in the post-rehabilitation model.

Table 6.1.17.2 Impact of wall thermal performance on annual space heat consumption.

Wall	R-Value	Annual Space Heat Consumption		Space Heat Savings from Baseline	2010 Dollar Savings from Baseline
		GJ	kWh/m^2/yr		
Pre-Rehabilitation					
Baseline	3.9	3786	81.3	-	-
No Balconies	4.4	3695	79.4	2.4%	$1,003
Effective R10	10.0	3249	69.8	14.2%	$5,910
ASHRAE 90.1	15.6	3094	66.5	18.3%	$7,606
ASHRAE 189	18.2	3053	65.6	19.3%	$8,056
Post-Rehabilitation					
Baseline	5.25	3271	70.3	-	-
No Balconies	6.52	3102	66.6	5.2%	$1,865
Effective R10	10.00	2820	60.6	13.8%	$4,968
ASHRAE 90.1	15.60	2626	56.4	19.7%	$7,093
ASHRAE 189.1	18.20	2577	55.4	21.2%	$7,639

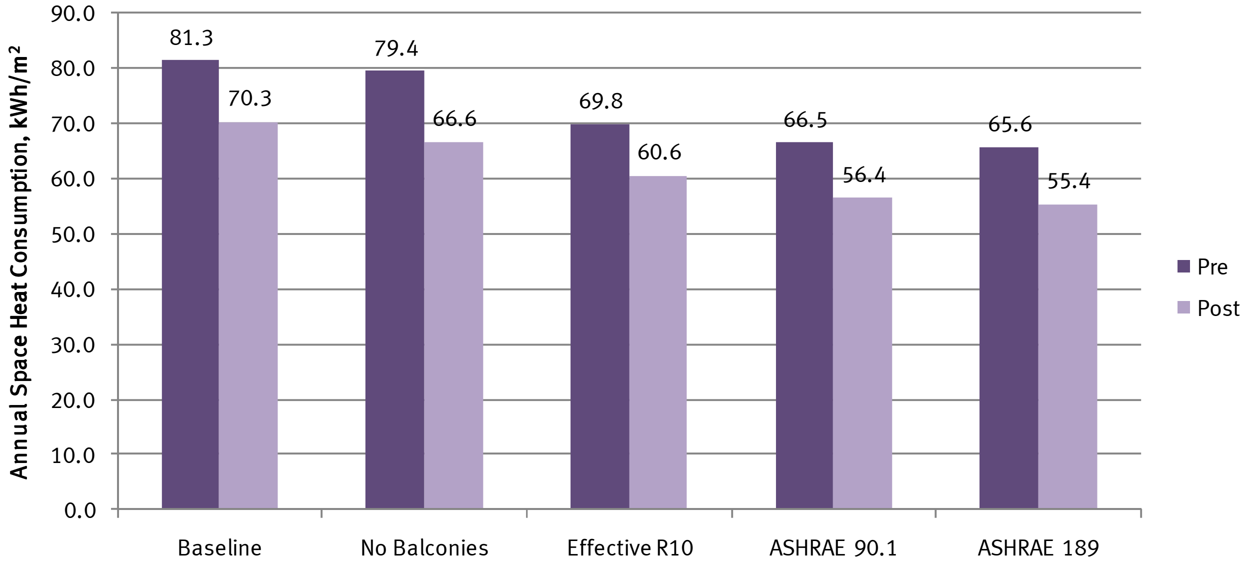


Fig. 6.1.17.2 Impact of wall thermal performance on annual space heat consumption.

The Impact of Roof Thermal Performance

Energy simulations were performed to assess the impact of modifying only the wall R-value on space heat energy consumption. Table 6.1.17.3 shows the R-values that were modeled by changing only the R-value in the calibrated pre- and post-rehabilitation models. The difference between the pre- and post- models are that the post scenarios include the upgraded wall R-value, window U-value and window SHGC.

Table 6.1.17.3 Summary of scenarios modeled for roof thermal performance.

	Pre R-Value [hr-ft^2-F/Btu]	Post R-Value [hr-ft^2-F/Btu]
Baseline	14.3	18.3
Effective R20	20	20
Effective R30	30	30
Effective R40	40	40
Effective R50	50	50

Table 6.1.17.4 and Fig. 6.1.17.3 show the annual space heating energy consumption of each scenario that was modeled. Dollar savings are based on a gas cost of $11/GJ. The baseline pre- and post- space heat consumption is 81.3 kWh/m^2 and 70.3 kWh/m^2, respectively. Increasing the roof R-value has a very small effect on space heating consumption. Increasing the roof R-value to R-50 reduces annual space heat consumption by only 2%. Other energy efficiency measures may provide much greater energy savings.

Table 6.1.17.4 Summary of scenarios modeled for roof thermal performance.

Wall	R-Value	Annual Space Heat Consumption		Space Heat Savings from Baseline	2010 Dollar Savings from Baseline
		GJ	kWh/m²/yr		
Pre-Rehabilitation					
Baseline	14.3	3786	81.3	-	-
Effective R20	20.0	3763	80.8	0.6%	$246
Effective R30	30.0	3743	80.4	1.1%	$466
Effective R40	40.0	3732	80.2	1.4%	$588
Effective R50	50.0	3725	80.0	1.6%	$668
Post-Rehabilitation					
Baseline	18.30	3271	70.3	-	-
Effective R20	20.00	3264	70.1	0.2%	$76
Effective R30	30.00	3235	69.5	1.1%	$399
Effective R40	40.00	3235	69.5	1.1%	$399
Effective R50	50.00	3207	68.9	2.0%	$704

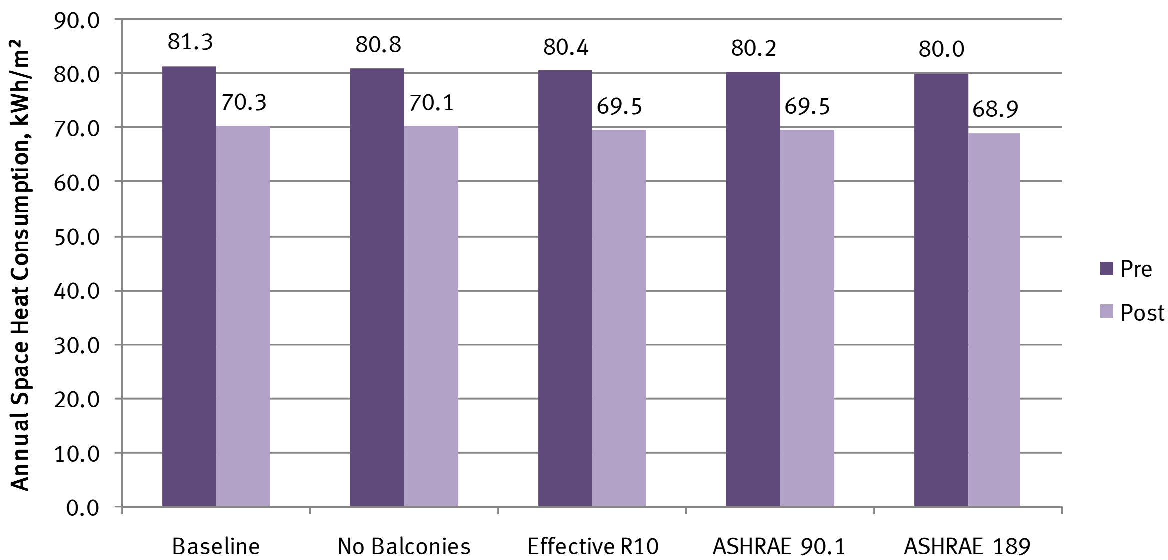


Fig. 6.1.17.3 Impact of roof thermal performance on annual space heat consumption.

The Impact of Window Thermal Performance

Energy simulations were performed to assess the impact of modifying the window (and door) U-value and solar heat gain coefficient (SHGC) on space heat energy consumption. The post-rehabilitation windows consist of thermally-broken aluminum window frames with relatively good IGUs which are typical with current construction practices. Higher performance aluminum frame windows with larger thermal breaks, better low-e coatings, and argon fill, will achieve U-values slightly better than U-0.48 overall; however, when all framing elements are considered (operable frames, corners, intermediate mullions etc.) the overall U-values for aluminum window frame assemblies, are typically limited to approximately U-0.40, possibly U-0.33 with triple glazing. However, significant improvements in overall window U-values can be made by switching from aluminum to low-conductivity frame materials. Overall window assembly U-values of U-0.29 to U-0.25 overall with double glazing and up to U-0.17 with triple glazing are possible when non-conductive frames are used.

Table 6.1.17.5 shows the scenarios that were modeled by changing only the U-value and SHGC in the calibrated pre- and post-rehabilitation models. The difference between the pre and post models is that the post scenarios also include the improved wall and roof R-values. The modeled U-values were chosen based on typical values for double and triple glazed windows with argon gas fill and thermally improved frames, such as vinyl or fibreglass frames. Windows that meet the *BC Energy Efficiency Act* were modeled, which requires a U-value of 0.45 hr-ft^2-F/Btu.

Table 6.1.17.5 Summary of scenarios modeled for window thermal performance.

	U-Value [hr-ft^2-F/Btu]	SHGC
Baseline Pre	0.73	0.68
Baseline Post	0.46	0.32
Baseline Post with Pre SHGC	0.46	0.68
BC Energy Efficiency Act (metal frames)	0.45	0.40
BC Energy Efficiency Act (metal frames)	0.45	0.30
Double Glazed with Vinyl or Fibreglass Frame	0.27	0.40
Double Glazed with Vinyl or Fibreglass Frame	0.27	0.30
Triple Glazed with Vinyl or Fibreglass Frame	0.17	0.30
Triple Glazed with Vinyl or Fibreglass Frame	0.17	0.20

Table 6.1.17.6 and Fig. 6.1.17.4 show the annual space heating energy consumption of each scenario that was modeled. Dollar savings shown in Table 6.1.17.2 are based on a gas cost of $11/GJ. The baseline pre- and post-space heat consumption is 81.3 kWh/m^2 and 70.3 kWh/m^2, respectively. The simulation results show that windows that meet the *BC Energy Efficiency Act* standard for metal frames would reduce the post-rehabilitation space heating energy consumption by an additional 3% (2 kWh/m^2/year) compared to the windows used for the rehabilitation work, which provide similar performance characteristics. Moving to double glazed with a non-metal frame would reduce post-rehabilitation space heating by 19% (13 kWh/m^2/year). Triple glazed windows with a non-metal frame would reduce post-rehabilitation space heating by 26% (18 kWh/m^2/year).

Table 6.1.17.6 Impact of window U-value and SHGC on annual space heat consumption.

Window	**Annual Space Heat Consumption**		**Space Heat Savings from Baseline**	**2010 Dollar Savings from Baseline**
	GJ	**kWh/m^2/yr**		
Pre-Rehabilitation				
Baseline	3786	81.3	-	-
U = 0.45, SHGC = 0.4	3465	74.4	8.5%	$3,533
U = 0.45, SHGC = 0.3	3556	76.4	6.1%	$2,529
U = 0.27, SHGC = 0.4	2997	64.4	20.8%	$8,672
U = 0.27, SHGC = 0.3	3082	66.2	18.6%	$7,740
U = 0.17, SHGC = 0.3	2783	59.8	26.5%	$11,028
U = 0.17, SHGC = 0.2	2928	62.9	22.7%	$9,434
Post-Rehabilitation				
Baseline	3271	70.3	-	-
Post U-Value with Pre SHGC	2974	63.9	9.1%	$3,274
U = 0.45, SHGC = 0.4	3178	68.3	2.9%	$1,029
U = 0.45, SHGC = 0.3	3273	70.3	0.0%	-$15
U = 0.27, SHGC = 0.4	2656	57.0	18.8%	$6,774
U = 0.27, SHGC = 0.3	2739	58.8	16.3%	$5,858
U = 0.17, SHGC = 0.3	2417	51.9	26.1%	$9,399
U = 0.17, SHGC = 0.2	2556	54.9	21.9%	$7,873

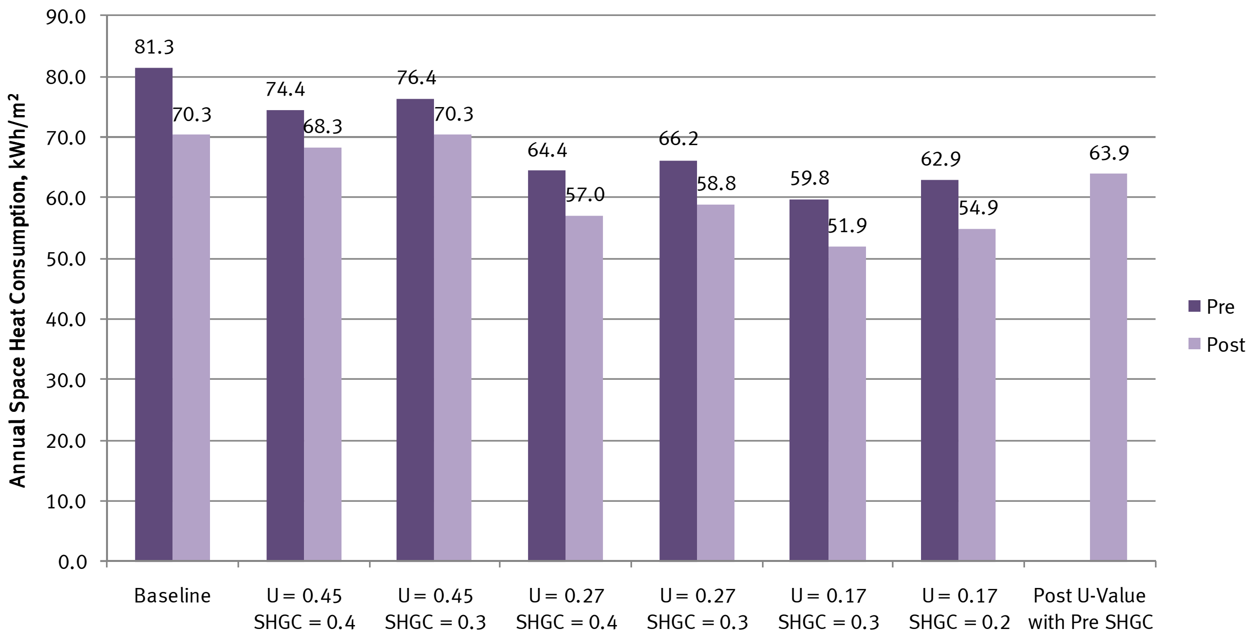


Fig. 6.1.17.4 Impact of window U-value and SHGC on annual space heat consumption.

While reducing the U-value reduces annual space heating energy consumption, lowering the SHGC increases space heating and total building energy consumption since solar heat gain may offset some or all of the required space heat. Building 19 does not have mechanical cooling; if it did, lowering the SHGC would decrease cooling energy. Some suites may have plug-in air conditioners, in which case lowering the SHGC would reduce suite electrical consumption, however, this effect is not captured by the model and it is unknown how many (if any) suites have air conditioners. Regardless of annual energy consumption, a low SHGC may be important for occupant comfort in preventing overheating of the suites. A high SHGC should not be selected just because the model shows that it results in lower energy consumption.

The effect of varying only the SHGC is seen in the model of the baseline post-rehabilitation scenario with the pre-rehabilitation SHGC. The baseline post space heating energy consumption is 70.3 kWh/m^2/year, and the post with pre SHGC is 63.9 kWh/m^2/year. Increasing the post SHGC from 0.37 to 0.68 reduced annual space heating energy consumption by 6.4 kWh/m^2/year, or 9%. However, low solar heat gain is typically preferred in the Lower Mainland to reduce overheating and offset the need for air-conditioning in MURBs. Changing the SHGC from 0.4 to 0.3 in the scenario with double glazed windows with a thermally improved frame (U = 0.27), post-rehabilitation space heating energy is increased from 57.0 kWh/m^2/year to 58.8 kWh/m^2/year, a difference of 1.8 kWh/m^2/year or 3%. Changing the SHGC from 0.3 to 0.2 in the scenario with triple glazed windows and a thermally improved frame (U = 0.17), post-rehabilitation space heating energy increases from 51.9 kWh/m^2/year to 54.9 kWh/m^2/year, a difference of 3.0 kWh/m^2/year or 4%. The effect of reducing the window U-value has a much greater impact on energy consumption than the SHGC.

Solar heat gain may be optimized through the use of exterior shading. Exterior shading strategies allow solar heat gain during heating seasons and block solar heat gain during cooling seasons. Exterior shading was not analyzed in this study.

6.1.18 The Impact of Airtightness and Air Leakage on Energy Consumption

Airtightness is a measure of the air-porosity of the assemblies that make-up the building enclosure at a certain pressure difference. Airtightness can be visualized in terms of an equivalent sized hole in the building enclosure. Typically airtightness is measured at a standard test pressure of 50 or 75 Pa to overcome the effects of wind and stack effect and obtain a repeatable measurement. The measured effective airtightness rate changes with building pressurization (both positive and negative) due to deformation of air barrier elements (i.e. membranes or gaskets) and as the result of complicated flow regimes through wall, roof and window assembly elements.

Air leakage is defined as the uncontrolled flow of air through the building enclosure (i.e. infiltration or exfiltration) as the result of building pressurization and the enclosure airtightness. Air leakage results in natural ventilation (albeit with limited ventilation effectiveness and mixing) and is separate from mechanical ventilation. Mechanical ventilation systems induce pressures across the building enclosure which also result in air leakage, in addition to uncontrolled natural infiltration/exfiltration (caused by stack or wind pressures). The air leakage rate for a building at a certain point in time is determined from the airtightness of the enclosure and the pressure that the building is operating under.

In terms of energy consumption, air that exfiltrates the building results in a direct loss of heat energy whereas air that infiltrates the building requires additional heat energy to bring it to indoor conditions. In a MURB, the heat energy input required to offset air leakage energy loss may not always be required in the suite in which it was lost from. For example, under winter-time stack-effect, air will typically infiltrate lower floor suites and exfiltrate at upper floor suites resulting in additional heating required at lower suites whereas upper floor suites may be too hot. Similarly wind and mechanical pressurization will also effect infiltration and exfiltration through suites in the building and vary with time and season. Add-in the compounding influence of operable windows and occupant behaviour (such as opening windows to reduce heat at the upper floor suites) and the effective airtightness becomes very difficult to determine, as does the building pressurization (suite and whole building) used to predict the air leakage rate of a MURB.

Because of the difficulty and costs associated with measuring MURB assembly airtightness under operating conditions, and the limited number of field measurements of natural infiltration/exfiltration rates and building pressures over extended periods, the quantitative understanding of air movement and air leakage in MURBs is limited. While there is a general understanding of the air flows and pressure regimes in MURBs, there is a lack of qualitative air leakage data which can be input with confidence into energy models. Therefore, the contribution of air leakage to space heat consumption in a MURB can only be estimated over a range of expected airtightness characteristics and assumed average building pressures.

As presented in the methodology, airtightness testing by the authors of sample wall/window assemblies as part of this study, along with airtightness test data from previous studies, provides a range of typical MURB enclosure airtightness rates (cfm/ft^2 of enclosure at standard test and average operating pressures). Airtightness data is converted to an air leakage rate in terms of air changes per hour (ACH) for input into the energy model. This is calculated by multiplying the enclosure airtightness (cfm/ft^2 at the average pressure) by the enclosure area (ft^2) and dividing by the whole building volume.

An average building pressure of 4 Pa is sometimes used for single-family homes. Pressures across the suite enclosure in high-rise buildings become increasingly more complex. Pressure will vary with building height, wind exposure, season and the relative airtightness of the interior and exterior components of the building. A more air tight building will typically be under a higher pressure than a leakier one. This pressure may be induced mechanically by an imbalanced ventilation system (i.e. supply or exhaust air only) or passively by wind or stack effect. Uniformly opening windows will make the building enclosure less air tight and hence the building will be under a lower pressure which in turn effects the air leakage rate.

As a rule of thumb, a pressure difference of 5 or 10 Pa across a high-rise MURB building enclosure is suggested in the reference literature. It is unknown, but is assumed that the lower pressure of 5 Pa does not consider mechanical pressures induced by an unbalanced mechanical ventilation system.

Using the representative enclosure airtightness rates discussed in the methodology at an average building pressure of 5 Pa, natural air leakage rates can be determined in terms of a flow (cfm) and hourly air exchange rate

(ACH). In addition to natural air leakage, air leakage caused by mechanical ventilation must also be considered. To account for a typical MURB ventilation system, the mechanical ventilation air exchange rate is added to the natural air leakage at 5 Pa. Interestingly the equivalent overall pressure that should result from natural and mechanical air leakage would be between 5 and 10 Pa for a relatively air tight building.

Table 6.1.18.1 presents the average air leakage rates (in cfm and ACH) for Building 19 based for a range of typical airtightness characteristics. For reference, the make-up air unit at Building 19 mechanically provides an airflow of 3500 cfm to the corridors, which likely results in a constant 0.18 ACH for the building. As another point of reference, ASHRAE recommends a minimum 0.3 ACH of mechanical ventilation for health. In our experience average ventilation rates of less than 0.5 ACH (mechanical plus natural infiltration/exfiltration) are likely normal for most suites based on indoor humidity and condensation issues observed in relatively air tight buildings. Experience has also shown that in an air tight building where the provided mechanical ventilation rates are too low for health or humidity control, occupants will almost certainly open windows to increase the ventilation, changing the air leakage behaviour of the enclosure.

Table 6.1.18.1 Typical Airtightness Measurements and Potential Air leakage Rates for Building 19.

Enclosure Airtightness	Representative of	Resulting Air leakage Rate for the Volume/Wall Ratio for Building 19	
		cfm	ACH
0.02 cfm/ft^2 @ 5 Pa	Very Tight	1,138	0.057
0.05 cfm/ft^2 @ 5 Pa	Tight – Low Average	2,845	0.143
0.10 cfm/ft^2 @ 5 Pa	Tight – Average	5,690	0.285
0.15 cfm/ft^2 @ 5 Pa	Tight – High Average	8,535	0.428
0.20 cfm/ft^2 @ 5 Pa	Leaky	11,381	0.571
0.40 cfm/ft^2 @ 5 Pa	Very Leaky (4x the average) with some windows open	22,761	1.141

**Airtightness rates can be converted to 10 Pa equivalents by multiplying by 1.57. Correspondingly the cfm and ACH would increase by a factor of 1.57.*

The energy model accounts for the effect of wind-speed using data in the climate file using the DOE air-change method, in addition to the baseline air leakage rate. Using the DOE formula for Building 19, and assuming an average tight enclosure, the hourly natural air-exchange increases from 0.30 ACH with no wind up to 0.40 ACH under a 5 km/h wind, 0.5 ACH under a 10 km/h wind and 0.68 ACH under a 20 km/h average wind speed.

Using the developed range of air-exchange rates for Building 19, energy modeling was performed to determine the potential impact of air leakage on space heat energy consumption. Space heat loss occurs as a result of either conduction through the enclosure (U-value dependent), by air leakage infiltration/exfiltration (airtightness and pressure dependent) and by ventilation (make-up and exhaust air). It is of interest to separate the natural infiltration/exfiltration from mechanical ventilation while both may appear as air leakage.

The contribution of infiltration/exfiltration air leakage to space heating can be analysed using the energy model. Energy simulations were performed for the range of air leakage rates shown in Table 6.1.18.1. The incremental energy consumption above the case with no air leakage is equal to the contribution of natural air leakage on the building space heat requirement.

The baseline model of Building 19 and other buildings in the study were modeled with a pre-rehabilitation airtightness of 0.15 cfm/ft^2. It is hypothesized that the effective air leakage rate did not change significantly from pre- to post-rehabilitation since the post energy model showed a similar reduction in space heating to the metered data with only enclosure R-value and SHGC changes. Had space heating energy shown a higher reduction in the metered data, this may have been explained by improved enclosure airtightness; however, based on our post construction observations and the owner reported problems of overheating, a significant number of windows and doors are left open at the building. This results in increased air flow through the building, offsetting improvements in airtightness of the building enclosure assemblies.

The theoretical space heat load that would be caused by the mechanical ventilation rate as air leakage is shown for reference, for comparison to natural air leakage rates.

Energy modeling was performed for the pre- and post-rehabilitation building models and is presented in Table 6.1.18.2, Table 6.1.18.2 and Fig. 6.1.18.2.

Table 6.1.18.2 Pre-Rehabilitation Building Enclosure Energy Modeling of the Impact of Air leakage on Space Heating.

Enclosure Airtightness (cfm/ft²)	Annual Space Heat Consumption		Heat Required for Air Leakage		Percent Difference from Baseline (0.15 cfm/ft²)	2010 Dollar Savings from Baseline (0.15 cfm/ft²)
	GJ	kWh/m²/yr	kWh/m²/yr	% of Total Heat		
0*	3,346	71.9	-	-	11.6%	$4,837
0.02	3,414	73.3	1.5	2.0%	9.8%	$4,094
0.05	3,501	75.2	3.3	4.4%	7.5%	$3,138
0.1	3,643	78.2	6.4	8.1%	3.8%	$1,576
0.15**	3,786	81.3	9.4	11.6%	-	-
0.2	3,872	83.2	11.3	13.6%	-2.3%	$943
0.4	4,208	90.4	18.5	20.5%	-11.1%	$4,643
MAU	3,534	75.9	4.0	5.3%	6.7%	$2,770

* No air leakage case includes make-up air flow

** Modeled baseline

Table 6.1.18.3 Post-Rehabilitation Building Enclosure Energy Modeling of the Impact of Air Leakage on Space Heating.

Enclosure Airtightness (cfm/ft²)	Annual Space Heat Consumption		Heat Required for Air Leakage		Percent Difference from Baseline (0.15 cfm/ft²)	2010 Dollar Savings from Baseline (0.15 cfm/ft²)
	GJ	kWh/m²/yr	kWh/m²/yr	% of Total Heat		
0*	2649	56.9	-	-	19.0%	$6,844
0.02	2734	58.7	1.8	3.1%	16.4%	$5,915
0.05	2866	61.6	4.7	7.6%	12.4%	$4,457
0.1	3078	66.1	9.2	13.9%	5.9%	$2,130
0.15**	3271	70.3	13.4	19.0%	-	-
0.2	3430	73.7	16.8	22.8%	-4.8%	-$1,744
0.4	3930	84.4	27.5	32.6%	-20.1%	-$7,244
MAU	2917	62.7	5.7	9.2%	10.8%	$3,902

* No air leakage case includes make-up air flow

** Modeled baseline

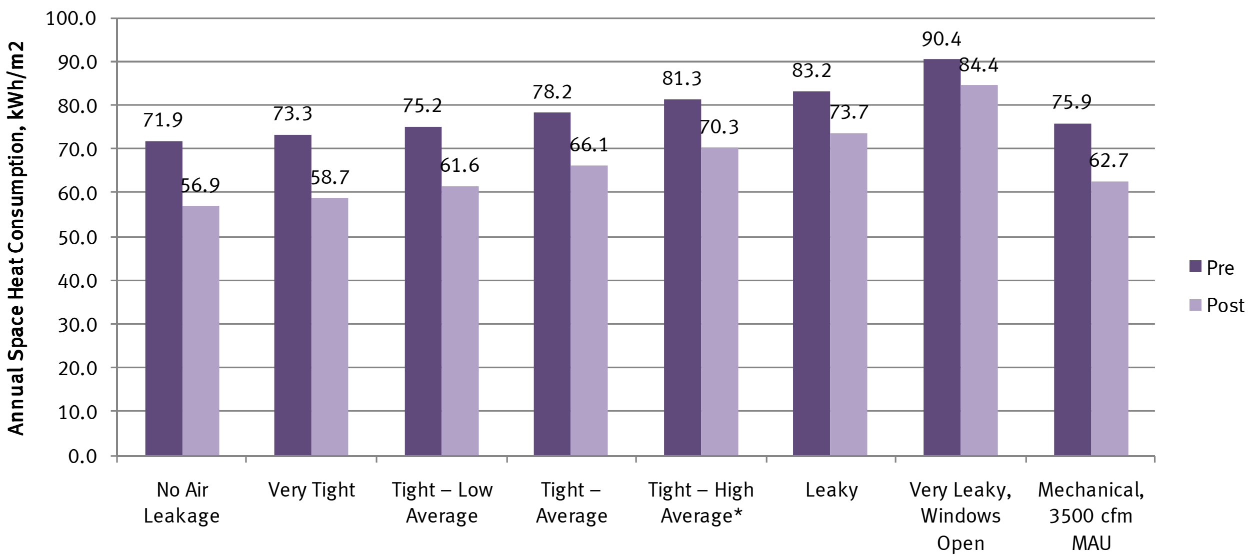


Fig. 6.1.18.2 Impact of airtightness on annual space heat consumption.

The energy modeling demonstrates the relative contribution of natural air leakage to space heat consumption for Building 19. In either the pre- or post-rehabilitation case, natural air leakage likely accounts for between 5% and 20% of the space heating load, or possibly up to 30% depending on occupant behaviour and window operation. This shows the relative importance of keeping windows closed during heating periods and possible savings from doing so; a reduction of up to 30% of the building's total space heat consumption could be realized.

6.1.19 Distribution of Space Heat Loss

The post-rehabilitation space heat load distribution estimated by the energy model is shown in Fig. 6.1.19.1 for low, average and high air leakage rates. This analysis will improve the understanding of the relative contributions of the thermal resistance of the building enclosure (conduction) and air leakage (convection, both forced and natural) on space heat loss.

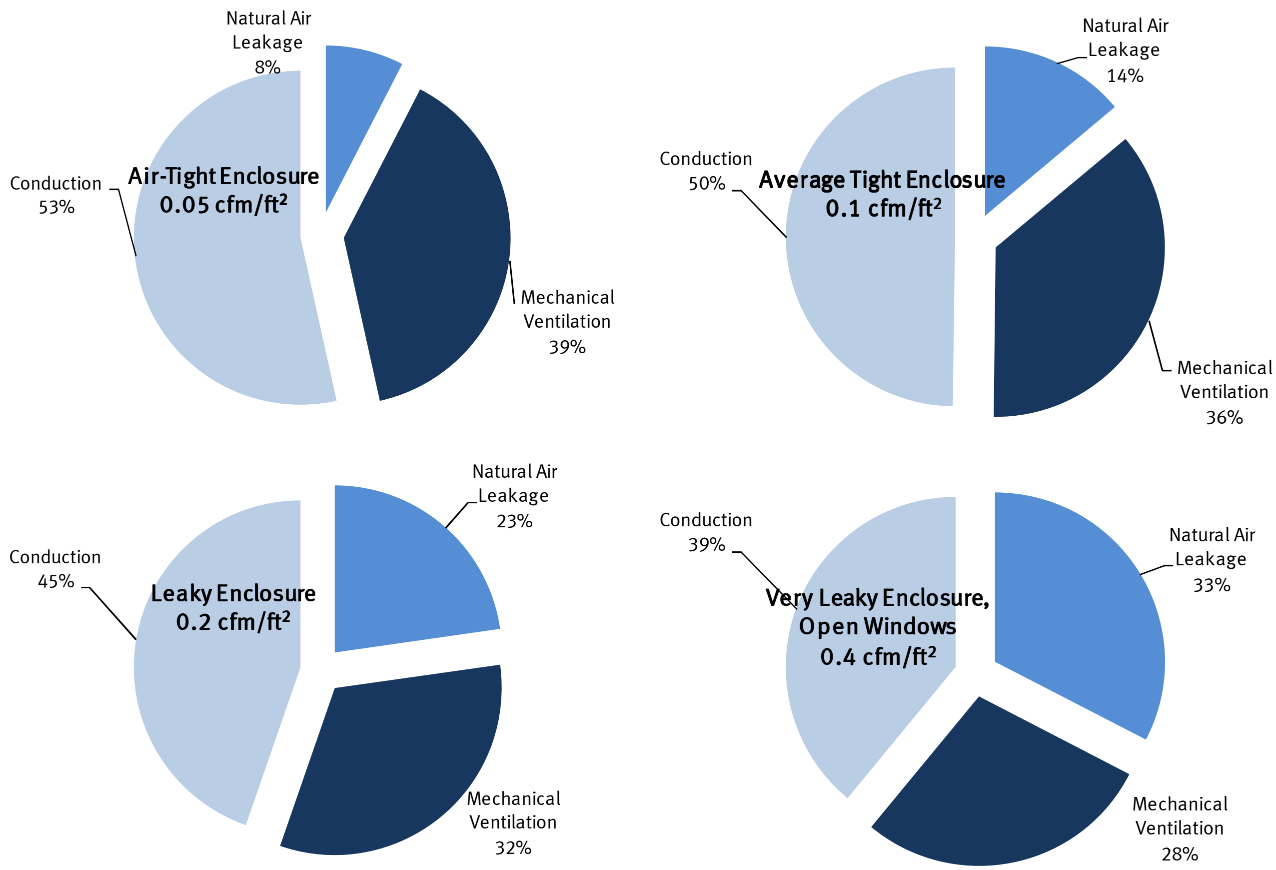


Fig. 6.1.19.1 Post-Rehabilitation Estimated Space Heat Loss Distribution for a Range of Potential Airtightness Levels.

Based on these results, it is shown that natural wind/stack pressure induced air leakage causes between 8% and 33% of the space heat loss depending on the airtightness of the building enclosure and the amount of windows open. At Building 19 it is estimated that the contribution of air leakage to space heat loss is between 14% and 23% as the model used an average to tight air leakage value of 0.15 cfm/ft^2. Mechanical ventilation heating also accounts for a significant portion of space heating energy, between 28% and 39%.

6.1.20 Energy Impacts from Mechanical Improvements and Adjustments

Mechanical upgrades and equipment adjustments have the potential to reduce input energy consumption of a building. Using the pre-rehabilitation calibrated energy model, mechanical system adjustments related to space heat were made to determine possible energy saving measures for MURBs. Other mechanical savings may be possible through lighting and plug load reductions, elevators, fan and pump upgrades, mechanical equipment upgrades and so on, however, these are beyond the scope of this report.

The Impact of Make-Up Air Temperature Set-point

The make-up air supply set-point temperature has a significant impact on gas consumption. Currently the unit is set at 21°C (70°F). Corridor temperature does not need to be maintained at 21°C, and a temperature of 16 to 18°C (60 to 64°F) would significantly reduce energy consumption. Table 6.1.20.1 and Fig. 6.1.20.2 compares the effect of varying the set-point temperature for the make-up air unit using the pre-rehabilitation energy model. The dollar savings assumes a gas price of $11/GJ.

Table 6.1.20.1 Energy Savings Potential for Make-up Air Temperature Set-point.

Set-Point Temperature	Space Heat Gas Consumption, GJ	% Savings From Baseline (70°F)	2010 Dollar Savings from Baseline
74°F (23°C)	3,968	-4.8%	-$2,030
72°F (22°C)	3,889	-2.7%	-$1,146
70°F (21°C)*	3,786	-	-
68°F (20°C)	3,689	2.6%	$1,078
66°F (19°C)	3,606	4.8%	$2,002
64°F (18°C)	3,532	6.7%	$2,819
62°F (17°C)	3,482	8.0%	$3,367
60°F (16°C)	3,434	9.3%	$3,907
55°F (13°C)	3,325	12.2%	$5,110

*Modeled baseline

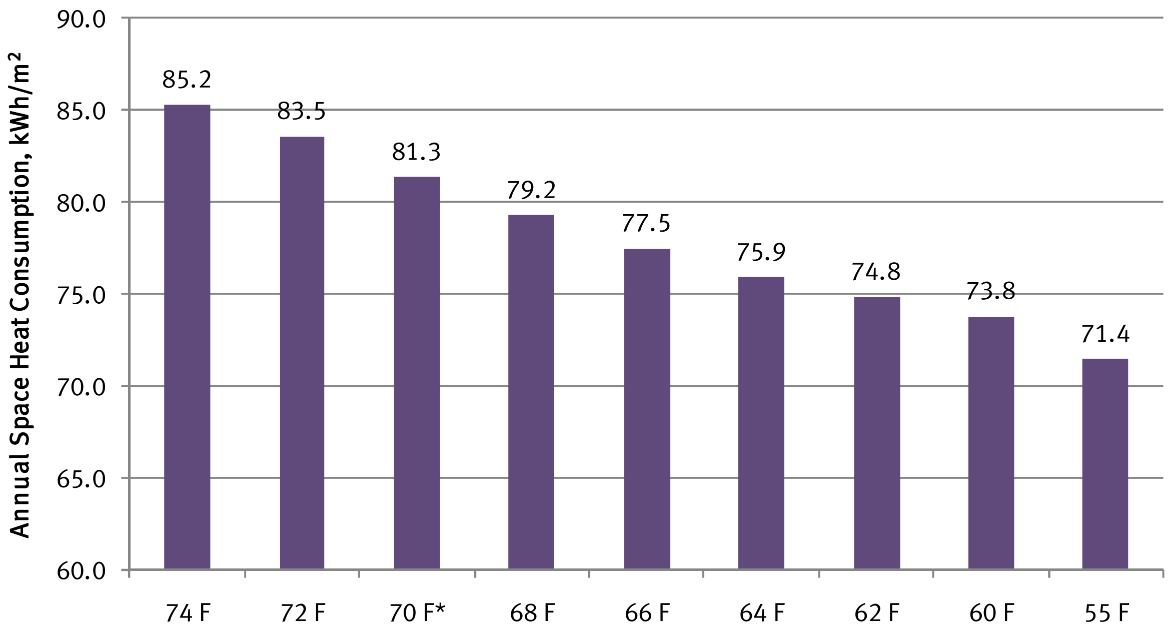


Fig. 6.1.20.2 Space Heat Energy Consumption of Make-up Air Temperature Set-points.

Lowering the make-up air temperature set-point to 16°C (60°F) reduces space heat consumption by 9%. Although decreasing make-up air temperature will reduce heating energy for make-up air, suite heating energy (hydronic baseboards in this case) will go up slightly. As shown, the decrease in make-up air heating energy is much greater than the increase in suite heating energy and the net effect is a reduction in energy consumption.

Significant gas energy savings may be realized by reducing the make-up air set-point temperature; however, reducing the temperature may affect occupant comfort. Occupants may complain of cold drafts and may block off door undercuts (and hence ventilation air) when corridor temperatures drop too low. Seasonal adjustments (i.e. to turn off the heat during the summer months) or night-time temperature setbacks will further reduce make-up air energy consumption.

The Impact of Make-Up Air Flow Rate

The make-up air unit in Building 19 is sized to deliver 3500 cfm of air, or 0.025 cfm/ft^2. The flow rate was adjusted in the pre-rehabilitation model to determine the energy impact of higher or lower airflow rates. Space heat consumption for various airflow rates is shown in Table 6.1.20.2 and Fig. 6.1.20.3. Dollar savings assume a gas price of $11/GJ. This analysis is hypothetical in nature as some ventilation rates will be too low for occupant health. In all cases, the ventilation rate that reaches the suite (not the corridor) is critical.

Table 6.1.20.2 Energy Savings Potential for Make-up Air Flow Rate.

Air Flow Rate (cfm/ft^2)	Representative of	Space Heat Gas Consumption, GJ	% Savings From Baseline	2010 Dollar Savings from Baseline
0.025*	100% of Nominal	3,786	-	-
0.024	95% of Nominal	3,740	0.6%	$527
0.023	90% of Nominal	3,694	1.1%	$1,052
0.021	85% of Nominal	3,603	2.2%	$2,090
0.020	80% of Nominal	3,559	2.8%	$2,601
0.019	75% of Nominal	3,515	3.3%	$3,102
0.018	70% of Nominal	3,472	3.9%	$3,599
0.016	65% of Nominal	3,387	4.9%	$4,571
0.015	60% of Nominal	3,346	5.4%	$5,043
0	No make-up air	2,843	11.7%	$10,848
0.100	Typical modern air flow rate	7,288	-43.0%	-$40,067

*Modeled baseline

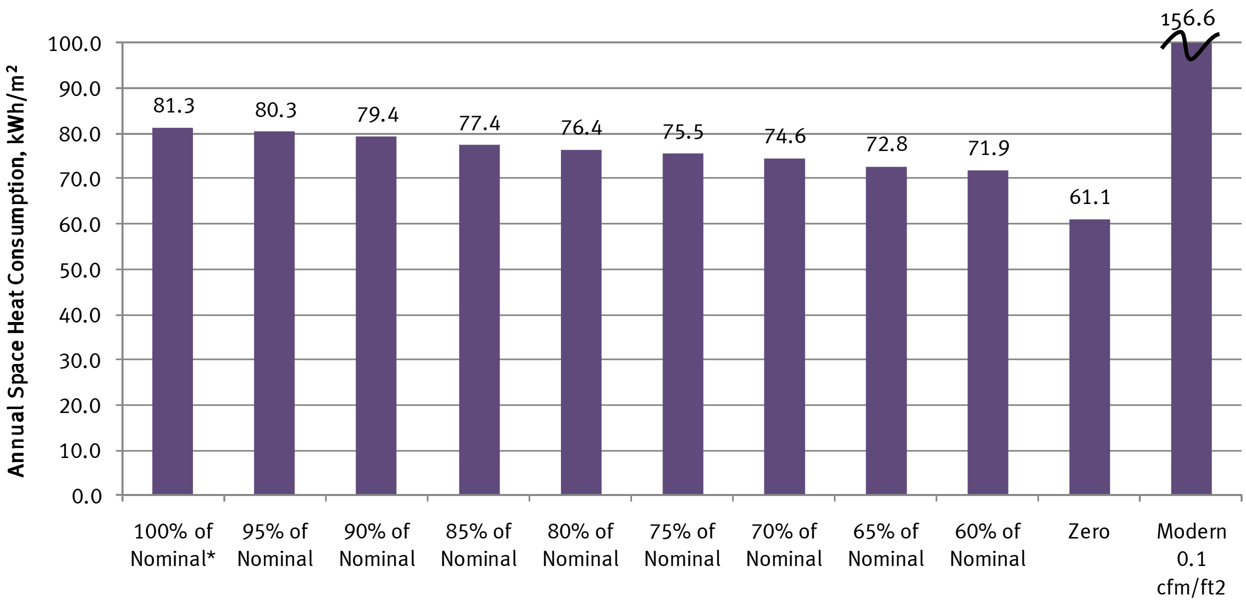


Fig. 6.1.20.3 Space Heat Energy Consumption of Make-up Air Flow Rate.

The make-up air flow rate can have a significant impact on energy consumption. The simulations show that reducing the flow rate by up to 40% reduces energy consumption by only 5%; however, increasing the make-up air flow rate to a rate more representative of modern buildings increases energy consumption by 43% for a building this size. Ventilation rate adjustments can only be considered if the minimum ventilation rate per occupant/suite is met in each suite. This points towards in-suite or ducted ventilation systems instead of the pressurized corridor approach.

The Impact of Heat Recovery Ventilation

Most large commercial buildings utilize central exhaust heat recovery systems. The buildings in the study, including Building 19, have no capability for central exhaust heat recovery as exhaust air is intermittently occupant controlled and is expelled at each suite through the exterior wall; there is no return ductwork. Exhaust air heat recovery could be implemented in existing buildings in two ways. First, return ductwork could be installed to remove air from the suites and exhaust it through a rooftop heat recovery unit. Second, in-suite heat recovery ventilators (HRVs) could be installed at each suite to provide individual ventilation to each unit. Either of these options could be applied to new buildings as well.

Central and in-suite HRV systems each have certain benefits and drawbacks. In terms of heat recovery efficiency, central HRV units are large and can achieve heat recovery efficiencies upwards of 90% while in-suite HRV units that are currently commercially available are limited to heat recovery efficiencies in the low 80% range. Similarly, the fans in large central HRV units are typically more efficient than the smaller in-suite systems, though small yet efficient fans are available. The primary benefit of in-suite HRVs is that they provide reliable ventilation. Central systems rely on cracks under the suite doors to transfer ventilation from the corridors to the suites, as well as user controlled intermittent kitchen and bathroom fans plus incidental enclosure penetrations for exhaust. In-suite HRVs provide good, reliable ventilation but must be carefully designed such that they operate at a high efficiency.

A simulation was performed for the hypothetical situation that at Building 19, the exhaust air could be recovered and run through a central HRV, or in-suite HRVs could be installed. Spreadsheet calculations were performed for the in-suite HRV scenario as this could not be modeled using the program. Fig. 6.1.20.4 and Table 6.1.20.3 show the model results for various heat recovery scenarios with the pre-rehabilitation building. Dollar savings are based on a gas price of $11/GJ.

Table 6.1.20.3 Energy Savings Potential for Ventilation Heat Recovery.

Scenario	Space Heat Gas Consumption, GJ	% Savings From Baseline	2010 Dollar Savings from Baseline
Baseline Pre (no heat recovery)	3,786	-	-
50% Central HRV	3,295	13.0%	$5,447
70% Central HRV	3,123	17.5%	$7,366
90% Central HRV	2,964	21.7%	$9,125
50% In-Suite HRV	3,381	10.7%	$3,000
70% In-Suite HRV	3,166	16.4%	$5,391
80% In-Suite HRV	3,058	19.2%	$6,586

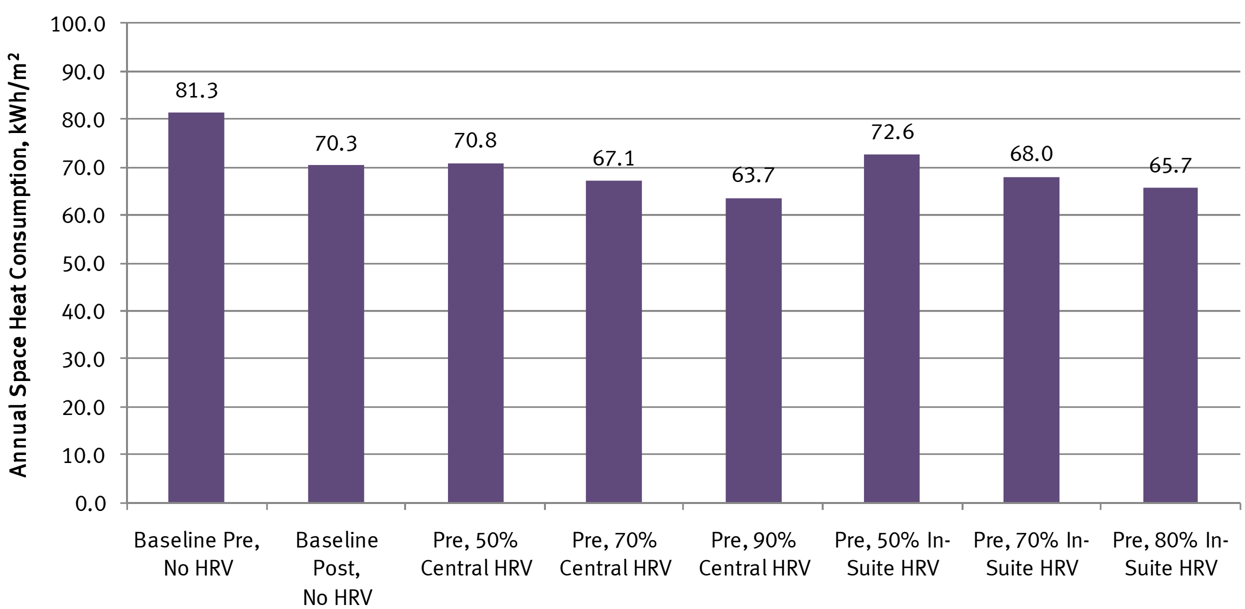


Fig. 6.1.20.4 Space Heat Energy Consumption of Ventilation Heat Recovery.

A 90% efficient central HRV reduces annual space heat energy consumption by 22%. An 80% efficient in-suite HRV reduces energy consumption by 19% per year. Heat recovery may significantly reduce energy consumption but may be challenging in rehabilitation scenarios.

6.1.21 The Impact of Combining Energy Efficiency Measures

The energy efficiency measures analysed thus far are not additive, as discussed previously. That is, one cannot add the individual energy reduction of improving the wall and window thermal performance, reducing air leakage, and so on, to obtain a total energy savings. These effects need to be combined in a separate model.

Two scenarios were modeled to determine the overall effect of increasing the wall R-value, decreasing the window U-value, improving airtightness, lowering the corridor make-up air temperature, and adding heat recovery to ventilation make-up air. The model results are compared to the pre- and post-rehabilitation simulation results. Table 6.1.21.1 shows the combinations of energy efficiency measures that were simulated, with the pre- and post-rehabilitation model inputs for reference. Table 6.1.21.2 and Fig. 6.1.21.2 show the simulation results for the improved scenarios. Dollar savings are based on a gas price of $11/GJ. Fig. 6.1.21.3 shows the total annual energy consumption for the improved scenarios.

Table 6.1.21.1 Combination Energy Efficiency Measures Simulated.

Scenario	Model Inputs
Actual Pre	⇢ Walls effective R-3.9 ⇢ Windows double glazed, air fill, aluminum frame; U = 0.73, SC = 0.78 ⇢ Airtightness “Tight – High Average”, 0.15 cfm/ft^2 ⇢ Make-up air temperature set-point 70ºF ⇢ No heat recovery
Actual Post	⇢ Walls effective R-5.3 ⇢ Windows double glazed, air fill, low-e, aluminum frame; U = 0.46, SC = 0.37 ⇢ Airtightness “Tight – High Average”, 0.15 cfm/ft^2 ⇢ Make-up air temperature set-point 70ºF ⇢ No heat recovery
“Good”	⇢ Walls effective R-10 ⇢ Windows double glazed, argon fill, low-e, vinyl or fibreglass frame; U = 0.27, SC = 0.35 ⇢ Airtightness “Tight – Low Average”, 0.05 cfm/ft^2 ⇢ Make-up air temperature set-point 64ºF ⇢ No heat recovery
“Best”	⇢ Walls effective R-18.2 ⇢ Windows triple glazed, argon fill, low-e, vinyl or fibreglass frame; U = 0.17, SC = 0.23 ⇢ Airtightness “Very Tight”, 0.02 cfm/ft^2 ⇢ Make-up air temperature set-point 60ºF ⇢ 80% Central Heat Recovery

Table 6.1.21.2 Energy Savings Potential for Improved Buildings.

Scenario	Space Heat Gas Consumption, GJ	% Savings From Baseline	2010 Dollar Savings from Baseline
Baseline Pre	3,786	-	-
Baseline Post	3,271	13.6%	$5,721
“Good”	1,626	57.1%	$24,005
“Best”	578	84.7%	$35,630

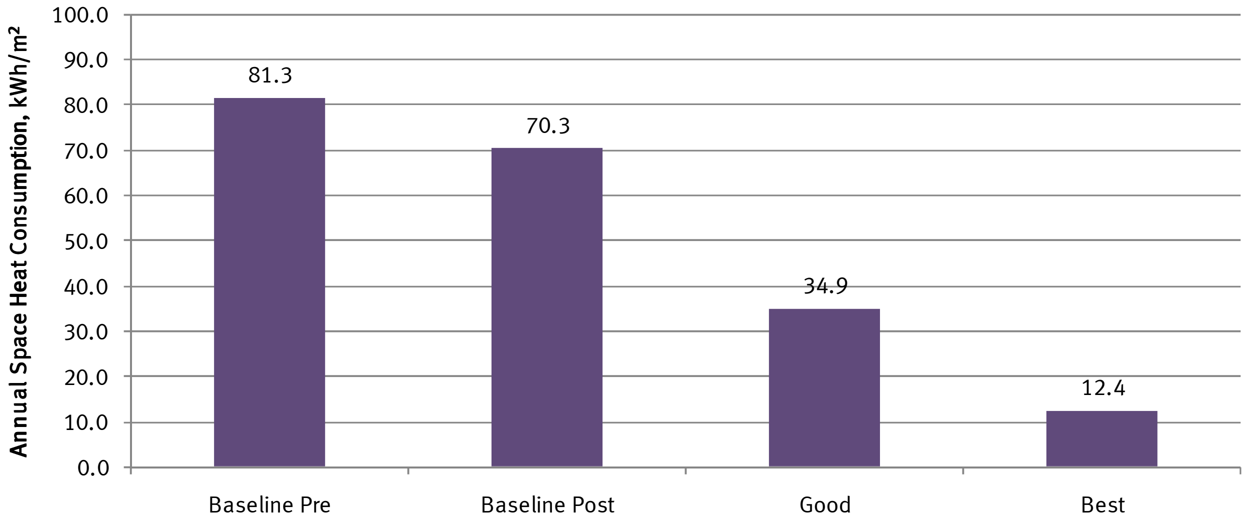


Fig. 6.1.21.2 Space Heat Energy Consumption of Improved Buildings.

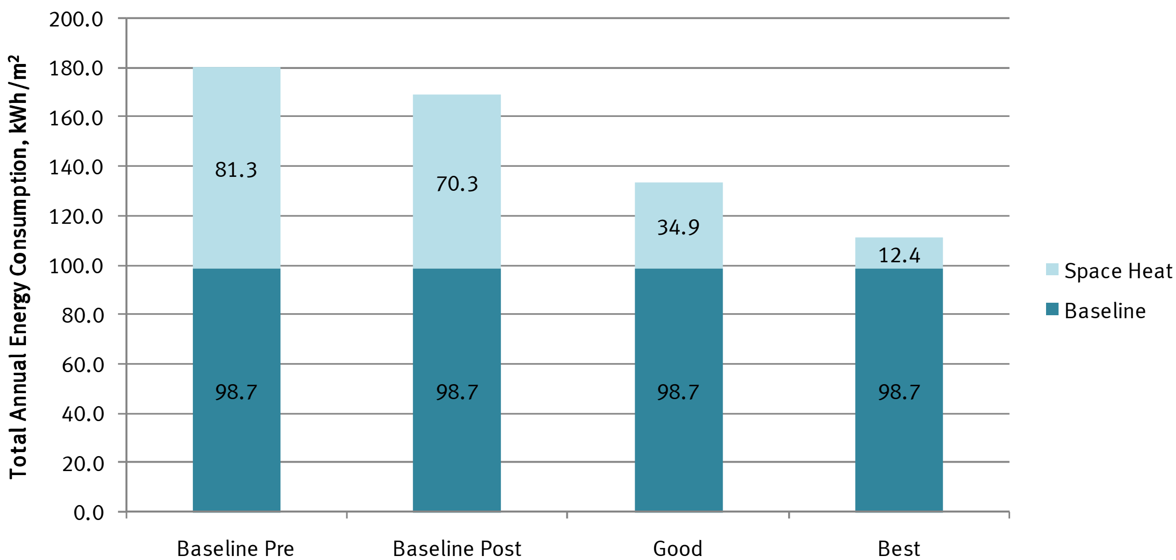


Fig. 6.1.21.3 Total annual Energy Consumption of Improved Buildings.

The models with multiple energy efficiency measures show that significant energy savings may be realized by combining the measures discussed in this report. The "best" scenario shows a space heat reduction of 85%, consuming only 12 kWh/m^2/year for space heat. The total building energy consumption for this building is only 111 kWh/m^2/year, without even addressing mechanical equipment upgrades and lighting and plug loads. Significant energy savings may be realized through enclosure and make-up air improvements. These findings are based on modeling only, and further research is needed to confirm actual savings.

6.1.22 The Impact of Modeling Nominal Values

An important step in this study was to determine the overall effective wall, roof and window thermal resistances. In practice, nominal values may be used in error. The calibrated energy model was used to determine the impact of modeling using nominal values instead of effective values. The nominal wall R-value is R-13.7 while the calculated effective pre-rehabilitation R-value is R-3.9. The window center of glass U-value is U-0.48 while the calculated effective pre-rehabilitation U-value is U-0.73. A model using the nominal values was compared to the pre-rehabilitation energy model. Table 6.1.22.1 and Fig. 6.1.22.2 show the results.

Table 6.1.22.1 Pre-rehabilitation and nominal energy model results.

Scenario	Space Heat Gas Consumption, GJ	% Difference From Baseline
Baseline Pre	3,786	-
Nominal	2,496	34.1%

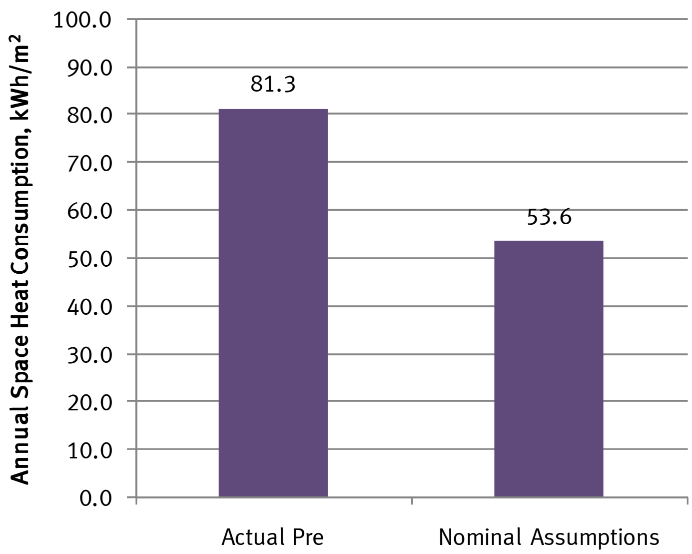


Fig. 6.1.22.2 Annual space heat consumption for pre-rehabilitation model and nominal model.

Modeling the nominal wall R-value and center of glass window U-value under-predicts annual space heat energy consumption by 34%. This shows the importance of using actual, effective values in energy modeling.

6.1.23 Energy Costs and Greenhouse Gas Emissions

Total Energy Costs and Greenhouse Gas Emissions

The total energy cost for the building including the common area and all strata units is combined and summarized in Fig. 6.1.23.1, in 2010 dollars. For comparison between buildings the assumed gas rate is $11/GJ, and the combined electrical rate is $0.07/kWh per previous discussion.

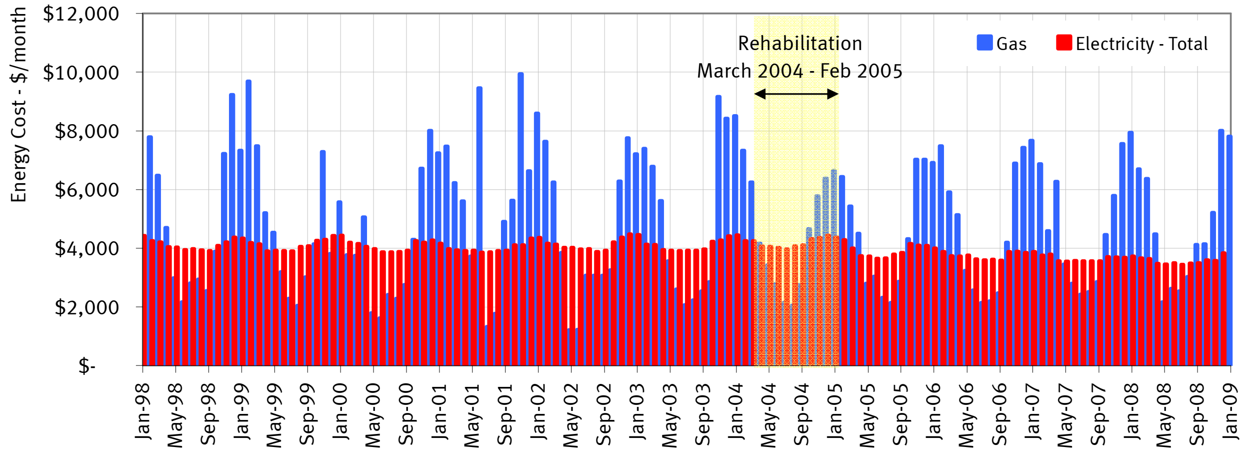


Fig. 6.1.23.1 Total Energy Cost, January 1st 1998 through January 1st, 2009.

In the past 11 years, compared in common 2010 dollars, the strata has spent between $56,000 and $66,000/yr on natural gas (average of $60,500) and between $13,800 and $16,800/yr on common electricity (average of $16,000). The combined electrical consumption in the 94 suites accounts for an additional $29,400 to $33,000 of suite electricity (average of $32,000).

The largest energy source within the building is natural gas, accounting for 69% of the energy use, but 56% of the total energy cost, the difference being from the lower cost of gas per unit of energy (0.040 vs. 0.070 $/kWh).

- The total energy consumption is $60,500/yr for natural gas, $16,000/yr for common electricity, and $32,000 kWh/yr for suite electricity for a total of $108,500/yr. Annual savings were found from energy reductions post-rehabilitation and are discussed in the following section.
- Assuming a Greenhouse Gas Emission (GHG) Factor of 0.179 tCO_2/MWh for burning natural gas and BC Hydro's published electrical GHG emission factor of 0.055 tCO_2/MWh for electricity in the Lower Mainland of BC, the total GHG emissions are on average 274 tCO_2 from gas and 38 tCO_2 from electricity for a total of 311 tCO_2. Considering a more polluted electrical source of 0.360 tCO_2/MWh as suggested by the MEMPR, electricity GHG emissions would be 247 tCO_2 for a total of 520 tCO_2. A reduction in the GHG emissions post-rehabilitation is discussed in the following section.

6.1.24 Pre- and Post-Rehabilitation Energy and GHG Savings

Energy cost savings as a result of the rehabilitation are calculated for the weather normalized year and are presented in Table 6.1.24.1

Table 6.1.24.1 Energy Cost and GHG Savings for Building 19 Post-Rehabilitation.

Energy Source		Pre-Rehabilitation	Post-Rehabilitation	Savings
		Energy Cost, 2010 $/yr	Energy Cost, 2010 $/yr	$/yr
Gas	Space heat: Hydronic Baseboard and MAU ventilation	$37,235	$32,411	$4,824
	Domestic Hot water	$26,268	26,268	-
Electricity	Suite: Space heat	$2,335	$1,651	$684
	Suite: All Other	$30,379	$28,891	$1,488
	Common: Space heat	$318	$6	$311
	Common: All Other	$16,266	$14,112	$2,154
Total Energy – $		**$112,800**	**$103,339**	**$9,460**
Total Energy - $/suite		**$1,200**	**$1,099**	**$101**
Greenhouse Gas Emissions, tCO_2		**326**	**300**	**26**

An annual energy savings of approximately $9,460/yr (8.4%) was realized as a result of the building enclosure rehabilitation for a typical weather year.

Greenhouse gas emissions were reduced by 26 tCO_2 (8.0%) using BC Hydro GHG emission rates.

6.2. Individual Building Summaries – Detailed Pre-Post Rehabilitation Assessment and Energy Simulation

The following sections provide a summary of the results from the detailed pre- and post-rehabilitation analysis of the thirteen selected MURBs.

Summaries for the following buildings are provided in the following order:

- Building 19
- Building 18
- Building 32
- Building 33
- Building 62
- Building 7
- Building 17
- Building 20
- Building 11
- Building 28
- Building 21
- Buildings 39 & 41

6.2.1 Building 19

Fig. 6.2.1 Building 19 – Greater Vancouver.

Building 19 was rehabilitated to address moisture related deterioration between March 2004 and February 2005. As part of the rehabilitation, the following key changes were made to the building enclosure assemblies:

- Original fibreglass batt insulation within the steel stud wall assemblies was removed, and replaced with semi-rigid mineral wool exterior insulated assemblies.
- Non-thermally broken aluminum glazing assemblies replaced with thermally broken aluminum glazing assemblies, complete with a moderate performance low-e coating within the new insulated sealed units.
- Reduced thermal bridging at details.

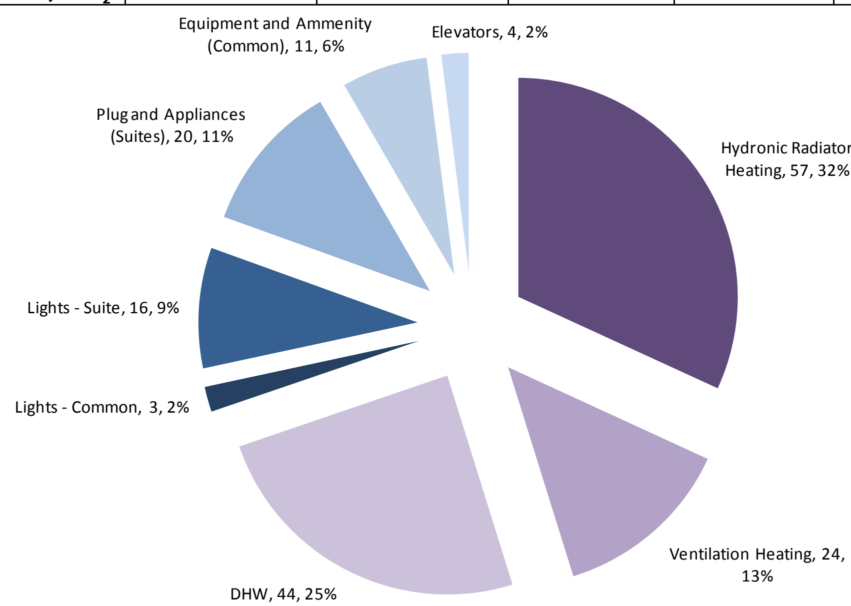
R-values of the pre- and post- rehabilitation building enclosure components were modeled in detail and corresponding area calculations were used to determine the overall effective R-value of the building enclosure. The overall effective R-value for Building 19 improved from R-2.92 to R-4.26 (+46%) as a result of the building enclosure rehabilitation work. This improvement was not intentional as the repair was designed to minimize the rehabilitation costs to address moisture damage; however, incidental improvements were realized as a result of the detail changes including an exterior insulated wall assembly, the new thermally improved window and door assemblies and increased airtightness. The energy consumption at the building was reduced by a total of 8.1% (13.9% of the space heat energy) as a result of the building enclosure rehabilitation work. The overall improvements are summarized in Table 6.2.1 for a standard weather year.

Table 6.2.1 Summary of Overall R-value and Energy Consumption Changes as the Result of the Building Enclosure Rehabilitation Work.

Enclosure Thermal Performance	Pre-Rehabilitation R-value	Post-Rehabilitation R-value	Improvement
	hr ft² F/Btu *(m² K/W)*	hr ft² F/Btu *(m² K/W)*	
Effective Window R-value	1.37 *(0.24)*	2.16 *(0.38)*	+57%
Effective Wall Area R-value	3.94 *(0.69)*	5.25 *(0.93)*	+33%
Effective Roof R-value	14.26 *(2.51)*	18.28 *(3.22)*	+28%
Overall Effective Building Enclosure R-value	**2.92** ***(0.51)***	**4.26** ***(0.75)***	**+46%**

Energy Consumption		Pre-Rehabilitation kWh/m²/yr	Post-Rehabilitation kWh/m²/yr	Energy Savings kWh/m²/yr	% of Space Heat Savings	% of Total Energy Savings
Gas	Space heat: Hydronic Baseboard and MAU ventilation	72.7	63.3	9.4	12.5%	5.3%
	Baseline : Estimated Domestic Hot water	51.3	51.3	0	-	0%
Electricity	Suite: Space heat	2.6	1.8	0.8	1.0%	0.4%
	Suite: All Other	33.6	31.9	1.6	-	0.9%
	Common: Space heat	0.4	0.1	0.3	0.5%	0.2%
	Common: All Other	18.0	15.6	2.4	-	1.3%
Total Space Heat – kWh/m²/yr		**75.7**	**65.1**	**10.5**	**13.9%**	**-**
Total Energy – kWh/m²/yr		**178.5**	**164.0**	**14.5**	**-**	**8.1%**
Total Energy – kWh/suite		**24,552**	**22,551**	**2,001**		
Greenhouse Gas Emissions, tCO_2		**326**	**300**			**7.8%**

Energy Distribution Determined by Energy Simulation



6.2.2 Building 18

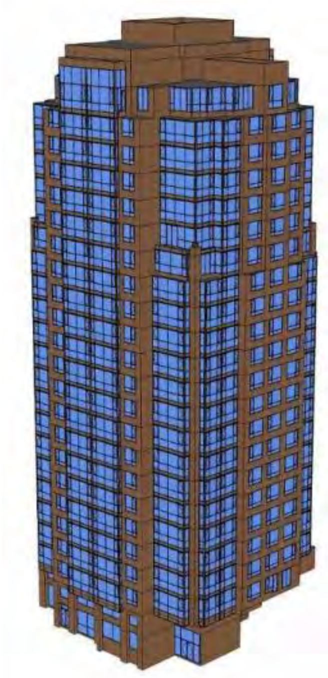


Fig. 6.2.2 Building 18 – Greater Vancouver.

Building 18 was rehabilitated to address moisture related deterioration between August 2006 and July 2007. As part of the rehabilitation, the following key changes were made to the building enclosure assemblies:

- Original fibreglass batt insulation within the steel stud wall assemblies was removed, and replaced with semi-rigid mineral wool exterior insulated assemblies. Window wall spandrel panel assemblies were improved.
- Original windows were a thermally broken aluminium glazing with a hard coat low-e and were replaced with an aluminium glazing assembly with a moderate performance soft coat low-e coating within the new insulated sealed units as well as a larger thermal break.
- Reduced thermal bridging at details.

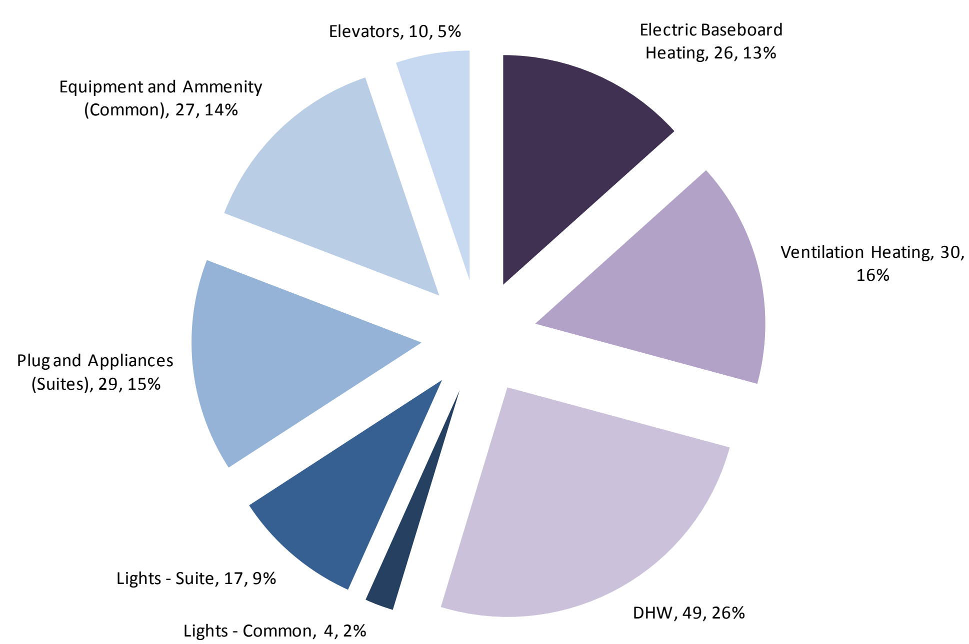
R-values of the pre- and post- rehabilitation building enclosure components were modeled in detail and corresponding area calculations were used to determine the overall effective R-value of the building enclosure. The overall effective R-value for Building 18 improved from R-2.68 to R-3.29 hr·ft^2·F/Btu (+23%) (U-0.37 to U-0.30 or a reduction of 19%), as a result of the building enclosure rehabilitation work. This improvement was not intentional as the repair was designed to minimize the rehabilitation costs to address moisture damage; however, incidental improvements were realized as a result of the detail changes including an exterior insulated wall assembly, the new thermally improved window and door assemblies and increased airtightness. The energy consumption at the building was increased by a total of 9.0% (and a 13.1% increase in space heat) as a result of mechanical changes performed during the time of the building enclosure rehabilitation work. The overall changes are summarized in Table 6.2.2 for a standard weather year.

Table 6.2.2 Summary of Overall R-value and Energy Consumption Changes as the Result of the Building Enclosure Rehabilitation Work.

Enclosure Thermal Performance	**Pre-Rehabilitation R-value** hr ft² F/Btu *(m² K/W)*	**Post-Rehabilitation R-value** hr ft² F/Btu *(m² K/W)*	**Improvement**
Effective Window R-value	1.98 (0.35)	2.27 (0.40)	+15%
Effective Wall Area R-value	4.38 *(0.77)*	6.84 (1.20)	+56%
Effective Roof R-value	*11.76* *(2.07)*	*13.22* *(2.33)*	+12%
Overall Effective Building Enclosure R-value	**2.68** ***(0.47)***	**3.29** **(0.58)**	**+23%**

Energy Consumption		**Pre-Rehabilitation kWh/m²/yr**	**Post-Rehabilitation kWh/m²/yr**	**Energy Savings kWh/m²/yr**	**% of Space Heat Savings**	**% of Total Energy Savings**
Gas	Space heat: MAU ventilation	27.8	34.4	-6.6	-11.7%	-3.4%
	Domestic Hot water	49.6	60.5	-10.9	-	-5.6%
Electricity	Suite: Space heat	23.4	24.3	-0.8	-1.5%	-0.4%
	Suite: All Other	48.2	47.4	0.8	-	0.4%
	Common: Space heat	0.4	0.1	0.3	0.4%	0.2%
	Common: All Other	39.9	39.9	0	-	-
Total Space Heat – kWh/m²/yr		**56.4**	**63.9**	**-7.4**	**-13.1%**	**-**
Total Energy – kWh/m²/yr		**194.2**	**211.6**	**-17.5**	**-**	**-9.0%**
Total Energy – kWh/suite		**13,189**	**14,375**	**1,186**		
Greenhouse Gas Emissions, tCO_2		**256**	**296**			**-15.4%**

Energy Distribution Determined by Energy Simulation



6.2.3 Building 32

Fig. 6.2.3 Building 32 – Greater Vancouver.

Building 32 was rehabilitated to address moisture related deterioration between May 2006 and July 2007. As part of the rehabilitation, the following key changes were made to the building enclosure assemblies:

- Typically, original fibreglass batt insulation within the steel stud wall assemblies was removed, and replaced with semi-rigid mineral wool exterior insulated assemblies.
- EIFS was installed over exposed concrete walls.
- Non-thermally broken aluminum glazing assemblies replaced with thermally broken aluminum glazing assemblies complete with a moderate performance low-e coating within the new insulated sealed units.
- Reduced thermal bridging at details.

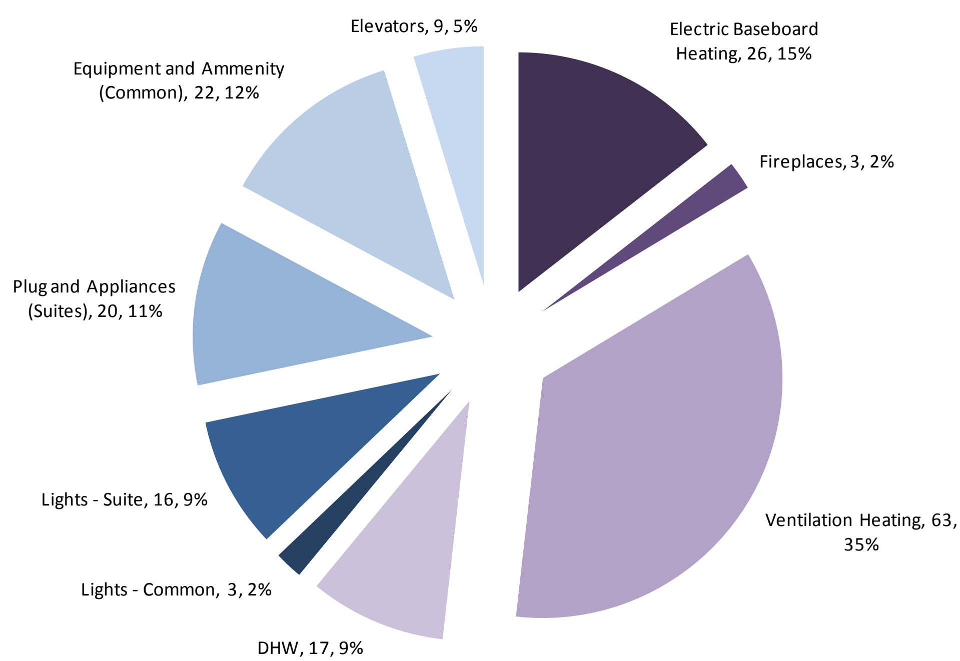
R-values of the pre- and post- rehabilitation building enclosure components were modeled in detail and corresponding area calculations were used to determine the overall effective R-value of the building enclosure. The overall effective R-value for Building 32 improved from R-2.28 to R-3.60 hr·ft^2·F/Btu (+58%) (U-0.44 to U-0.28 or a reduction of 36%) as a result of the building enclosure rehabilitation work. This improvement was not intentional as the repair was designed to minimize the rehabilitation costs to address moisture damage; however, incidental improvements were realized as a result of the detail changes including an exterior insulated wall assembly, the new thermally improved window and door assemblies and increased airtightness. The energy consumption at the building was reduced by a total of 10.9% (17.7% of the space heat) as a result of the building enclosure rehabilitation work. The overall improvements are summarized in Table 6.2.3 for a standard weather year.

Table 6.2.3 Summary of Overall R-value and Energy Consumption Changes as the Result of the Building Enclosure Rehabilitation Work.

Enclosure Thermal Performance	Pre-Rehabilitation R-value hr ft² F/Btu *(m² K/W)*	Post-Rehabilitation R-value hr ft² F/Btu *(m² K/W)*	Improvement
Effective Window R-value	1.34 (0.24)	2.02 (0.36)	+51%
Effective Wall Area R-value	3.81 *(0.67)*	7.09 (1.25)	+86%
Effective Roof R-value	*10.99 (1.93)*	*12.79 (2.25)*	+16%
Overall Effective Building Enclosure R-value	**2.28 *(0.40)***	**3.60 (0.63)**	**+58%**

Energy Consumption		Pre-Rehabilitation kWh/m²/yr	Post-Rehabilitation kWh/m²/yr	Energy Savings kWh/m²/yr	% of Space Heat Savings	% of Total Energy Savings
Gas	Space heat: MAU ventilation & 8 fireplaces	58.3	46.9	11.4	12.8%	6.4%
	Domestic Hot water	23.7	23.7	0	-	0%
Electricity	Suite: Space heat	27.9	23.5	4.4	4.9%	2.5%
	Suite: All Other	32.1	28.6	3.5	-	2.0%
	Common: Space heat	3.5	3.5	0	-	0%
	Common: All Other	32.5	32.5	0	-	0%
Total Space Heat – kWh/m²/yr		**89.7**	**73.8**	**15.9**	**17.7%**	**-**
Total Energy – kWh/m²/yr		**178.0**	**158.6**	**19.4**	**-**	**10.9%**
Total Energy – kWh/suite		**19,473**	**17,355**	**2,118**		
Greenhouse Gas Emissions, tCO_2		**295**	**258**			**12.4%**

Energy Distribution Determined by Energy Simulation



6.2.4 Building 33

Fig. 6.2.4 Building 33 – Greater Vancouver.

Building 33 was rehabilitated to address moisture related deterioration between May 2006 to July 2007. As part of the rehabilitation, the following key changes were made to the building enclosure assemblies:

- Typically, original fibreglass batt insulation within the steel stud wall assemblies was removed, and replaced with semi-rigid mineral wool exterior insulated assemblies.
- EIFS was installed over exposed concrete walls.
- Non-thermally broken aluminum glazing assemblies replaced with thermally broken aluminium glazing assemblies complete with a moderate performance low-e coating within the new insulated sealed units.
- Reduced thermal bridging at details.

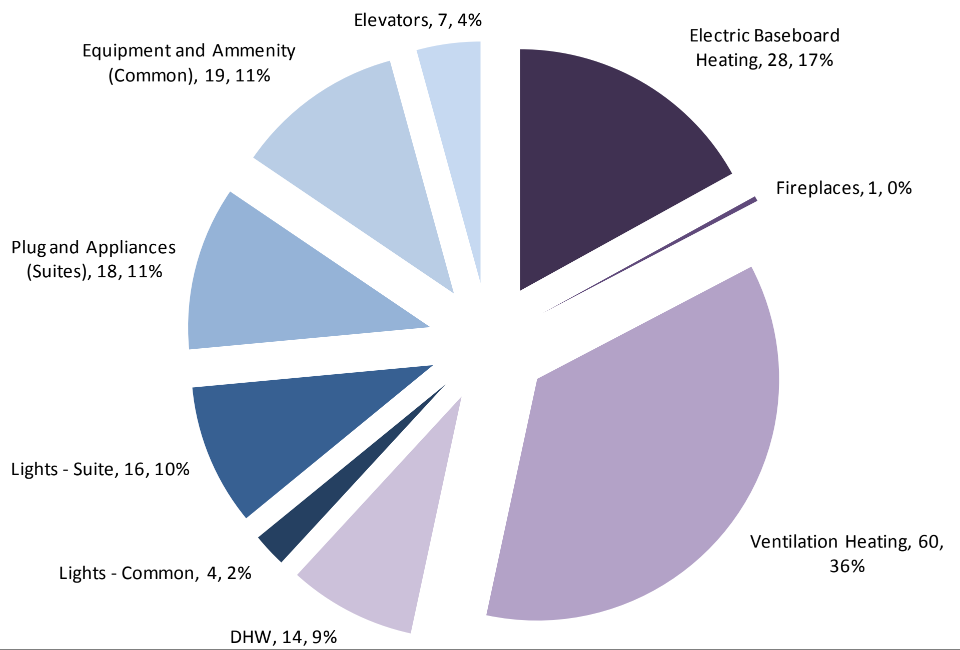
R-values of the pre- and post- rehabilitation building enclosure components were modeled in detail and corresponding area calculations were used to determine the overall effective R-value of the building enclosure. The overall effective R-value for Building 33 improved from R-2.19 to R-3.49 hr·ft^2·F/Btu (+59%) (U-0.46 to U-0.29 or a reduction of 37%) as a result of the building enclosure rehabilitation work. This improvement was not intentional as the repair was designed to minimize the rehabilitation costs to address moisture damage; however, incidental improvements were realized as a result of the detail changes including an exterior insulated wall assembly, the new thermally improved window and door assemblies and increased airtightness. The energy consumption at the building was reduced by a total of 9.1% (17.4% of the space heat) as a result of the building enclosure rehabilitation work. The overall improvements are summarized in Table 6.2.4.

Table 6.2.4 Summary of Overall R-value and Energy Consumption Changes as the Result of the Building Enclosure Rehabilitation Work.

Enclosure Thermal Performance	**Pre-Rehabilitation R-value** hr ft^2 F/Btu *(m^2 K/W)*	**Post-Rehabilitation R-value** hr ft^2 F/Btu *(m^2 K/W)*	**Improvement**
Effective Window R-value	1.34 (0.24)	2.03 (0.36)	+51%
Effective Wall Area R-value	3.78 *(0.67)*	7.20 (1.27)	+90%
Effective Roof R-value	*11.22* *(1.98)*	*12.90* *(2.27)*	+15%
Overall Effective Building Enclosure R-value	**2.19** ***(0.39)***	**3.49** **(0.61)**	**+59%**

Energy Consumption		**Pre-Rehabilitation kWh/m²/yr**	**Post-Rehabilitation kWh/m²/yr**	**Energy Savings kWh/m²/yr**	**% of Space Heat Savings**	**% of Total Energy Savings**
Gas	Space heat: MAU ventilation & 2 fireplaces	49.9	46.3	3.6	4.3%	2.2%
	Domestic Hot water	23.0	23.0	0	-	-
Electricity	Suite: Space heat	31.6	20.6	11.0	13.1%	6.7%
	Suite: All Other	28.9	28.5	0.5	-	0.3%
	Common: Space heat	2.1	2.1	0	-	-
	Common: All Other	28.9	28.9	0	-	-
Total Space Heat – kWh/m²/yr		**83.6**	**69.0**	**14.6**	**17.4%**	**-**
Total Energy – kWh/m²/yr		**164.4**	**149.4**	**15.0**	**-**	**9.1%**
Total Energy – kWh/suite		**17,361**	**15,774**	**1,587**		
Greenhouse Gas Emissions, tCO_2		**315**	**293**			**7.0%**

Energy Distribution Determined by Energy Simulation



6.2.5 Building 62

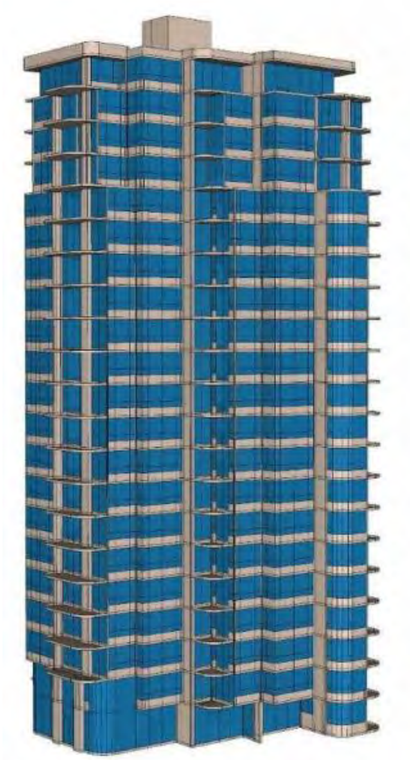


Fig. 6.2.5 Building 62 – Greater Vancouver.

Building 62 was rehabilitated to address moisture related deterioration between May 2004 and May 2005. As part of the rehabilitation, the following key changes were made to the building enclosure assemblies:

- Original fibreglass batt insulation within the steel stud wall assemblies was removed, and replaced with semi-rigid mineral wool exterior insulated assemblies.
- Non-thermally broken aluminum glazing assemblies replaced with thermally broken aluminum glazing assemblies.
- Reduced thermal bridging at details.

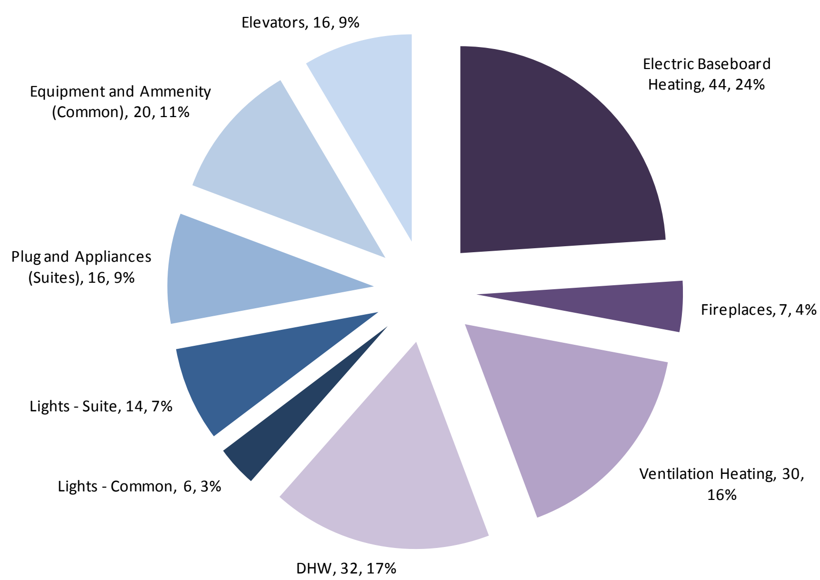
R-values of the pre- and post- rehabilitation building enclosure components were modeled in detail and corresponding area calculations were used to determine – the overall effective R-value of the building enclosure. The overall effective R-value for Building 62 improved from R-2.07 to R-2.60 hr·ft^2·F/Btu (+21%) (U-0.48 to U-0.38 or a reduction of 21%) as a result of the building enclosure rehabilitation work. This improvement was not intentional as the repair was designed to minimize the rehabilitation costs to address moisture damage; however, incidental improvements were realized as a result of the detail changes including an exterior insulated wall assembly, the new thermally improved window and door assemblies and increased airtightness. The energy consumption at the building was reduced by a total of 15.0% (20.8% of the space heat) as a result of the building enclosure rehabilitation work. The overall improvements are summarized in Table 6.2.5.

Table 6.2.5 Summary of Overall R-value and Energy Consumption Changes as the Result of the Building Enclosure Rehabilitation Work.

Enclosure Thermal Performance	Pre-Rehabilitation R-value hr ft² F/Btu *(m² K/W)*	Post-Rehabilitation R-value hr ft² F/Btu *(m² K/W)*	Improvement
Effective Window R-value	1.35 (0.24)	1.67 (0.29)	+24%
Effective Wall Area R-value	3.49 *(0.61)*	4.55 (0.80)	+30%
Effective Roof R-value	*8.18 (1.44)*	*12.53 (2.21)*	+53%
Overall Effective Building Enclosure R-value	**2.07 *(0.36)***	**2.50 (0.46)**	**+21%**

Energy Consumption		Pre-Rehabilitation kWh/m²/yr	Post-Rehabilitation kWh/m²/yr	Energy Savings kWh/m²/yr	% of Space Heat Savings	% of Total Energy Savings
Gas	Space heat: MAU ventilation and fireplaces	38.0	22.4	15.6	17.7%	8.3%
	Domestic Hot water*	29.5	17.6	11.8	-	15.0%
Electricity	Suite: Space heat	40.5	40.5	0.0	0.0%	0.0%
	Suite: All Other	23.2	22.1	1.0	-	0.6%
	Common: Space heat	11.3	8.3	3.0	3.4	1.6%
	Common: All Other	45.0	41.7	3.2	-	1.7%
Total Space Heat – kWh/m²/yr		**89.8**	**71.2**	**18.6**	**20.8%**	**-**
Total Energy – kWh/m²/yr		**187.5**	**152.7**	**34.8**	**-**	**18.5%**
Total Energy – kWh/suite		**26,452**	**21,546**	**4,906**		
Greenhouse Gas Emissions, tCO_2		**145**	**104**			**28.5%**

Energy Distribution Determined by Energy Simulation



* A Domestic Hot water Upgrade was performed at the same time as the enclosure rehabilitation.

6.2.6 Building 7

Fig. 6.2.6 Building 7 – Greater Victoria.

Building 7 was rehabilitated to address moisture related deterioration between February 2004 and October 2004. As part of the rehabilitation, the following key changes were made to the building enclosure assemblies:

- Original fibreglass batt insulation within the steel stud wall assemblies was removed, and replaced with semi-rigid mineral wool exterior insulated assemblies.
- Thermally broken aluminium glazing assemblies replaced with thermally broken aluminium glazing assemblies complete with a moderate performance low-e coating within the new insulated sealed units.
- Reduced thermal bridging at details.

R-values of the pre- and post- rehabilitation building enclosure components were modeled in detail and corresponding area calculations were used to determine the overall effective R-value of the building enclosure. The overall effective R-value for Building 7 improved from R-3.32 to R-4.11 hr·ft^2·F/Btu (+24%) (U-0.30 to U-0.24 or a reduction of 19%) as a result of the building enclosure rehabilitation work. This improvement was not intentional as the repair was designed to minimize the rehabilitation costs to address moisture damage; however, incidental improvements were realized as a result of the detail changes including an exterior insulated wall assembly, the new thermally improved window and door assemblies and increased airtightness.

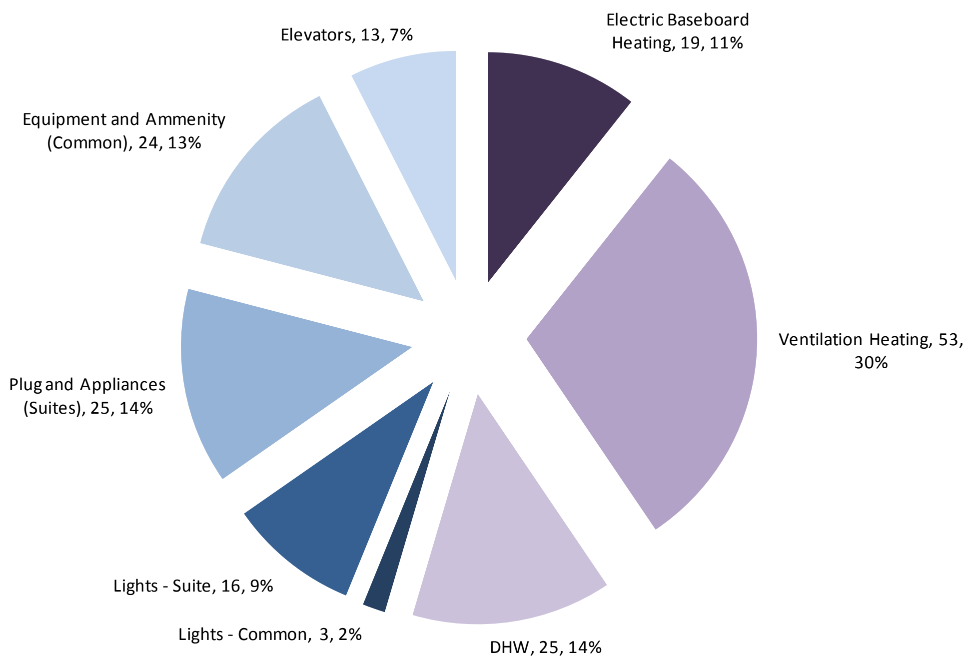
The energy consumption at the building was reduced by a total of 4.8% (8.9% of the space heat) as a result of the building enclosure rehabilitation work. The overall improvements are summarized in Table 6.2.6.

Table 6.2.6 Summary of Overall R-value and Energy Consumption Changes as the Result of the Building Enclosure Rehabilitation Work.

Enclosure Thermal Performance	**Pre-Rehabilitation R-value hr ft² F/Btu *(m² K/W)***	**Post-Rehabilitation R-value hr ft² F/Btu *(m² K/W)***	**Improvement**
Effective Window R-value	1.62 (0.29)	2.17 (0.38)	+34%
Effective Wall Area R-value	4.58 *(0.81))*	5.29 (0.93)	+16%
Effective Roof R-value	*10.00 (1.76)*	*10.75 (1.89)*	+8%
Overall Effective Building Enclosure R-value	**3.32 *(0.58)***	**4.11 (0.72)**	**+24%**

Energy Consumption		**Pre-Rehabilitation kWh/m²/yr**	**Post-Rehabilitation kWh/m²/yr**	**Energy Savings kWh/m²/yr**	**% of Space Heat Savings**	**% of Total Energy Savings**
Gas	Space heat: MAU ventilation	48.4	42.9	5.2	7.0%	2.9%
	Domestic Hot water	30.1	30.1	0	-	0%
Electricity	Suite: Space heat	24.6	23.3	1.4	1.8	0.7%
	Suite: All Other	37.2	37.5	-0.2	-	-0.1%
	Common: Space heat	0.7	0.7	-	-	0%
	Common: All Other	39.6	37.2	2.4	-	1.3%
Total Space Heat – kWh/m²/yr		**73.4**	**66.9**	**6.5**	**8.9%**	**-**
Total Energy – kWh/m²/yr		**180.3**	**171.7**	**8.7**	**-**	**4.8%**
Total Energy – kWh/suite		**13,255**	**12,618**	**638**		
Greenhouse Gas Emissions, tCO_2		**185**	**174**			**5.7%**

Energy Distribution Determined by Energy Simulation



6.2.7 Building 17

Fig. 6.2.7 Building 17 – Greater Vancouver.

Building 17 was rehabilitated to address moisture related deterioration between January 2004 and December 2004. As part of the rehabilitation, the following key changes were made to the building enclosure assemblies:

- Original fibreglass batt insulation within the steel stud wall assemblies was removed, and replaced with extruded polystyrene exterior insulated assemblies.
- Non-thermally broken aluminum glazing assemblies replaced with thermally broken aluminum glazing assemblies complete with a moderate performance low-e coating within the new insulated sealed units.
- Reduced thermal bridging at details.

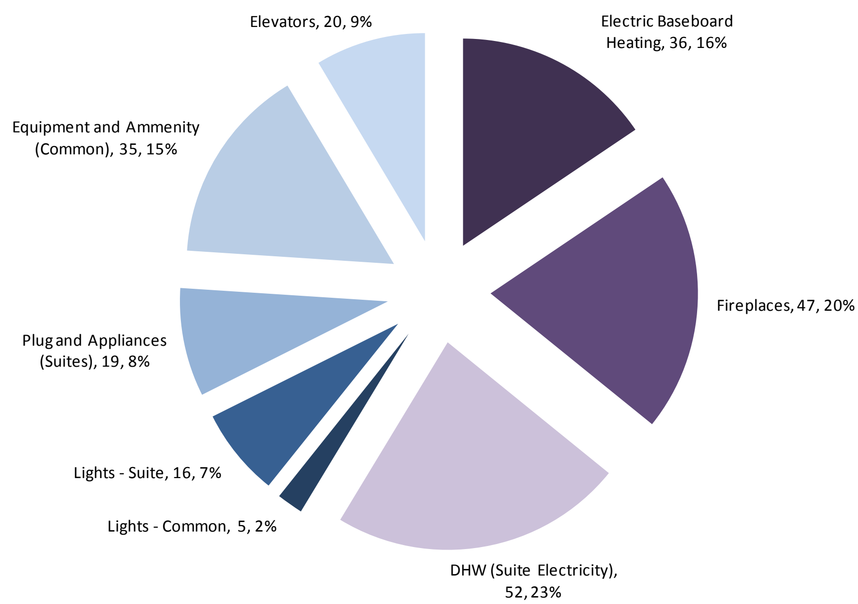
R-values of the pre- and post- rehabilitation building enclosure components were modeled in detail and corresponding area calculations were used to determine the overall effective R-value of the building enclosure. The overall effective R-value for Building 17 improved from R-2.72 to R-3.58 hr·ft^2·F/Btu (+32%) (U-0.37 to U-0.18 or a reduction of 51%) as a result of the building enclosure rehabilitation work. This improvement was not intentional as the repair was designed to minimize the rehabilitation costs to address moisture damage; however, incidental improvements were realized as a result of the detail changes including an exterior insulated wall assembly, the new thermally improved window and door assemblies and increased airtightness. Building 17 is unique in the study compared to the typical MURB, in that it has electric hot water within suites, gas fireplaces within all suites and un-heated make-up air. The energy consumption at the building was reduced by a total of 13.4% (19.1.% of the space heat) as a result of the building enclosure rehabilitation work. The overall improvements are summarized in Table 6.2.7.

Table 6.2.7 Summary of Overall R-value and Energy Consumption Changes as the Result of the Building Enclosure Rehabilitation Work.

Enclosure Thermal Performance	Pre-Rehabilitation R-value hr ft² F/Btu *(m² K/W)*	Post-Rehabilitation R-value hr ft² F/Btu *(m² K/W)*	Improvement
Effective Window R-value	1.28 (0.23)	1.59 (0.28)	+24%
Effective Wall Area R-value	3.92 *(0.69)*	5.51 (0.97)	+41%
Effective Roof R-value	*13.33* *(2.35)*	*18.68* *(3.29)*	+40%
Overall Effective Building Enclosure R-value	**2.72** ***(0.48)***	**3.58 (0.63)**	**+32%**

Energy Consumption*		Pre-Rehabilitation kWh/m²/yr	Post-Rehabilitation kWh/m²/yr	Energy Savings kWh/m²/yr	% of Space Heat Savings	% of Total Energy Savings
Gas	Suite: Gas Fireplaces for Space heat	46.7	31.9	14.8	16.4%	6.5%
Electricity	Suite: Space heat	32.3	32.4	-0.1	-0.1%	0.0%
	Suite: All Other *Including Domestic Hot water*	83.0	69.6	13.4	-	5.8%
	Common: Space heat	11.6	9.1	2.6	2.8%	1.1%
	Common: All Other	56.4	56.4	0.0	-	-
Total Space Heat – kWh/m²/yr		**90.6**	**73.3**	**17.3**	**19.1%**	**-**
Total Energy – kWh/m²/yr		**230.0**	**199.2**	**30.7**	**-**	**13.4%**
Total Energy – kWh/suite		**21,603**	**18,718**	**2,884**		
Greenhouse Gas Emissions, tCO_2		**118**	**95**	**23**		**19%**

Energy Distribution Determined by Energy Simulation



6.2.8 Building 20

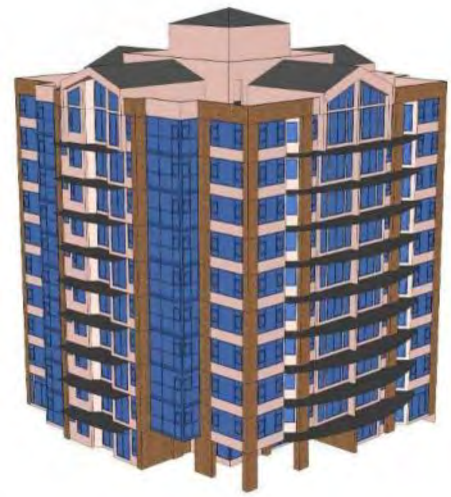


Fig. 6.2.8 Building 20 – Greater Vancouver.

Building 20 was rehabilitated to address moisture related deterioration between March 2005 and January 2006. As part of the rehabilitation, the following key changes were made to the building enclosure assemblies:

- Original fibreglass batt insulation within the steel stud wall assemblies was removed, and replaced with semi-rigid mineral wool exterior insulated assemblies. In some locations, EPS was removed from behind brick cladding and replaced with semi-rigid mineral wool exterior insulation and new brick cladding.
- Non-thermally broken aluminum glazing assemblies replaced with thermally broken aluminum glazing assemblies complete with a moderate performance low-e coating within the new insulated sealed units.
- Reduced thermal bridging at details.

R-values of the pre- and post- rehabilitation building enclosure components were modeled in detail and corresponding area calculations were used to determine the overall effective R-value of the building enclosure. The overall effective R-value for Building 20 improved from R-2.16 to R-3.14 hr·ft^2·F/Btu (+45%) (U-0.46 to U-0.32 or a reduction of 31%) as a result of the building enclosure rehabilitation work. This improvement was not intentional as the repair was designed to minimize the rehabilitation costs to address moisture damage; however, incidental improvements were realized as a result of the detail changes including an exterior insulated wall assembly, the new thermally improved window and door assemblies and increased airtightness.

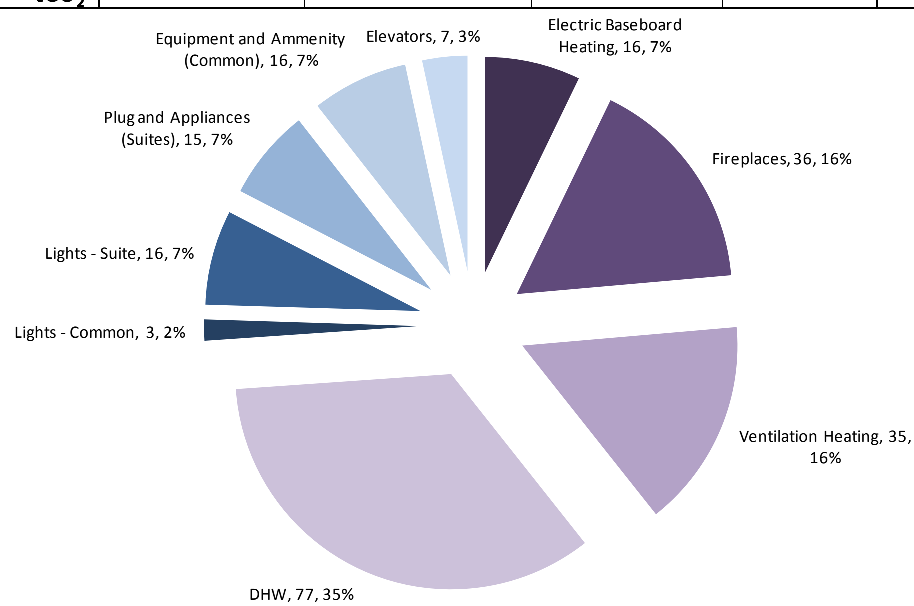
The energy consumption at the building was reduced by a total of 8.2% (18.0% of the space heat) as a result of the building enclosure rehabilitation work. The overall improvements are summarized in Table 6.2.8.

Table 6.2.8 Summary of Overall R-value and Energy Consumption Changes as the Result of the Building Enclosure Rehabilitation Work.

Enclosure Thermal Performance	Pre-Rehabilitation R-value	Post-Rehabilitation R-value	Improvement
	$hr\ ft^2\ F/Btu$ *($m^2\ K/W$)*	$hr\ ft^2\ F/Btu$ *($m^2\ K/W$)*	
Effective Window R-value	1.34 (0.24)	2.16 (0.38)	+61%
Effective Wall Area R-value	3.38 *(0.60)*	4.00 (0.70)	+18%
Effective Roof R-value	*7.14* *(1.26)*	*7.78* *(1.37)*	+9%
Overall Effective Building Enclosure R-value	**2.16** ***(0.38)***	**3.14** **(0.55)**	**+45%**

Energy Consumption		Pre-Rehabilitation kWh/m^2/yr	Post-Rehabilitation kWh/m^2/yr	Energy Savings kWh/m^2/yr	% of Space Heat Savings	% of Total Energy Savings
Gas	Space heat: Gas Fireplaces & MAU ventilation	81.8	69.2	12.5	12.5%	5.7%
	Domestic Hot water	66.0	66.0	0	-	0%
Electricity	Suite: Space heat	18.0	12.4	5.6	5.6%	2.5%
	Suite: All Other	28.1	28.1	0	-	0%
	Common: Space heat	0.4	0.5	+0.1	-0.1%	-0.1%
	Common: All Other	26.9	26.9	0	-	0%
Total Space Heat – kWh/m^2/yr		**100.2**	**82.1**	**18.0**	**18.0%**	**-**
Total Energy – kWh/m^2/yr		**221.3**	**203.2**	**18.0**	**-**	**8.2%**
Total Energy – kWh/suite		**24,467**	**22,472**	**1,995**		
Greenhouse Gas Emissions, tCO_2		**196**	**179**			**8.3%**

Energy Distribution Determined by Energy Simulation



6.2.9 Building 11

Fig. 6.2.9 Building 11 – Greater Vancouver.

Building 11 was rehabilitated to address moisture related deterioration between January 2001 and October 2001. As part of the rehabilitation, the following key changes were made to the building enclosure assemblies:

- Original fibreglass batt insulation within the steel stud wall assemblies was removed, and replaced with semi-rigid mineral wool exterior insulated assemblies.
- Non-thermally broken aluminum glazing assemblies replaced with thermally broken aluminum glazing assemblies.
- Reduced thermal bridging at details.

The overall effective R-value for Building 11 improved from R-2.27 to R-2.62 hr·ft^2·F/Btu (+15%) (U-0.44 to U-0.38 or a reduction of 14%) as a result of the building enclosure rehabilitation work. This improvement was not intentional as the repair was designed to minimize the rehabilitation costs to address moisture damage; however, incidental improvements were realized as a result of the detail changes including an exterior insulated wall assembly, the new thermally improved window and door assemblies and increased airtightness.

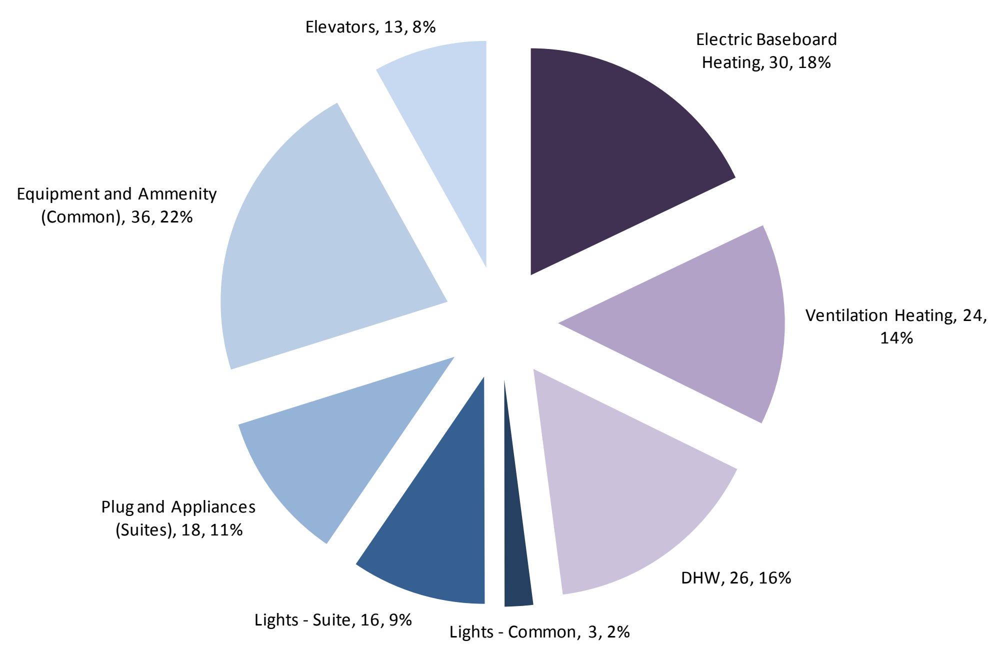
The energy consumption at the building was reduced by a total of 0.9% (but 22.0% of the space heat) as a result of the building enclosure rehabilitation work. The overall improvements are summarized in Table 6.2.9.

Table 6.2.9 Summary of Overall R-value and Energy Consumption Changes as the Result of the Building Enclosure Rehabilitation Work.

Enclosure Thermal Performance	**Pre-Rehabilitation R-value** hr ft^2 F/Btu *(m^2 K/W)*	**Post-Rehabilitation R-value** hr ft^2 F/Btu *(m^2 K/W)*	**Improvement**
Effective Window R-value	1.33 (0.23)	1.52 (0.27)	+14%
Effective Wall Area R-value	3.74 *(0.67)*	4.31 (0.76)	+15%
Spandrel Panel Area R-value	0.93 (0.16)	2.50 (0.44)	+170%
Effective Roof R-value	*12.99* *(2.29)*	*12.99* *(2.29)*	0%
Overall Effective Building Enclosure R-value	**2.27** ***(0.40)***	**2.62** **(0.46)**	**+15%**

Energy Consumption		**Pre-Rehabilitation kWh/m²/yr**	**Post-Rehabilitation kWh/m²/yr**	**Energy Savings kWh/m²/yr**	**% of Space Heat Savings**	**% of Total Energy Savings**
Gas	Space heat: MAU ventilation	21.8	19.0	2.8	4.9%	1.7%
	Domestic Hot water	27.6	25.7	1.9	-	1.1%
Electricity	Suite: Space heat	32.0	23.7	8.3	14.8%	5.0%
	Suite: All Other	30.2	45.0	-14.8	-	-8.9%
	Common: Space heat	2.3	1.1	1.3	2.3%	0.8%
	Common: All Other	52.1	50.0	2.1	-	1.3%
Total Space Heat – kWh/m²/yr		**56.1**	**43.8**	**12.3**	**22.0%**	**-**
Total Energy – kWh/m²/yr		**166.0**	**164.5**	**1.6**	**-**	**0.9%**
Total Energy – kWh/suite		**12,119**	**12,005**	**114**		
Greenhouse Gas Emissions, tCO_2		**142.5**	**136.3**			**4.4%**

Energy Distribution Determined by Energy Simulation



6.2.10 Building 28

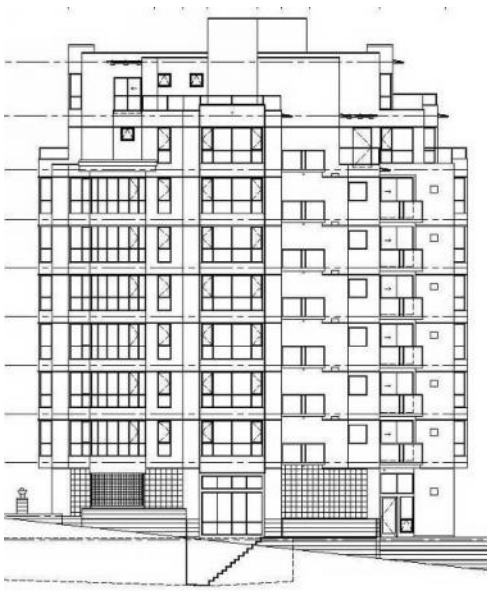


Fig. 6.2.10 Building 28 – Greater Vancouver.

Building 28 was rehabilitated to address moisture related deterioration between May 2005 through March 2006. As part of the rehabilitation, the following key changes were made to the building enclosure assemblies:

- Original fibreglass batt insulation within the steel stud wall assemblies was removed, and replaced with semi-rigid mineral wool exterior insulated assemblies.
- Non-thermally broken aluminum glazing assemblies replaced with thermally broken aluminum glazing assemblies complete with a moderate performance low-e coating within the new insulated sealed units.
- Reduced thermal bridging at details.

R-values of the pre- and post- rehabilitation building enclosure components were modeled for a typical floor and corresponding area calculations were used to determine the overall effective R-value of that floor. The R-value of each component of that floor was found using the average value of similar components in other buildings. The values from this typical floor, including the R-values and areas, were extrapolated and used to represent the building as a whole. Comparison of the R-value for a building where the whole building was modeled, with the R-value of that building if only the typical floor had been used, indicates that this method is appropriate with the average uncertainty being approximately 1%. The overall effective R-value for Building 28 improved from R-2.23 to R-3.52 hr·ft^2·F/Btu (+58%) (U-0.45 to U-0.28 or a reduction of 38%) as a result of the building enclosure rehabilitation work. This improvement was not intentional as the repair was designed to minimize the rehabilitation costs to address moisture damage; however, incidental improvements were realized as a result of the detail changes including an exterior insulated wall assembly, the new thermally improved window and door assemblies and increased airtightness.

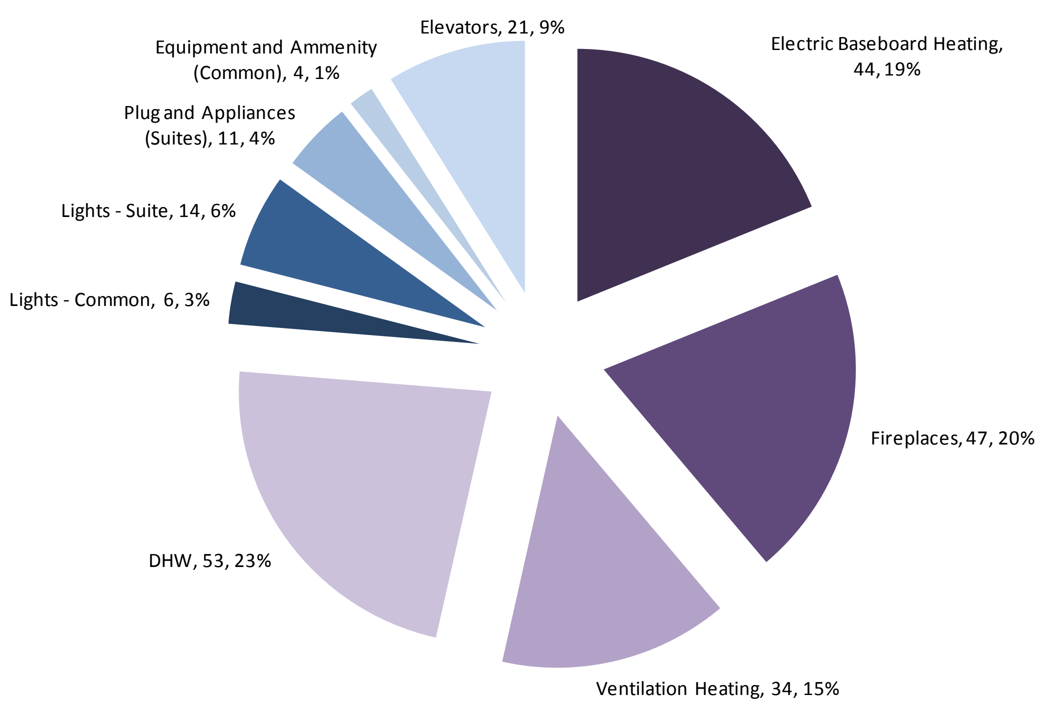
The energy consumption at the building was reduced by a total of 13.7% (24.7% of the space heat) as a result of the building enclosure rehabilitation work. The overall improvements are summarized in Table 6.2.10.

Table 6.2.10 Summary of Overall R-value and Energy Consumption Changes as the Result of the Building Enclosure Rehabilitation Work.

Enclosure Thermal Performance	Pre-Rehabilitation R-value	Post-Rehabilitation R-value	Improvement
	hr ft² F/Btu *(m² K/W)*	hr ft² F/Btu *(m² K/W)*	
Effective Window R-value	1.33 (0.23)	2.13 (0.38)	+60%
Effective Wall Area R-value	3.95 *(0.70)*	6.14 (1.08)	+55%
Effective Roof R-value	*10.00* *(1.76)*	*12.99* *(2.29)*	+30%
Overall Effective Building Enclosure R-value	**2.23** ***(0.39)***	**3.52** **(0.62)**	**+58%**

Energy Consumption		Pre-Rehabilitation kWh/m²/yr	Post-Rehabilitation kWh/m²/yr	Energy Savings kWh/m²/yr	% of Space Heat Savings	% of Total Energy Savings
Gas	Space heat: Fireplaces and MAU ventilation	80.4	57.6	22.9	18.4%	9.9%
	Domestic Hot water	51.0	51.0	0	-	0%
Electricity	Suite: Space heat	38.1	30.3	7.8	6.3%	3.4%
	Suite: All Other	23.1	24.4	-1.3	-	-0.6%
	Common: Space heat	5.5	5.5	0	0%	0%
	Common: All Other	32.0	29.8	2.3	-	1.0%
Total Space Heat – kWh/m²/yr		**124.0**	**93.4**	**30.6**	**24.7%**	**-**
Total Energy – kWh/m²/yr		**230.1**	**198.5**	**31.6**	**-**	**13.7%**
Total Energy – kWh/suite		**32,915**	**28,393**	**4,522**		
Greenhouse Gas Emissions, tCO_2		**66.3**	**55.8**	**10.5**		**15.8%**

Energy Distribution Determined by Energy Simulation



6.2.11 **Building 21**

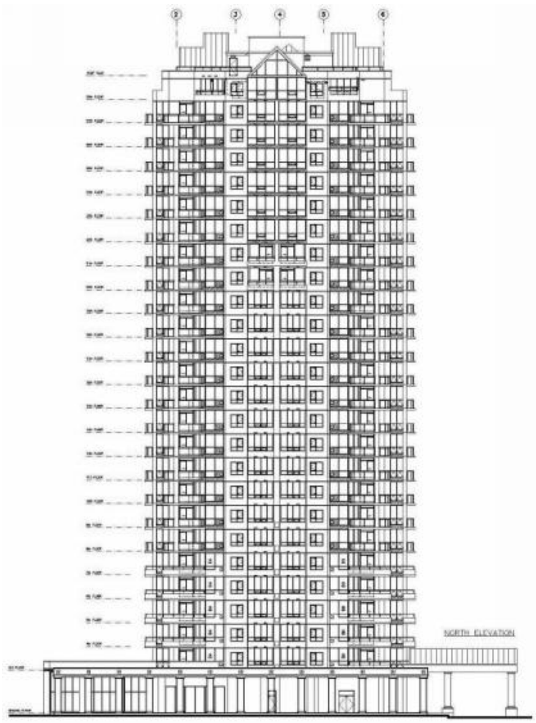


Fig. 6.2.11 Building 21 – Greater Vancouver.

Building 21 was rehabilitated to address moisture related deterioration between May 2003 and May 2004. As part of the rehabilitation, the following key changes were made to the building enclosure assemblies:

- Original fibreglass batt insulation within the steel stud wall assemblies was removed, and replaced with semi-rigid mineral wool exterior insulated assemblies.
- Non-thermally broken aluminum glazing assemblies replaced with thermally broken aluminum glazing assemblies complete with a moderate performance low-e coating within the new insulated sealed units.
- Reduced thermal bridging at details.

R-values of the pre- and post- rehabilitation building enclosure components were modeled for a typical floor and corresponding area calculations were used to determine the overall effective R-value of that floor. The R-value of each component of that floor was found using the average value of similar components in other buildings. The values from this typical floor, including the R-values and areas, were extrapolated and used to represent the building as a whole. Comparison of the R-value for building where the whole building was modeled, with the R-value of that building if only the typical floor had been used, indicates that this method is appropriate with the average uncertainty being approximately 1%. The overall effective R-value for Building 21 improved from R-1.84 to R-2.97 $hr\cdot ft^2\cdot F/Btu$ (+61%) (U-0.55 to U-0.34 or a reduction of 38%) as a result of the building enclosure rehabilitation work. This improvement was not intentional as the repair was designed to minimize the rehabilitation costs to address moisture damage; however, incidental improvements were realized as a result of the detail changes including an exterior insulated wall assembly, the new thermally improved window and door assemblies and increased airtightness.

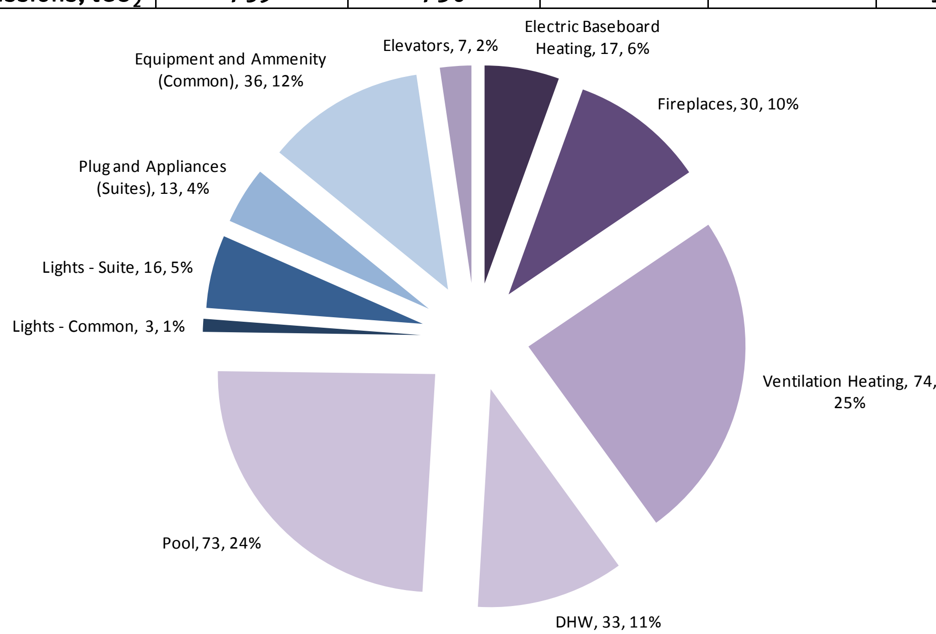
The energy consumption at the building was reduced by a total of 3.4% as a result of the building enclosure rehabilitation work; however, total gas and electric space heating was not apparently reduced (due to baseline changes). The overall improvements are summarized in Table 6.2.11.

Table 6.2.11 Summary of Overall R-value and Energy Consumption Changes as the Result of the Building Enclosure Rehabilitation Work.

Enclosure Thermal Performance	Pre-Rehabilitation R-value hr ft² F/Btu *(m^2 K/W)*	Post-Rehabilitation R-value hr ft² F/Btu *(m^2 K/W)*	Improvement
Effective Window R-value	1.33 (0.23)	2.13 (0.38)	+60%
Effective Wall Area R-value	3.01 *(0.53)*	4.68 (0.82)	+55%
Spandrel Panels	0.93 (0.16)	2.50 (0.44)	+169%
Effective Roof R-value	*12.99* *(2.29)*	*12.99* *(2.29)*	0%
Overall Effective Building Enclosure R-value	**1.84** ***(0.32)***	**2.97 (0.17)**	**+61%**

Energy Consumption		Pre-Rehabilitation kWh/m^2/yr	Post-Rehabilitation kWh/m^2/yr	Energy Savings kWh/m^2/yr	% of Space Heat Savings	% of Total Energy Savings
Gas	Space heat: MAU ventilation & gas fireplaces	98.3	104.6	-6.2	-5.3%	-2.1%
	Baseline, Domestic Hot water	114.3	99.1	15.2	-	5.0%
Electricity	Suite: Space heat	17.4	12.8	4.6	3.9%	1.5%
	Suite: All Other	27.9	35.3	-7.4	-	-2.4%
	Common: Space heat	2.0	1.3	0.8	0.7%	0.3%
	Common: All Other	44.1	40.7	3.4	-	1.1%
Total Space Heat – kWh/m^2/yr		**117.8**	**118.7**	**-0.8**	**-0.7%**	**-**
Total Energy – kWh/m^2/yr		**304.2**	**293.8**	**10.4**	**-**	**3.4%**
Total Energy – kWh/suite		**36,712**	**35,454**	**1,258**		
Greenhouse Gas Emissions, tCO_2		**759**	**730**			**3.9%**

Energy Distribution Determined by Energy Simulation



6.2.12 Buildings 39 & 41

Fig. 6.2.12 Buildings 39 and 41 – Greater Vancouver.

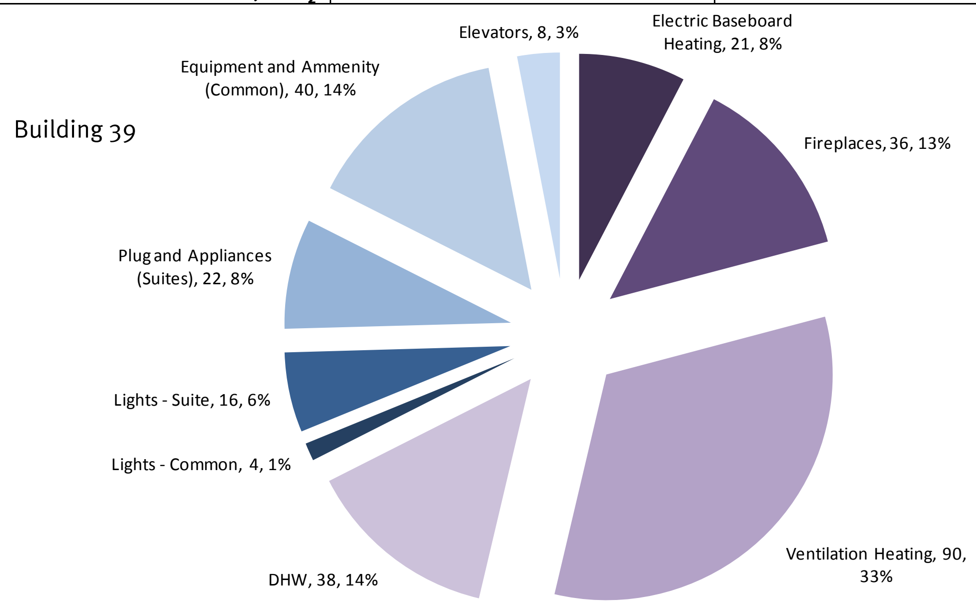
Buildings 39 and 41 are sister buildings within the same three-tower building complex. The buildings have not been rehabilitated, however, they have been included in this detailed analysis because they are representative of modern construction (post 2000's), are twin buildings, and use more than the average intensity of energy compared to MURBs constructed in the 1980's and 1990's. The layout, construction, age, and location of these two buildings are nearly identical. Because these two buildings are so similar (identical floor plans, wall assemblies and windows), the effective R-value of the current building enclosure was only calculated for Building 39, and Building 41 was assumed to be the same. The overall effective R-value for both buildings is R-2.06 hr·ft^2·F/Btu (U-0.48). The overall R-value for the building components are summarized in Table 6.2.12 and is so poor due the low performing windows occupying 62% of the overall wall area.

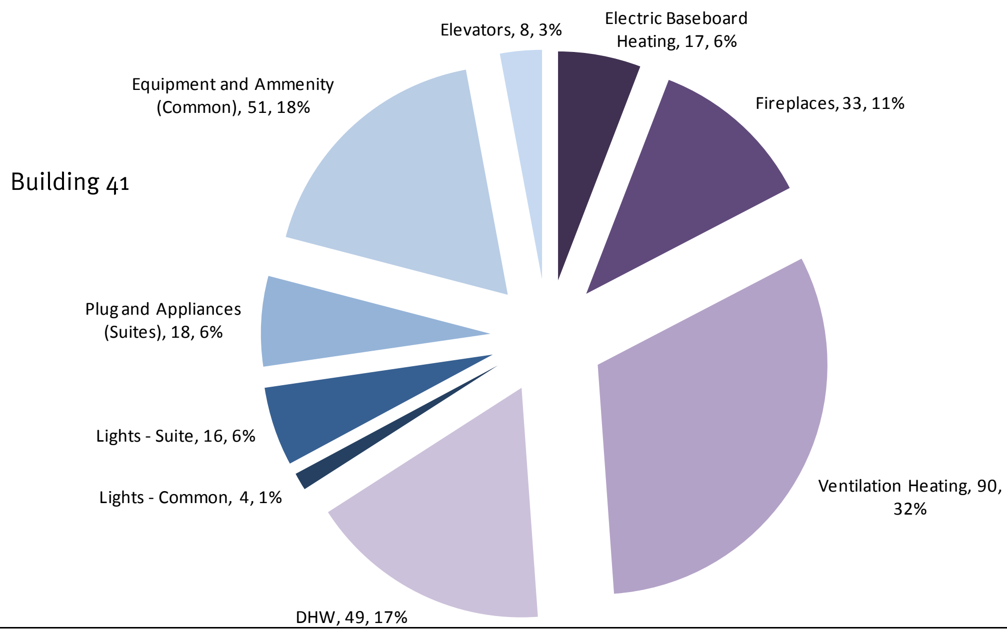
Table 6.2.12 Summary of Overall R-value and Energy Consumption.

Enclosure Thermal Performance	Enclosure R-value hr ft^2 F/Btu *(m^2 K/W)*
Effective Window R-value	1.58 (0.28)
Effective Wall Area R-value	2.95 *(0.52)*
Effective Roof R-value	*21.25* *(3.74)*
Overall Effective Building Enclosure R-value	**2.06** ***(0.36)***

Energy Consumption		Building 39 - kWh/m²/yr	Building 41 – kWh/m²/yr
Gas	Space heat: Fireplaces (every suite) and MAU ventilation heat	117.9	110.7
	Domestic hot water	46.5	57.5
Electricity	Suite: Space heat	25.9	17.7
	Suite: All Other	32.4	31.8
	Common: Space heat	0.0	4.1
	Common: All Other	53.3	59.2
Total Space Heat – kWh/m²/yr		**143.8**	**132.5**
Total Energy – kWh/m²/yr		**275.9**	**281.0**
Total Energy – kWh/suite		**32,325**	**32,167**
Greenhouse Gas Emissions, tCO_2		**533.2**	**544.6**

Energy Distribution Determined by Energy Simulation





6.3. Summary of Pre- Post- Rehabilitation Energy Consumption

The plots within the following sections provide a summary of the results from the analysis of the 13 buildings.

6.3.1 Overall Enclosure R-values – Pre- and Post- Rehabilitation

Overall Enclosure R-values were improved significantly in each of the buildings in the study. Fig. 6.3.1.1 plots the effective R-value improvement for each building and Fig. 6.3.1.2 plots the percentage improvement made by the rehabilitation. Each building is shown, and the typical average building "Typ Avg" in the plots represents the averages from all buildings except: Building 17 (electric hot water), Building 18 (mechanical system change affected consumption significantly), Building 39/41 (new construction no rehabilitation).

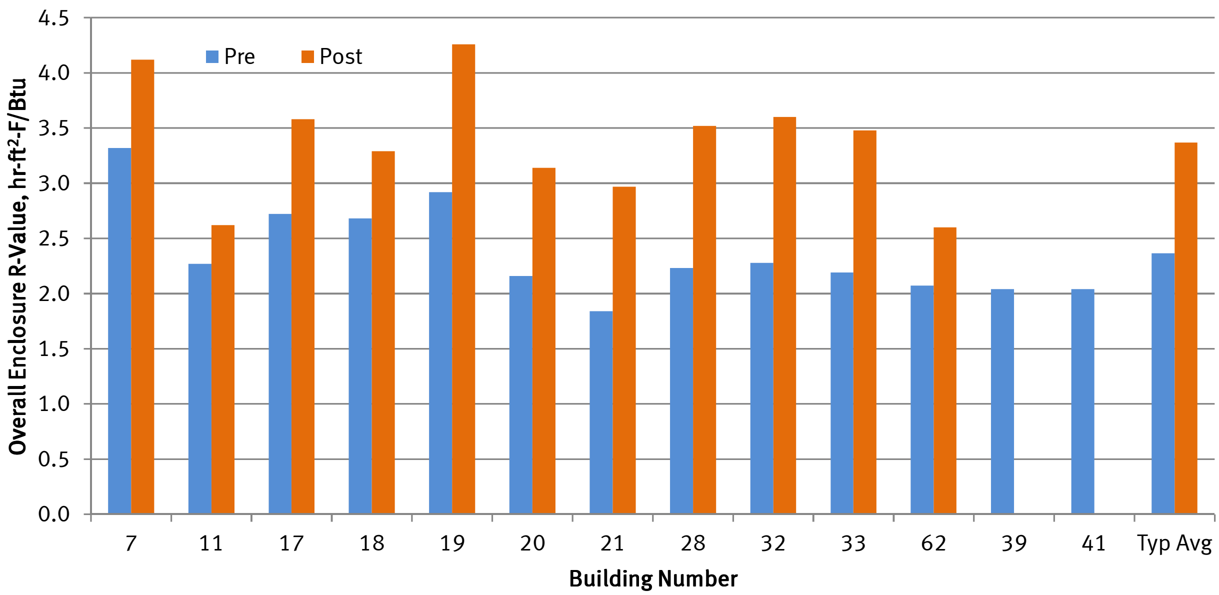


Fig. 6.3.1.1 Summary of calculated Pre- and Post-Rehabilitation Overall Effective Enclosure R-values.

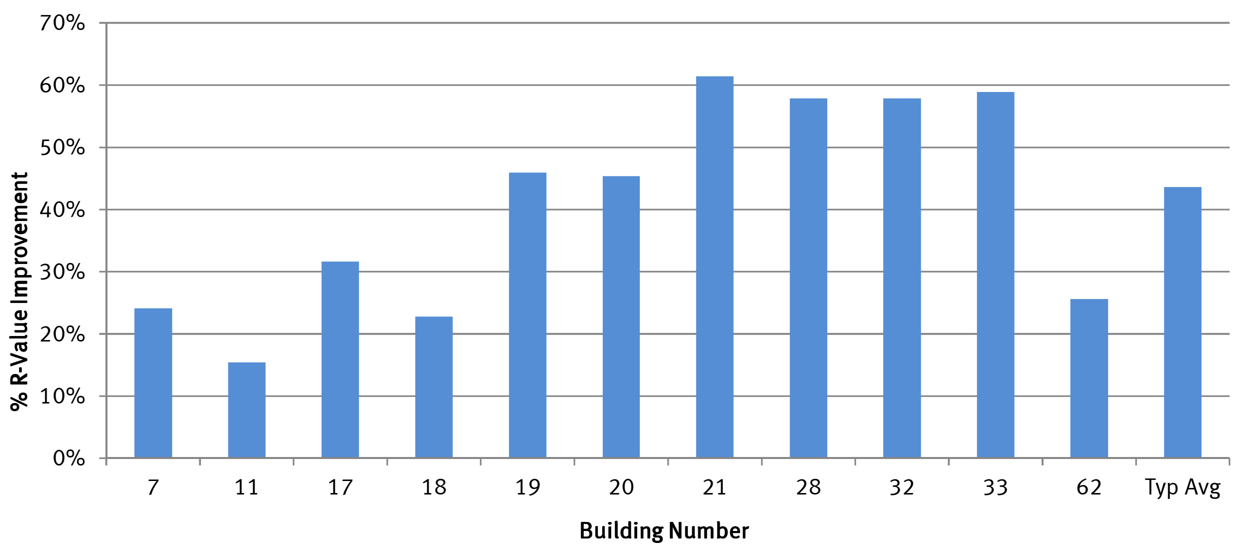


Fig. 6.3.1.2 Summary of Overall Effective R-value Improvement made by Rehabilitation.

The overall effective enclosure R-value is plotted by year of initial construction for each of the buildings in

Fig. 6.3.1.3 demonstrating the lack of improvement made over the past almost 30 years to current practice. While not a statistically significant sample, the R-values are representative of typical past and current MURBs (i.e. an effective range of R-2 to R-3 is fairly representative of MURB construction).

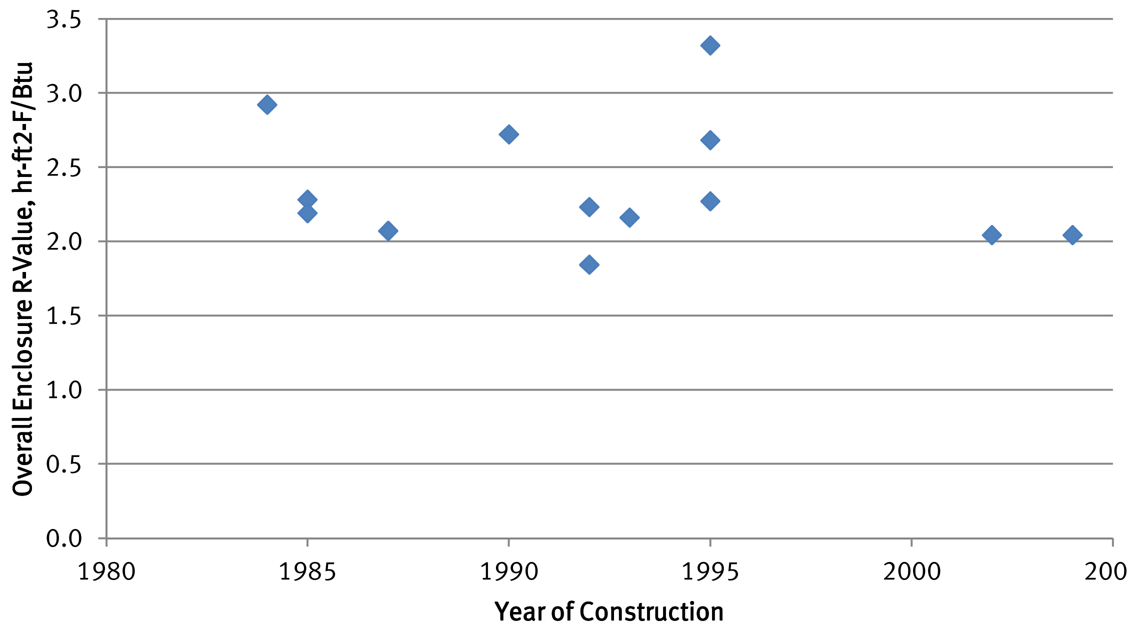


Fig. 6.3.1.3 Summary of Overall Effective R-Value versus Year of Construction.

6.3.2 Total Building Energy Consumption Pre- and Post-Rehabilitation

The total pre- and post-rehabilitation energy consumption is shown for each of the buildings in Fig. 6.3.2.1 and in absolute kWh/m²/yr in Fig. 6.3.2.2 and Fig. 6.3.2.3 and as a total percentage in Fig. 6.3.2.4.

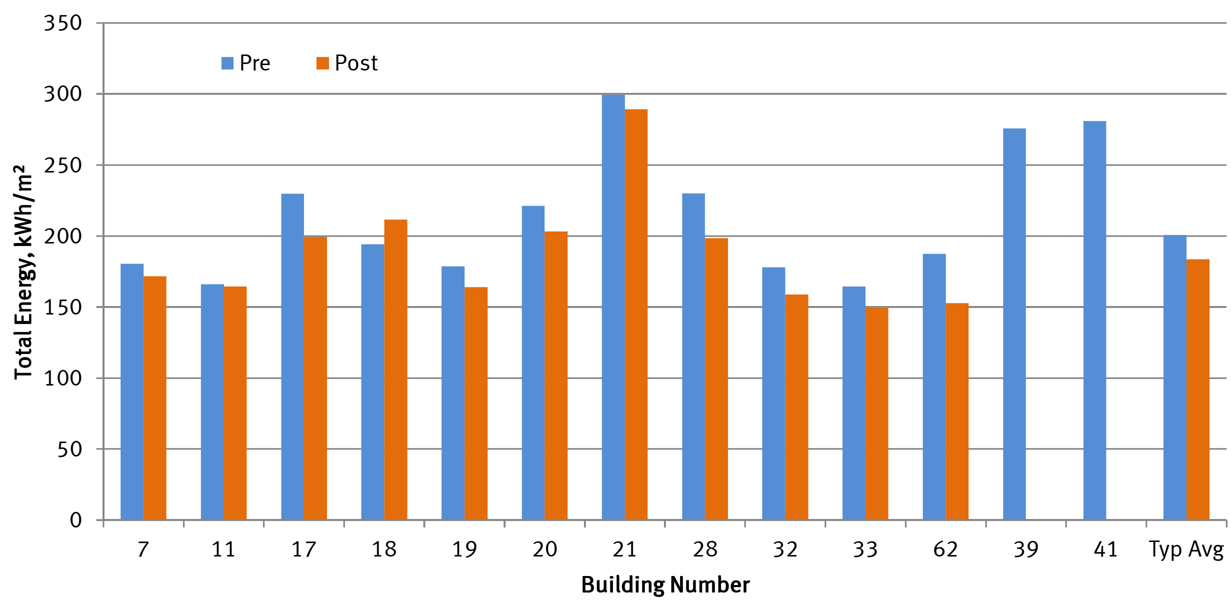


Fig. 6.3.2.1 Summary of Total Energy Consumption Pre- and Post-Rehabilitation.

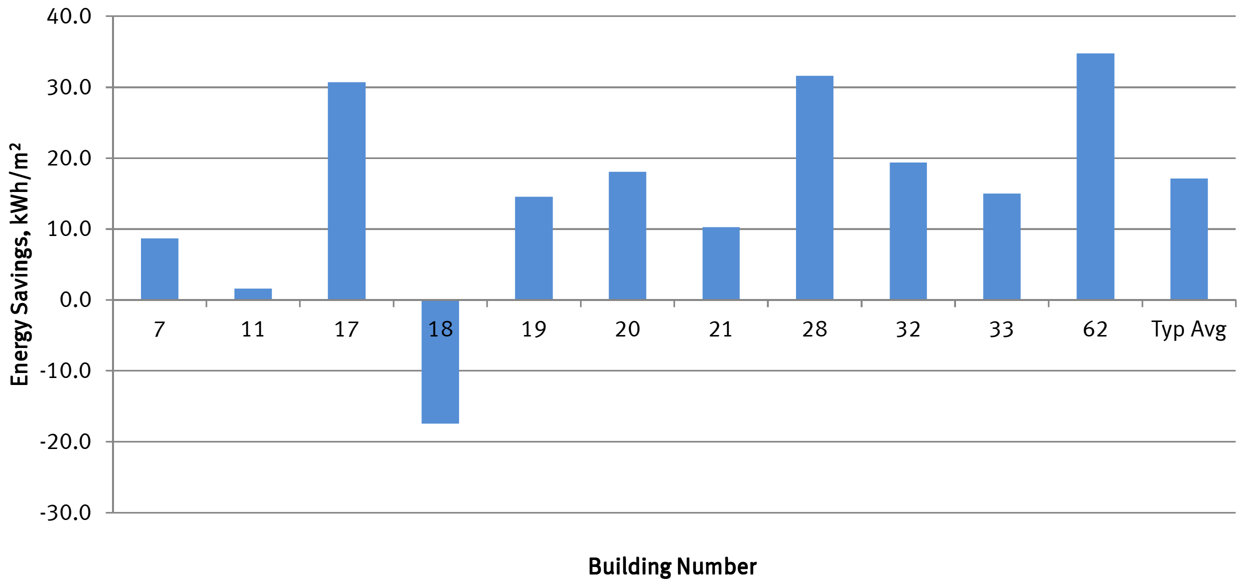


Fig. 6.3.2.2 Summary of Total Energy Consumption Savings (Absolute kWh/m^2/yr) Pre- and Post-Rehabilitation.

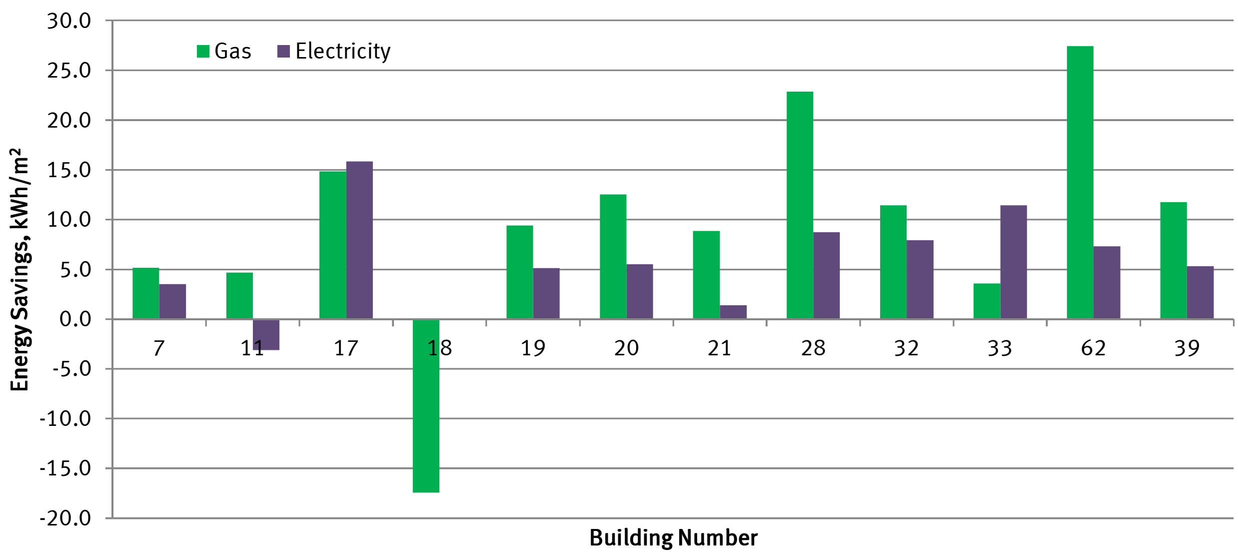


Fig. 6.3.2.3 Summary of Total Energy Consumption Savings (Absolute kWh/m^2/yr) Pre- and Post-Rehabilitation.

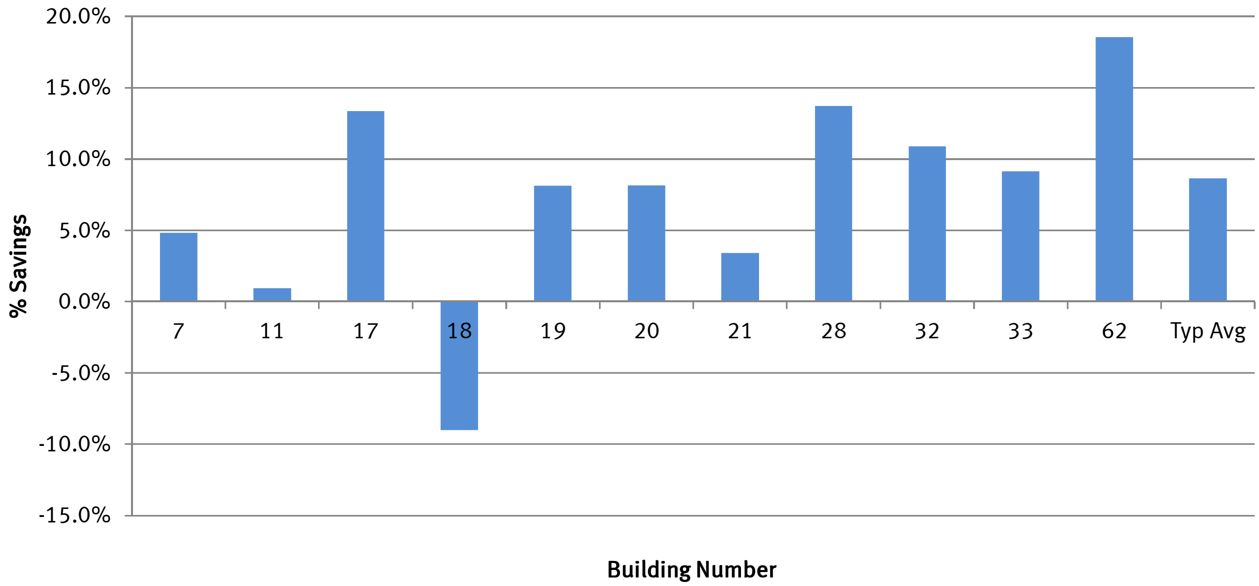


Fig. 6.3.2.4 Summary of Total Energy Consumption Savings (%) Pre- and Post-Rehabilitation.

With the exception of Building 18, a reduction in total energy was observed post-rehabilitation. Mechanical system changes within Building 18 during the rehabilitation resulted in an apparent increase in total energy which eliminated any potential space heat savings from the enclosure improvements (U-value reduction).

6.3.3 Space Heat Energy Consumption Pre- and Post-Rehabilitation

The total pre- and post-rehabilitation space heat energy consumption is shown for each of the buildings in Fig. 6.3.3.1. Separately gas space heat is shown in Fig. 6.3.3.2, Suite electrical space heat is shown in Fig. 6.3.3.3 and common electrical (if present) is shown in Fig. 6.3.3.4. Absolute space heat savings in kWh/m^2/yr are shown in Fig. 6.3.3.5 and as an overall percentage of the space heating load in Fig. 6.3.3.6.

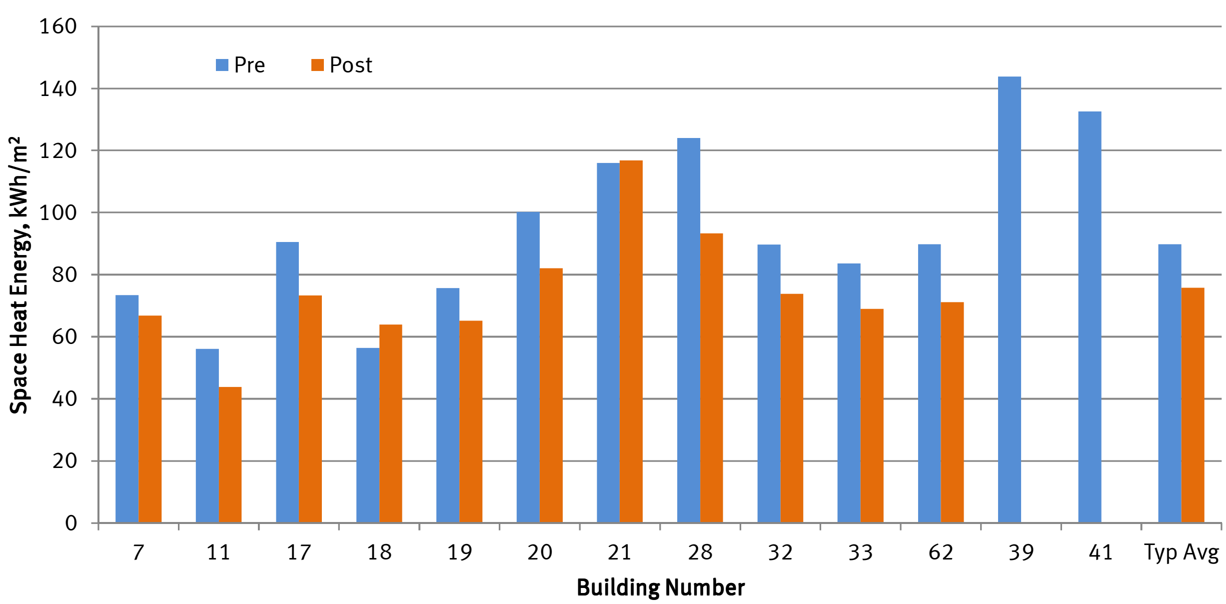


Fig. 6.3.3.1 Summary of Total Gas and Electrical Space Heat Energy Consumption Pre- and Post-Rehabilitation.

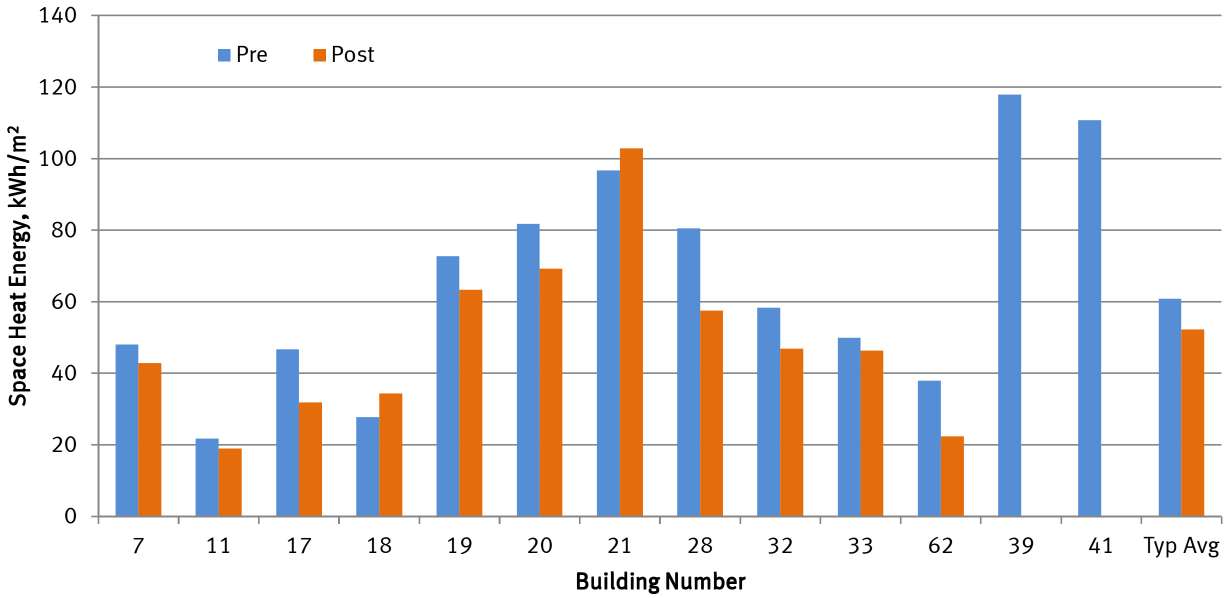


Fig. 6.3.3.2 Summary of Gas Space Heat Energy Consumption Pre- and Post-Rehabilitation.

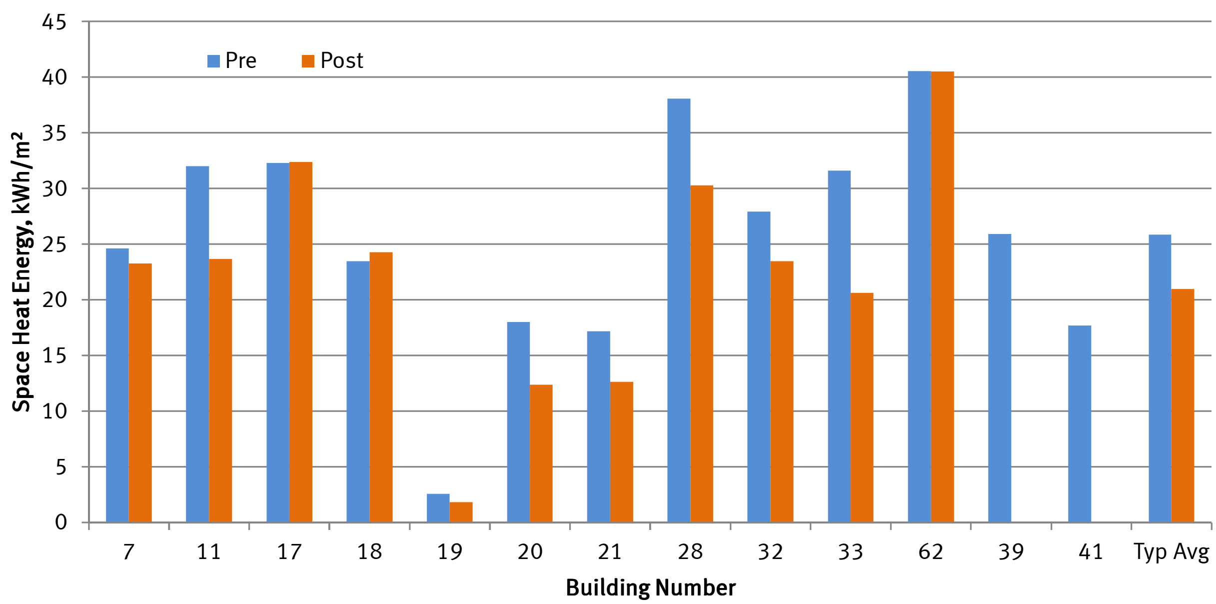


Fig. 6.3.3.3 Summary of Suite Electrical Space Heat Energy Consumption Pre- and Post-Rehabilitation.

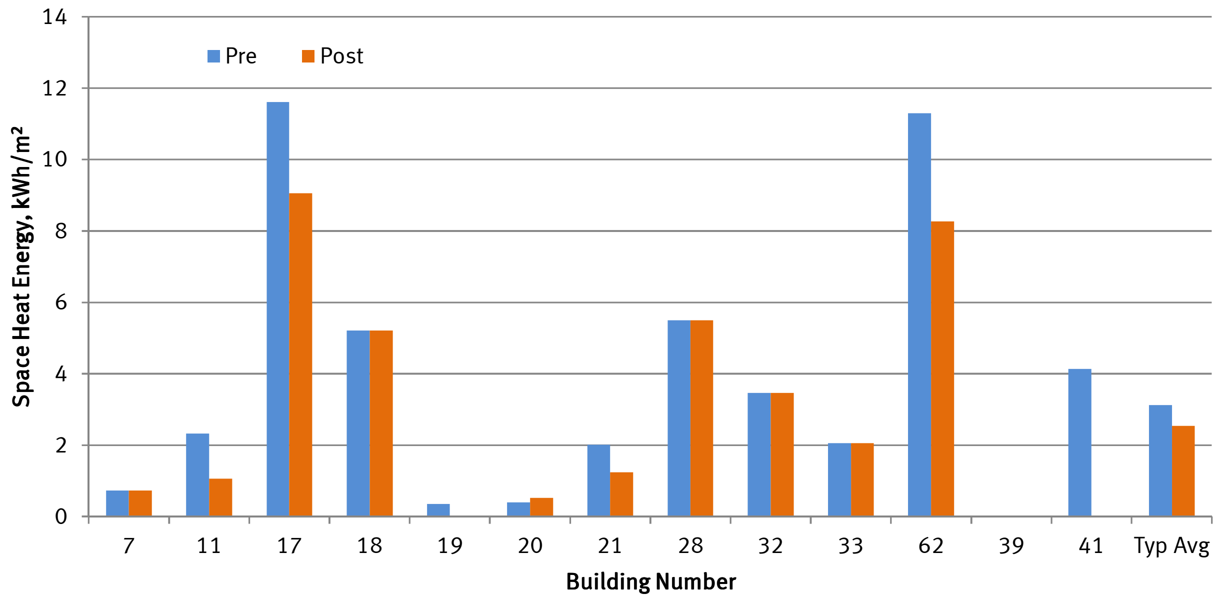


Fig. 6.3.3.4 Summary of Common Electrical Space Heat Energy Consumption Pre- and Post-Rehabilitation.

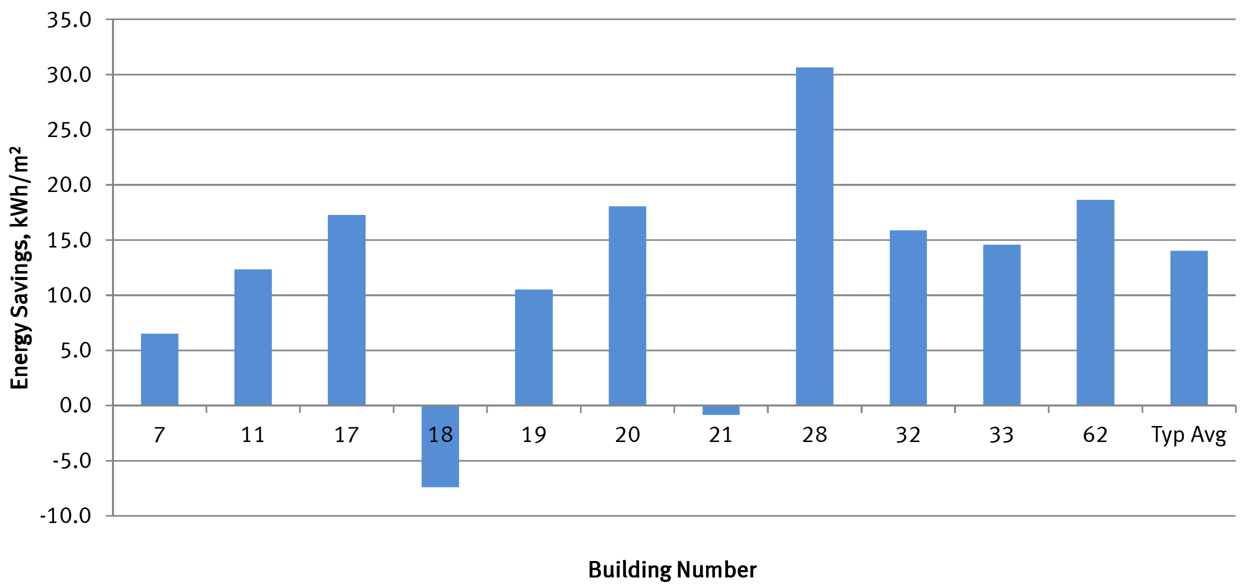


Fig. 6.3.3.5 Summary of Space Heat Energy Consumption Savings (Absolute $kWh/m^2/yr$) Pre- to Post-Rehabilitation.

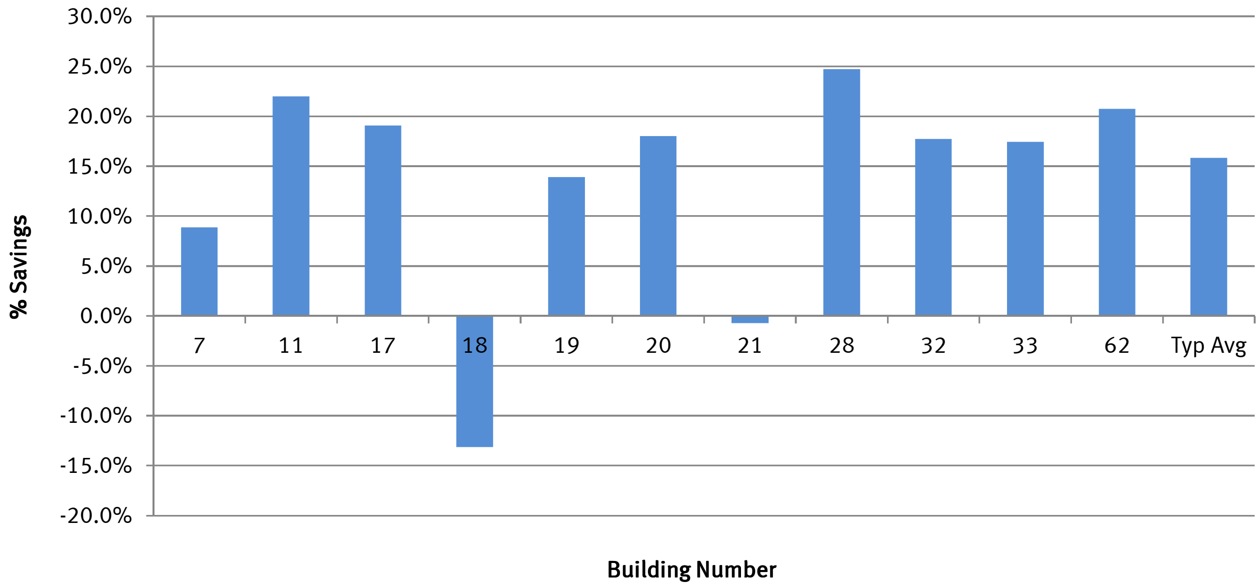


Fig. 6.3.3.6 Summary of Space Heat Energy Consumption Savings (%) Pre- to Post-Rehabilitation.

The results of the analysis for the thirteen buildings demonstrate typical space heat energy savings as the result of building enclosure rehabilitations in the order of 10% to 20% (average of approximately 15%) for the 11 study buildings. Space heat savings were smaller than anticipated or overshadowed by changes to mechanical systems in Buildings 18 and 21, and potentially higher than anticipated in Building 62 for similar reasons.

The space heat reductions are the result of improvements to the thermal resistance of the overall enclosure (reduced thermal bridging, improved windows and insulation) and airtightness. Mechanical changes within the MURBs (DHW systems, MAU set-point, Electrical loads etc.) also had an impact on the space heat and total energy savings (or increases) in each of the MURBs.

7. MURB ENERGY MODELING AND SIMULATION

Energy simulations were performed for the 13 buildings to assess the pre- and post-rehabilitation energy savings and perform further analyses on the impact of airtightness, effective wall and window R-values, solar heat-gain, and mechanical system efficiencies which cannot be performed using the billing data alone. Energy simulations were performed using the Facilities Analysis Simulation Tool (FAST), a DOE2-based program developed by EnerSys Analytics.

7.1. Energy Simulation Summary and Observations

The following sections summarize the energy simulation exercise for the 13 study buildings, including trends and lessons learned. Based on the characteristics and findings from the 13 buildings, a typical building model was created to further assess the impact of a variety of energy conservation measures. The results from building energy consumption simulations are also further discussed in later chapters of this report.

7.1.1 Energy Simulation Inputs and Calibrations

As a result of previous work combined with audits undertaken as part of the study, some of the inputs to the energy simulation were known for the building while others, particularly the mechanical and electrical inputs, were estimated and adjusted in order to calibrate the simulation to match the metered data. A number of critical observations are made from the input and calibration process.

Inputs: Outdoor Air Flow

A minimum outdoor air flow rate was taken from the nameplate for 10 of the buildings as the total capacity of the make-up air unit. The make-up air flow rate could not be obtained for three of the buildings, and had to be estimated based on the calibrations for these simulations. Of the remaining 10 buildings, four required a lower make-up air flow rate than the nameplate (90% of the nominal capacity) in order to calibrate the simulation to the metered data. This is a reasonable change since it is not known whether the nominal make-up air flow rate is actually delivered to the building, or whether this rate is slightly higher or lower. The actual make-up air flow rate may be different than the nominal rate due to backflow pressures, duct sizing, stack effect pressures within the building, or other factors.

Inputs: Baseboard Capacity

In the un-calibrated buildings, baseboard capacity was initially left to the program to automatically determine the appropriate baseboard heating energy based on the calculated load. However, in all of the un-calibrated simulations, the program significantly over-predicted space heating energy consumption compared to the metered data by as much as 125%. A baseboard capacity had to be applied in order to limit space heating energy consumption. The applied baseboard capacities ranged from a low of 5.1 W/m^2 (1.6 Btu/sf) to a high of 12.0 W/m^2 (3.8 Btu/sf), with an average of 8.5 W/m^2 (3.0 Btu/sf).

Inputs: Domestic Hot Water

Domestic hot water was input into the energy simulation in the form of average daily peak flow rate for the entire building. This value was calibrated for each building simulation to match the metered data. One would expect buildings with a greater number of suites to have a higher flow rate as they are likely use more hot water. As shown in Fig. 7.1.1.1, there may have been a slight correlation of DHW increasing with number of suites. However, much of the data was inconsistent. It is not known why some buildings with a lower number of suites had higher domestic hot water consumption. This could be due to economy of scale; large building DHW systems operate more efficiently since more people are using the equipment.

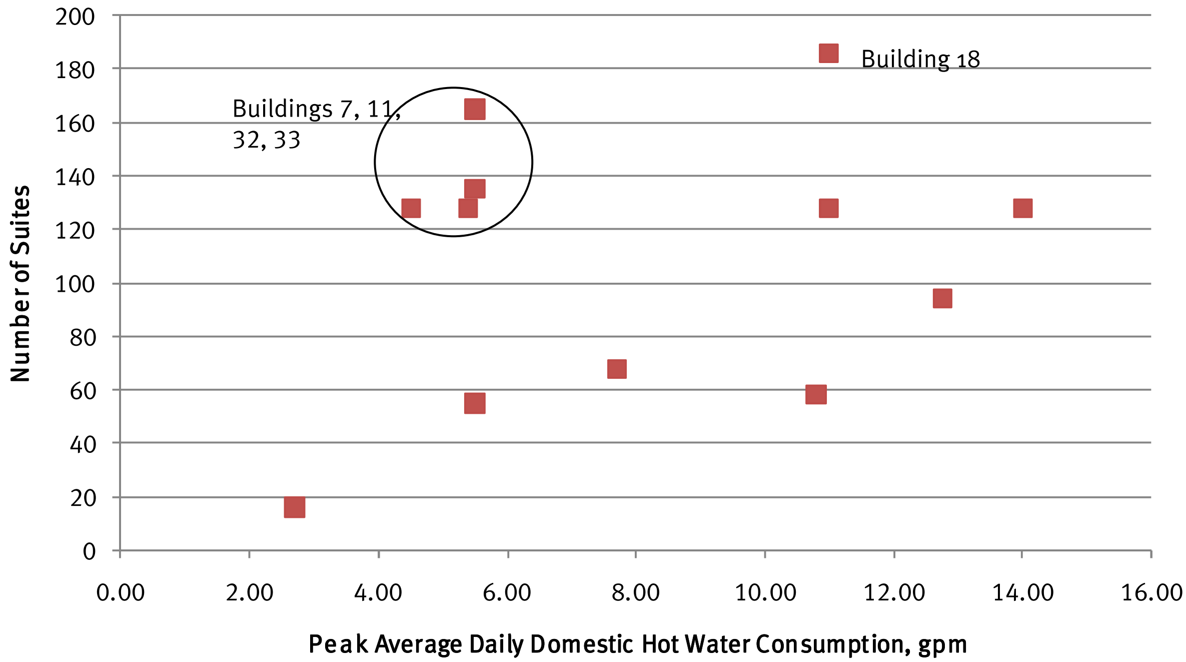


Fig. 7.1.1.1 Domestic hot water daily flow rate versus number of suites.

Inputs: Lighting and Equipment

Lighting and equipment power densities were estimated for each of the buildings. These parameters were estimated from typical values in the un-calibrated simulation and varied in the calibration simulations in order to match the metered data. The initial assumptions of 0.80 W/sf for suite lighting and 0.55 W/sf for plug and miscellaneous loads were good, as few adjustments were required to calibrate the simulations. Plug and miscellaneous loads include electrical energy consumed in the suites from things like appliances, televisions, computers, and so on. For comparison, the ASHRAE 90.1 limit for lighting power density in multi-family buildings is 0.7 W/sf. The plug and miscellaneous load density was raised in three buildings and lowered in four buildings in order to calibrate the simulations. The average plug and miscellaneous load density of the calibrated simulations was 0.52 W/sf. Fig. 7.1.1.2 shows the final calibrated lighting and plug/miscellaneous load densities.

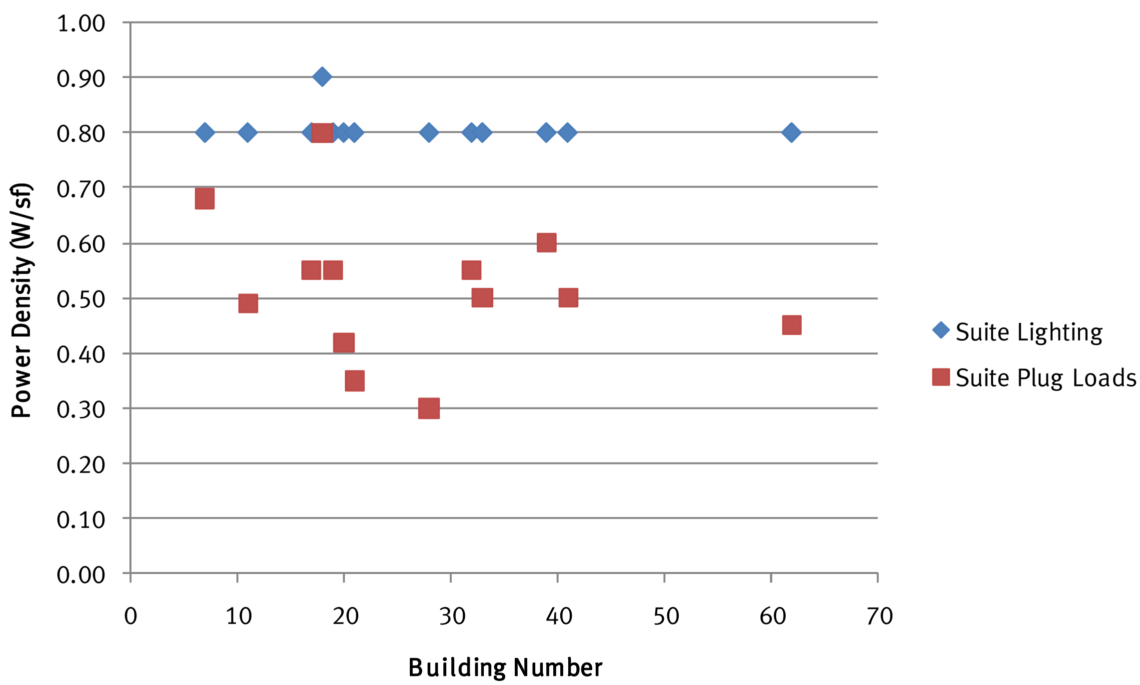


Fig. 7.1.1.2 Calibrated suite lighting and plug load densities.

Inputs: Elevators

Elevator consumption was initially estimated based on an elevator energy consumption study (Sachs 2005). However, during the calibrations it was found that common area electrical consumption varied significantly across the study buildings, and some of the buildings seemed to have unreasonably high common area electrical consumption. An independent elevator consultant was commissioned to provide an estimate of the elevator energy consumption at one of the study buildings, Building 33, that is representative of the age, controls and operation of the majority of the study buildings. During the inspection it was found that the two elevator motors (AC/DC converters) at this building remained constantly in operation and did not time out after a certain time period, as is typical of similar control systems. This resulted in a higher than necessary energy consumption. Fig. 7.1.1.3 shows a photo of the elevator AC to DC converters in Building 62.

Buildings with low common electricity consumption were assumed to have elevators operating with the normal time-out function (and therefore lower energy consumption). Buildings with high common electricity consumption were assumed to have a high elevator energy consumption. The estimates from this analysis formed the basis for the two (high and low) elevator consumption input values used in the simulations, formed with observations of elevator operation during the site visit. The high consumption value estimated by the elevator consultant is 84 kW peak average hourly vertical transport (approximately 122,000 kWh/year) and the low value is 32 kW (approximately 46,000 kWh/year).

Fig. 7.1.1.3 Two 10HP Elevator Motor AC to DC converters.

Inputs: Miscellaneous Common Electrical

After accounting for high elevator energy consumption, the remainder of the common electrical consumption seen in the metered data was simulated in the program using exterior miscellaneous loads (that is, loads that do not contribute to space heat within the building). Even after accounting for high elevator consumption in some buildings there was still a wide range of miscellaneous common electrical consumption, ranging from less than 1 kW to 85 kW, with an average of 36 kW. The reason for this variability may be due to the amount of common space in each of the study buildings. For example, some buildings may have meeting rooms, exercise rooms, sauna or spa rooms, parkade lighting and so on.

Inputs and Calibrations: Impact of Air Leakage Assumptions

The air leakage infiltration rate input was fixed at 0.15 cfm/sf for all building simulations. This rate was not adjusted in the calibration process since insufficient pre- and post-rehabilitation data or literature suggesting appropriate values exists for this variable. Calibrating the air leakage rate did not have a big enough impact on space heating energy consumption to account for the large difference in the metered and un-calibrated modeled heating energy; this required a baseboard capacity. Since adjusting the air leakage rate could not account for the difference in modeled and metered heating energy, and since the infiltration rate was not known for any of the buildings but was based on typical values from previous research (none of the buildings underwent air leakage testing), the value was kept constant for all simulations. Further research is required to better understand air leakage rates and their effect on energy consumption.

For example, the air leakage rate is adjusted as part of the calibration for Building 62. Fig. 7.1.1.4 shows the metered and simulated suite electricity after the baseline electrical consumption is calibrated by adjusting the plug load. Heating is un-calibrated, the standard air leakage rate of 0.15 cfm/sf is used and no baseboard capacity has been applied.

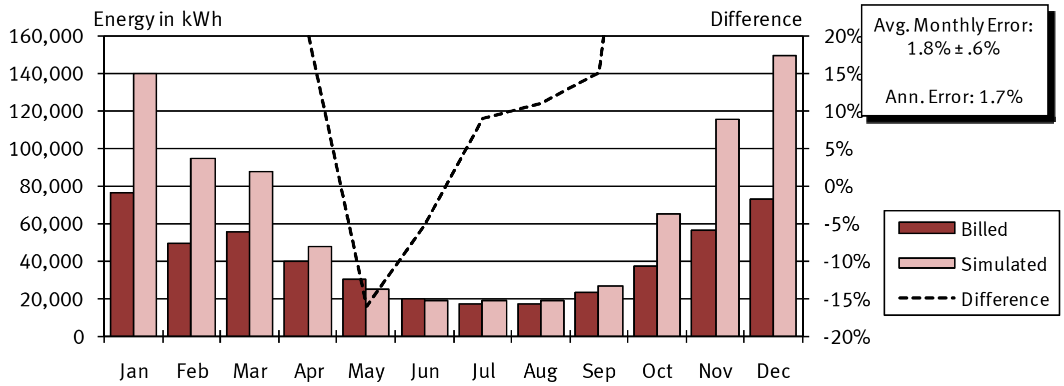


Fig. 7.1.1.4 Suite electricity metered and simulated after calibrating the baseline.

Fig. 7.1.1.5 shows the same plot after the air leakage rate is reduced to 0.05 cfm/sf in an attempt to decrease the suite electrical heating consumption to match the metered consumption. A baseboard capacity has not been applied in this simulation. The plot shows that simulated electrical heating energy is still much greater than metered consumption.

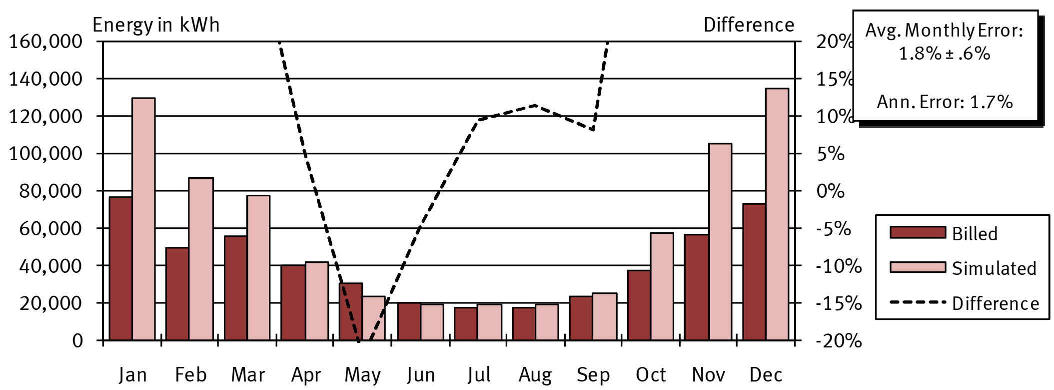


Fig. 7.1.1.5 Suite electricity metered and simulated, air leakage decreased to 0.05 cfm/sf.

In Fig. 7.1.1.6 air leakage is reduced to 0 cfm/sf to attempt to force the simulated electrical heating energy to match the metered consumption. However, even with no air leakage the simulated electrical heating consumption is much greater than metered consumption. This indicates the difference in heating consumption is not just due to air leakage. As a result, a baseboard capacity had to be applied to calibrate the simulation.

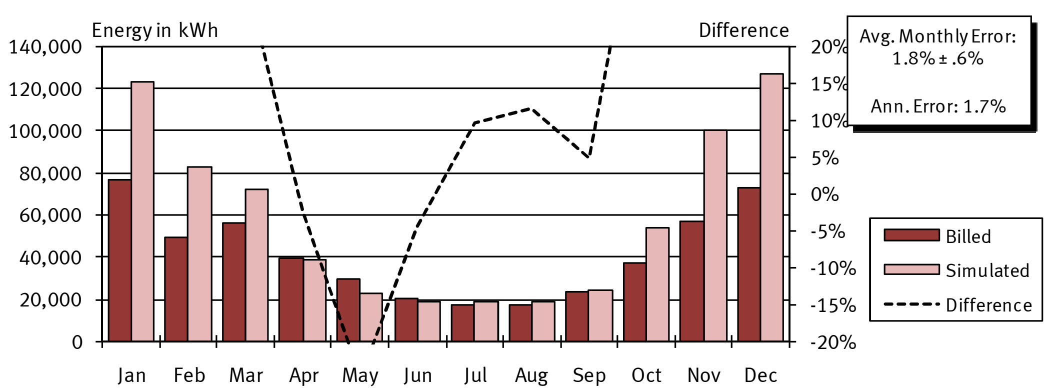


Fig. 7.1.1.6 Suite electricity metered and simulated, zero air leakage.

Calibrations: Suite Electricity

Table 7.1.1 provides a summary of the 13 study buildings for reference. The percent difference between the final calibrated energy simulations and the metered data was generally low. For suite electricity, the average annual difference between the calibrated simulation results and the metered data was 0.03%, with maximum of 3.6% (Building 7) and a minimum of 0.1% (Buildings 11, 32, 33). Suite electric consumption includes space heating for all buildings except 19. Space heating was sometimes difficult to calibrate as it is highly dependent on occupant behaviour, which can vary from month to month.

Table 7.1.1 Summary of buildings simulated.

Building	Number of Storeys	Number of Suites	Suite Space Heating	Ventilation	Domestic Hot Water	Other Notes
Building 7	15	128	Electric baseboards	Gas-heated make-up air	Gas-fired boiler	Located in Victoria
Building 11	16	128	Electric baseboards	Gas-heated make-up air	Gas-fired boiler	
Building 17	12	68	Electric baseboards	Unconditioned make-up air	Electrically heated	
Building 18	22	186	Electric baseboards	Gas-heated make-up air	Gas-fired boiler	
Building 19	10	94	Hydronic Radiators	Gas-heated make-up air	Gas-fired boiler	
Building 20	10	58	Electric baseboards	Gas-heated make-up air	Gas-fired boiler	
Building 21	26	146	Electric baseboards	Gas-heated make-up air	Gas-fired boiler	Gas consumption includes pool area
Building 28	9	16	Electric baseboards	Gas-heated make-up air	Gas-fired boiler	
Building 32	20	135	Electric baseboards	Gas-heated make-up air	Gas-fired boiler	
Building 33	23	165	Electric baseboards	Gas-heated make-up air	Gas-fired boiler	
Building 39	25	128	Electric baseboards	Gas-heated make-up air	Gas-fired boiler	No enclosure rehabilitation
Building 41	25	128	Electric baseboards	Gas-heated make-up air	Gas-fired boiler	No enclosure rehabilitation
Building 62	21	55	Electric baseboards	Gas-heated make-up air	Gas-fired boiler	

Calibrations: Common Electricity

Common electricity generally calibrated well as the simulated miscellaneous electrical load could be increased or decreased in order to match the metered data. The annual average percent difference between the metered and simulated common electricity consumption after calibration was 0.3%, with a maximum of 1.6% (Building 32) and a minimum of 0% (Building 62). In six of the 13 study buildings, the metered common electrical consumption showed a clear increase during winter months and decrease during summer months. This would be caused by baseboard heating in the lobby and common areas, and indicates that enclosure performance and airtightness at the lobby has an impact on energy consumption.

Calibrations: Gas

The annual average percent difference between the metered and simulated gas consumption after calibration was 0.7%, with a maximum of 2.3% (Building 28) and a minimum of 0.2% (Buildings 7, 20, 21). A common difference between the simulated and metered gas consumption after calibration was the distribution of DHW and heating (make-up air for ventilation and fireplaces, use and pilot light) energy. Simulated DHW was often lower than the metered analysis while simulated gas heating was higher than the metered analysis, with the simulated annual total close to the metered total. This occurred because the metered analysis determined the DHW load based on the gas consumption in the summer, since there is little space heating in the summer; however, the simulation predicts a small amount of gas heating in the summer. The metered analysis, therefore, slightly over-predicted DHW and under-predicted heating gas consumption as summer heating could not be accounted for in the metered analysis. This indicates that another possible energy efficiency measure is to turn down the MAU temperature set-point in the summer to prevent summer MAU heating.

Calibrations: Pre- and Post-Rehabilitation Electricity

Fig. 7.1.1.7 shows the metered and simulated total electrical consumption for the pre- and post-rehabilitations, Fig. 7.1.1.8 shows the suite electricity and Fig. 7.1.1.9 shows the common electricity. Buildings 39 and 41 are not shown in these plots since they did not undergo enclosure rehabilitations. Note that Building 17 has a high electrical consumption since its hot water is heated electrically, and Building 19 has a low electrical consumption since gas-fired hydronic radiators provide space heating in this building.

The suite electricity plot shows that six of the simulated buildings showed a greater pre- to post-rehabilitation space heat savings in the metered data than in the energy simulation (Buildings 7, 20, 28, 32, 33, 62). This could be due to an improvement in airtightness with the enclosure rehabilitation. In three buildings (Buildings 11, 18, 21) the simulated space heat savings was greater than the simulated space heat savings. In one building (Building 17) the simulated and metered pre- and post-rehabilitation suite electrical consumption was the same.

There were a number of pre- to post-rehabilitation changes in energy consumption that could not be explained by the energy simulations. Common electrical consumption dropped pre- to post-rehabilitation in the metered data for seven of the study buildings (Buildings 7, 11, 17, 19, 21, 28, 62). Common electrical consumption consists of lights and plug loads in common spaces, fans, and other miscellaneous electrical loads. The reason for the metered decrease is not known, and common electrical consumption did not change pre- to post-rehabilitation in the energy models.

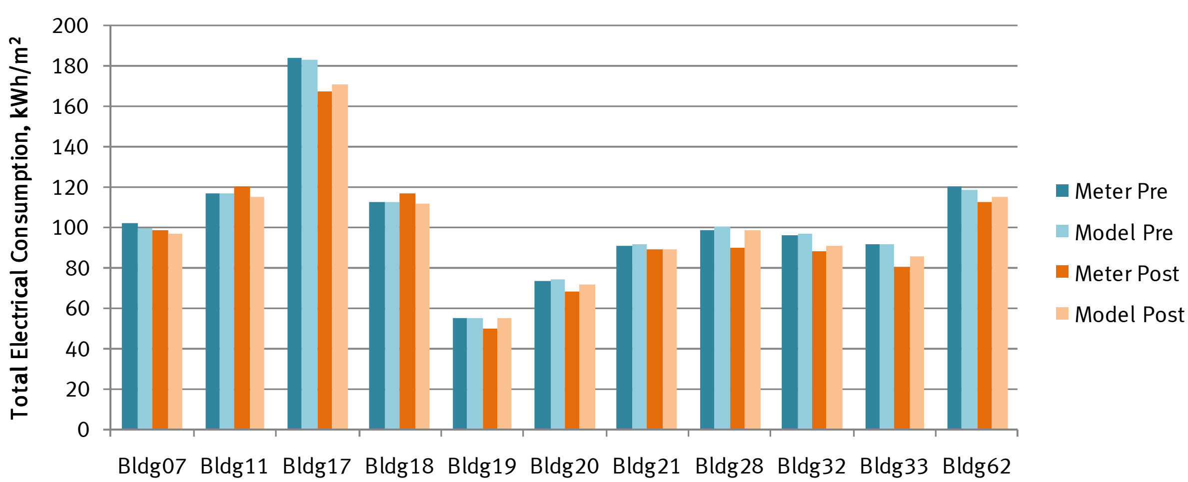


Fig. 7.1.1.7 Metered and simulated total electrical consumption, pre- and post-rehabilitation.

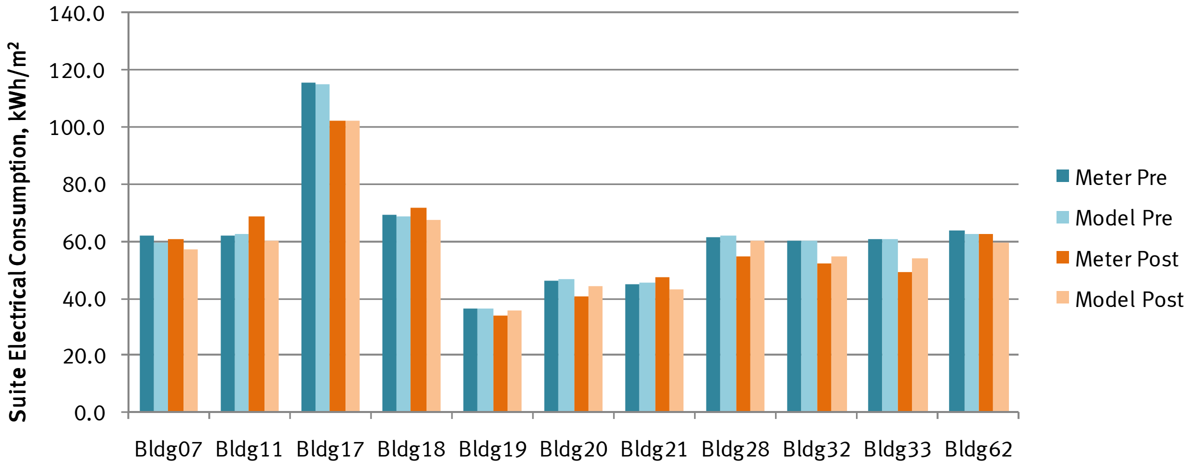


Fig. 7.1.1.8 Metered and simulated suite electrical consumption, pre- and post-rehabilitation.

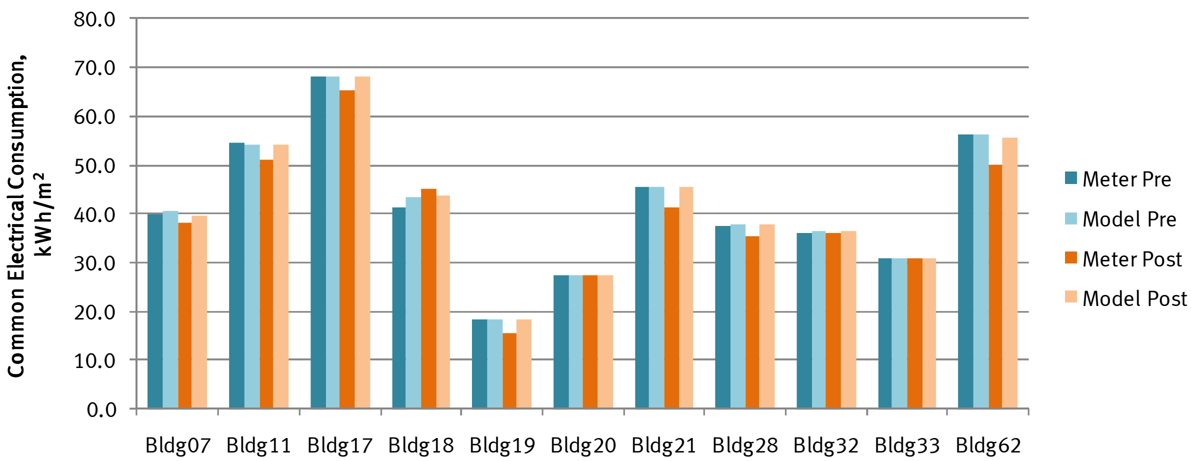


Fig. 7.1.1.9 Metered and simulated common electrical consumption, pre- and post-rehabilitation.

Calibrations: Pre- and Post-Rehabilitation Gas

Fig. 7.1.1.10 shows the metered and simulated total gas consumption, pre- and post-rehabilitation. Fig. 7.1.1.11 and Fig. 7.1.1.12 show the gas DHW and gas heating consumption, respectively. Note that Building 17 has relatively low gas consumption because its DHW is heated electrically and make-up air was unheated, and Building 21 has a high gas consumption because it includes gas consumption for the pool.

DHW gas consumption decreased pre- to post-rehabilitation in the metered data for four of the buildings (Building 7, 11, 21, 62), and increased in one of the buildings (Building 18). Simulated DHW remained the same pre- to post-rehabilitation in all of the buildings. The reason for the metered changes in DHW are not known. It may be due to a change in occupancy or occupant behaviour, or an unreported change to the domestic hot water system.

Gas heating consumption decreased pre- to post-rehabilitation in the metered data for nine of the buildings (Building 7, 11, 17, 19, 20, 28, 32, 33, 62). In Building 19 gas heating consumption decreased as a direct result of the enclosure rehabilitation, since this building has hydronic radiators to provide in-suite space heating. Gas space heat consumption consists of make-up ventilation air heating and, in some buildings, in-suite occupant controlled fireplaces. Buildings 7 and 11 do not have fireplaces, and so the pre-post drop in space heat consumption is entirely in make-up air heating. In Building 17, make-up air is not heated and the only gas consumption is for fireplaces, and so the pre-post drop in gas consumption shows that occupants used their fireplaces less post-rehabilitation (the annual drop in gas space heat consumption was 46%). Buildings 20, 28, 32, 33 and 62 have fireplaces and make-up air heating, so the change may be due to either a change in make-up air (change in flow) and/or a decrease in fireplace use (occupant behaviour). At Building 18, gas space heat consumption increased pre- to post-rehabilitation in the metered data. This building does not have fireplaces, so there must have been a change to the make-up air. The MAU temperature set-point was reportedly not changed post-rehabilitation in any of the buildings.

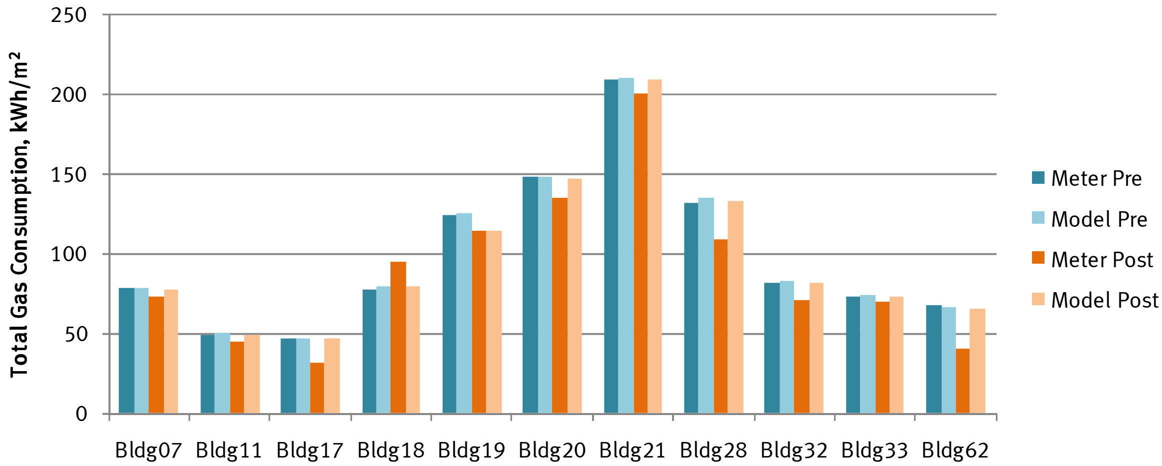


Fig. 7.1.1.10 Metered and simulated total gas consumption, pre- and post-rehabilitation.

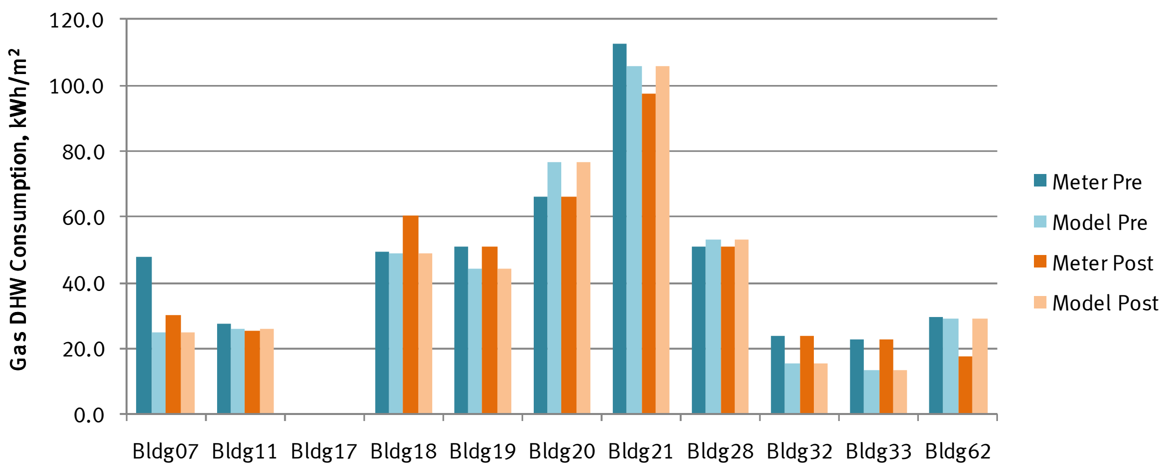


Fig. 7.1.1.11 Metered and simulated gas DHW consumption, pre- and post-rehabilitation.

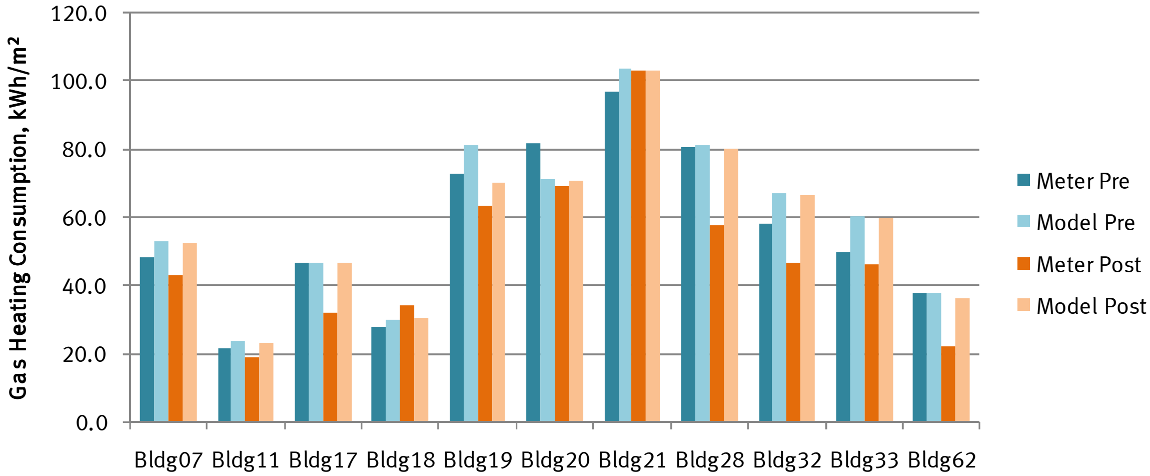


Fig. 7.1.1.12 Metered and simulated gas heating consumption, pre- and post-rehabilitation.

7.1.2 The Impact of Enclosure Upgrades on Energy Consumption

The Impact of Wall Thermal Performance

Simulations were run to determine the energy impact of increasing the effective R-value of the wall to R-10, R-15.6 (to meet ASHRAE 90.1-2007 for steel frame construction) and R-18.2 (to meet ASHRAE 189.1-2009). As expected, the greater the effective R-value, the greater the energy savings compared to the pre- or post-rehabilitation baseline case. The average post-rehabilitation space heat savings from an effective R-10 wall was 4.7%; the average savings from an ASHRAE 90.1 compliant wall (R-15.6) was 7% and the savings from an ASHRAE 189 compliant wall (R-18.2) was 7.6%.

The Impact of Window Thermal Performance

Simulations were run to determine the energy impact of decreasing the window U-value and the solar heat gain coefficient (SHGC). Three window U-values were simulated: windows that meet the *BC Energy Efficiency Act* for metal frames in high-rise buildings, double glazed windows with a low conductivity frame, and triple glazed windows with a low conductivity frame. Each U-value case was simulated with two different SHGC options. As expected, energy consumption decreased as U-value decreased. *BC Energy Efficiency Act* compliant windows reduced space heating by only 2.9% on average in the post-rehabilitation study buildings, as many had windows that performed close to the Act standards. Double glazed, low-conductivity framed windows reduced space heating by 13.9% on average and triple glazed, low conductivity framed windows reduced space heating by 18.8% on average in the post-rehabilitation buildings.

Energy consumption increased as SHGC decreased due to the loss in passive solar space heating (there was no energy reduction since the buildings do not have central mechanical cooling). However, there may be important benefits to occupant comfort by specifying low solar heat gain windows. Furthermore, low solar heat gain may reduce electrical consumption if it prevents occupants from using individual suite air conditioning units. The increase in energy consumption from a lower solar heat gain was small. The average increase in space heating from a SHGC of 0.3 to 0.4 with double glazed, low conductivity frame windows was 2.1%. The average increase in space heating from a SHGC of 0.2 to 0.3 with triple glazed, low conductivity frame windows was 3.5%. The increase in energy consumption due to lowering the solar heat gain is much smaller than the energy savings achieved with lower U-value windows.

The Impact of Airtightness and Air leakage on Energy Consumption

Simulations were completed to determine the impact of the air leakage rate (or the airtightness of the building enclosure) on energy consumption. The baseline simulations assumed an average airtightness of 0.15 cfm/sf at normal operating pressures. A series of air leakage rates were simulated, ranging from very tight to average to very leaky, to determine the energy impact of varying the air leakage rate. As expected, energy consumption increased as the air leakage rate increased. The average impact on space heat consumption in the post-rehabilitation building ranged from an 8.0% savings for a tight building to a 9.0% increase for a leaky building.

The Distribution of Space Heat Loss

Space heat loss occurs by conduction, air leakage and mechanical ventilation. The distribution of space heat loss in the post-rehabilitation study buildings was estimated for a variety of air leakage rates ranging from tight to leaky enclosures. The results showed that mechanical ventilation accounts for a significant portion of space heating energy. For an airtightness of 0.10 cfm/sf (average tightness), the average space heat loss distribution for the study buildings is 36% conduction, 6% air leakage and 58% mechanical ventilation. These buildings include a range of older and newer buildings with low to high mechanical ventilation rates. In the typical building, where mechanical ventilation was set at 50 cfm/suite (somewhere between older buildings with lower ventilation rates and modern buildings with high ventilation rates), mechanical ventilation accounted for between 76% and 85% of space heat energy consumption, depending on the air leakage rate. Conduction was between 11% and 13%, while natural air leakage accounted for between 3% and 13% depending on the enclosure airtightness.

7.1.3 The Impact of Mechanical Improvements on Energy Consumption

Countless mechanical improvements could be investigated for a new or existing building to improve its energy performance. These could include new or different types of systems, more efficient equipment, renewable energy, and others. Most mechanical improvements were beyond the scope of this study; however, a few parameters that affect ventilation air were investigated.

All of the study buildings are mechanically ventilated by a continuous supply of outdoor air to the corridors with intermittent point exhaust within bathrooms and kitchens of the suites. Bathroom and kitchen exhaust fans are not continuously operated and are occupant controlled. The ventilation system is designed so that make-up air flows into the suites through suite door undercuts as the corridor is intended to be positively pressurized with respect to the suites. Make-up air is heated at all buildings except for Building 17, where it is delivered to the corridors unconditioned. The energy impact of varying the make-up air temperature and flow rate were investigated, as well as the potential impact of ventilation heat recovery.

The Impact of Make-Up Air Temperature Set-point

The actual make-up air temperature set-point was known for several of the study buildings. In buildings where the make-up air temperature was unknown it was estimated in the simulation through the calibrations. The average set-point temperature used in the study buildings was 68°F (20°C). Corridor temperature does not need to be maintained at 20°C since occupants spend little time in the corridors; a temperature of 16 to 18°C (60 to 64°F) would significantly reduce energy consumption. Simulations were completed to determine the impact of varying the make-up air temperature set-point.

Using only the buildings with an initial temperature set-point of 68°F in the baseline simulation, raising the temperature to 74°F (23°C) resulted in an average space heating increase of 15.6% in the pre-rehabilitation simulation. Lowering the temperature set-point to 60°F (16°C) resulted in an average total space heating savings of 16.9%. Adjusting make-up air temperature affects both gas consumption for make-up air heating and in-suite space heating consumption since make-up air can offset or increase the suite space heating load. However, the gas savings from lowering the make-up air temperature are much greater than the additional energy consumption on the suite space heating system, and the net effect is a reduction in total energy consumption. Energy consumption may be significantly reduced in MURBs simply by turning down the make-up air temperature.

The Impact of Make-Up Air Flow Rate

The make-up air flow rate was determined from the mechanical equipment for all but three of the study buildings that were simulated. The three undetermined flow rates were estimated through the calibrations. In four of the buildings with known make-up air flow rates, a rate of 90% of the nominal value had to be used in the simulation in order to calibrate the simulation to the metered data. Simulations were run to determine the impact of lowering the make-up air flow rate. As expected, lowering the make-up air flow rate lowered space heating energy consumption. Decreasing the make-up rate to 40% of the nominal value resulted in an average space heat savings of 18.4%. The greater the nominal make-up air flow rate was, the greater the savings from lowering the air flow rate. However, decreasing make-up air flow rate could impact occupant health and comfort.

The Impact of Heat Recovery Ventilation

Most large commercial buildings utilize central exhaust heat recovery systems. The buildings in the study have no capability for central exhaust heat recovery as exhaust air leaves the building through intermittently occupant controlled kitchen and bathroom fans as well as windows and incidental penetrations in the exterior enclosure. There is no return ductwork. Exhaust air heat recovery could be implemented in existing buildings in two ways. First, return ductwork could be installed to remove air from the suites and exhaust it through a rooftop heat recovery unit. Second, in-suite heat recovery ventilators (HRVs) could be installed at each suite to provide individual ventilation to each unit. Either of these options could be applied to new buildings as well.

Central and in-suite HRV systems each have certain benefits and drawbacks. In terms of heat recovery efficiency, central HRV units are large and can achieve heat recovery efficiencies upwards of 90% while in-suite HRV units that are currently commercially available are limited to heat recovery efficiencies in the low 80% range. Similarly, the fans in large central HRV units are typically more efficient than the smaller in-suite systems, though small yet efficient fans are available. The primary benefit of in-suite HRVs is that they provide reliable ventilation. Central systems rely on cracks under the suite doors to transfer ventilation from the corridors to the suites, as well as user-controlled intermittent kitchen and bathroom fans plus incidental enclosure penetrations for exhaust. In-suite HRVs provide good, reliable ventilation but must be carefully designed such that they operate at a high efficiency.

Simulations were performed for the hypothetical situation that at the study buildings the exhaust air could be recovered and run through a central HRV, or in-suite HRVs could be installed. Central HRVs used the same air flow rate as the existing make-up air system in the building, while in-suite HRVs assumed an air flow rate of 50 cfm/suite in accordance with ASHRAE 62.1-2007. The average space heat savings from a 90% efficient central HRV was 36.1%, while the average space heat savings from 80% efficient in-suite HRVs was 33.8%.

These simulations show that significant savings may be achieved through heat recovery ventilation. Heat recovery ventilation had the greatest individual savings out of all of the individual measures that were evaluated in this study.

Central and in-suite heat recovery systems showed similar energy savings. Buildings with low make-up air flow rates had greater savings with central heat recovery since the in-suite system (which was simulated to provide modern, ASHRAE 62 compliant ventilation rates) had a high fan power. However, it is important to note that an in-suite system would provide much better performance in these buildings than the central system with a low ventilation flow rate. Buildings with modern, high make-up air flow rates had greater savings with in-suite heat recovery; in other words, when the same per-suite ventilation rate is provided by central and in-suite heat recovery, in-suite provides better performance and lower energy consumption. New buildings that are designed to modern ventilation standards would realize greater energy savings through in-suite ventilation heat recovery systems.

7.1.4 The Impact of Gas Fireplaces

Fireplace gas consumption within high-rise MURBs is not well understood as the gas is not commonly individually metered to suite owners. Studies on fireplace consumption within single family houses may not apply to suites within MURBs due to occupant behaviour differences between single-family and multi-unit dwelling buildings. For reference Terasen Gas estimates gas fireplace consumption within multifamily residences to be approximately 20 GJ/year (9 GJ for pilot and 11 GJ for main burner).

As part of this study, it was of interest to determine gas fireplace consumption within several of the study buildings. This was estimated by using energy simulations developed for several of the buildings with fireplaces within all or some of the suites. Each simulation was calibrated to the actual bill consumption where the gas fireplace heat was separated from make-up air heat and domestic hot water consumption. Essentially the MAU gas use can be determined with reasonable certainty knowing the flow rate and set-point temperature, and the baseline domestic hot water use can also be calculated based on average DHW use and baseline data. These values were confirmed with buildings without fireplaces and other buildings with fireplaces and found to be generally consistent and relatively easy to determine. Fireplace consumption was found based on the number of fireplaces, and typical equipment efficiencies, and was fit to the remaining data.

Fireplaces are located within some or all of the suites within buildings 32, 33, 62, 17, 20, 39, 41, 28 and 21. The average fireplace consumption per suite (GJ and kWh/year) is provided in Table 7.1.4.1. For comparison, the total suite electricity (lights, appliances, baseboard heat etc.) is shown for reference within that building to provide an indication of the relative quantity of energy being used by the fireplaces.

Table 7.1.4.1 Comparison of Annual Fireplace Consumption in Sample MURBs.

Building	**32**	**33**	**62**	**17**	**20**	**39**	**41**	**21**	**28**	**Average**
Suites in building	135	165	55	68	58	128	128	16	146	-
Suites w/ fireplaces	8	2	10	68	58	128	128	16	146	-
GJ/yr	**22.5**	**18.0**	**20.6**	**15.8**	**14.5**	**15.4**	**13.8**	**24.1**	**13.3**	**17.6**
kWh/yr	6250	5000	5722	4389	4028	4278	3833	6694	3694	**4877**
Cost/yr	$248	$198	$227	$174	$160	$170	$152	$265	$146	**$194**
Total Suite Electricity kWh/yr	4991	6403	8786	10811	5154	6845	5921	8860	5598	**6104**

The average per suite gas consumption for a fireplace within a MURB suite in the study is 17.6 GJ/year (or approximately $200/yr). The range of estimated fireplace consumption is between 13.3 to 24.1 GJ/year. This range appears to be the result of occupant behaviour and whether or not pilot lights are shut-off for periods during the year. From the energy analysis, this is shown to offset some of the electrical space heat, but only a small portion.

Terasen Gas also estimates that gas fireplace pilot light consumption is in the order of 0.75 GJ/month (9.0 GJ/year) depending on pilot light type. Newer electronic ignition starters which remove the standing pilot were not present in any of the buildings in the study.

Building 17 (68 suites) provided a unique opportunity to assess accurately monthly gas fireplace use within a typical MURB where some gas fireplaces are shut-off during the summer. Within this MURB the suite gas fireplaces are the only gas use within the building and therefore the fireplace model within FAST could also be calibrated. Fig. 7.1.4.2 plots the monthly average fireplace gas consumption and Fig. 7.1.4.3provides a summary of the total annual energy end-use breakdown for the building.

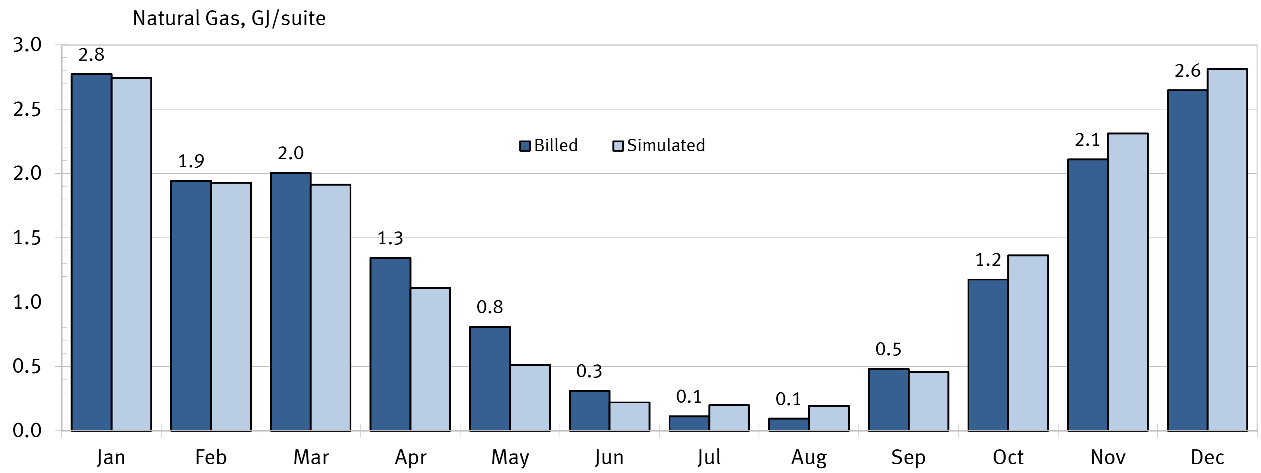


Fig. 7.1.4.2 Monthly Average Suite Fireplace Gas Consumption – Billed Actual and Simulated Estimated GJ/suite.

From the data, it is apparent that some, but not all of the pilot lights are shut-off during the summer months.

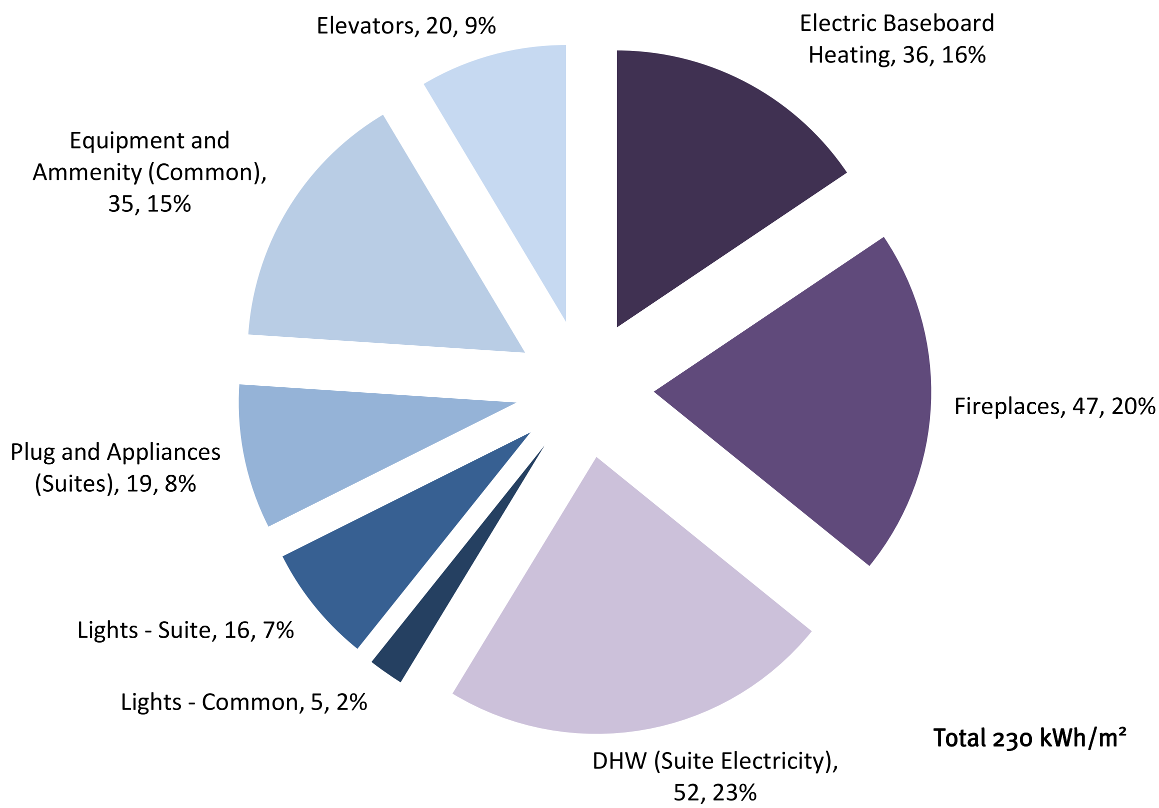


Fig. 7.1.4.3 Resulting Distribution of Energy in Building 17 – kWh/m^2/yr and % of Total Energy Consumption.

7.1.5 The Impact of Combining EEMs

The energy efficiency measures discussed thus far are not additive. That is, one cannot add the energy savings of multiple measures to determine the total energy savings when multiple measures are applied to a building. Two final simulations were performed to determine the energy impact of multiple energy efficiency measures. A “good” and “best” scenario were established and simulated for each of the study buildings. “Good” was defined as R-10 (effective) walls, double glazed windows with low conductivity frames, a low airtightness of 0.05 cfm/sf, and a make-up air set-point temperature of 64°F. “Best” was defined as R-18.2 (effective) walls (ASHRAE 189 compliant), triple glazed windows with low conductivity frames, a very tight enclosure of 0.02 cfm/sf, a make-up air temperature set-point of 60°F and 80% central ventilation heat recovery.

The average space heat savings (gas make-up air, fireplaces and electric baseboards) of the study buildings was 36.0% for the “good” scenario and 70.5% for the “best” scenario. These simulations show that significant energy savings are possible with good enclosure and ventilation design. Fig. 7.1.5.1 shows the average savings of the 11 study buildings with these scenarios.

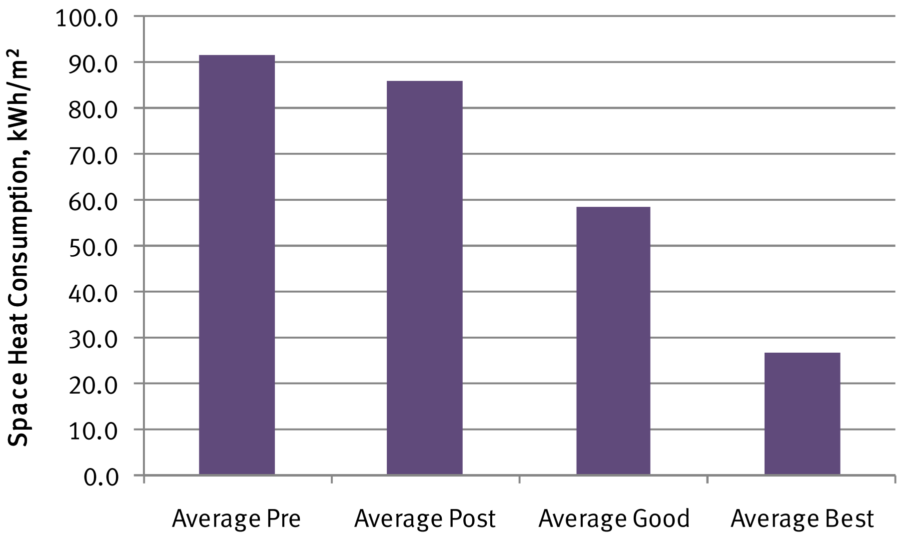


Fig. 7.1.5.1 Average potential space heat consumption of 11 study buildings.

7.2. Typical Building Energy Model

The results of the energy simulations performed for the 13 study buildings can be analyzed in two ways. First, the results obtained for each of the 13 buildings can be averaged. This will show the average energy consumption of the MURBs and the average savings obtained by applying each energy efficiency measure. Second, the input parameters for the 13 study buildings can be averaged to determine a single typical building model, which can then be simulated to determine typical energy savings for the various energy efficiency measures. A typical building model will be presented and analyzed in this section. The average of the results from the thirteen study buildings will be compared to the typical building model results for the energy efficiency measures that were analyzed thus far. Then, the typical building model will be used for further analysis as described in this chapter, and in later chapters of this report.

7.2.1 Typical Building Description and Inputs

The 13 buildings that were simulated as part of this study were used to determine the characteristics of a typical MURB in the Lower Mainland of British Columbia. The typical building was simulated to determine standard performance characteristics for MURBs, such as typical energy savings that would be achieved through the various energy efficiency measures that were examined. The results from the energy simulations of the thirteen buildings were also averaged for comparison to the typical building model.

Architectural Inputs

Table 7.2.1 shows the architectural inputs for the typical building model. These inputs were determined by averaging the input parameters of the 13 buildings that were simulated in the study. The average value for all 39 study buildings is also shown for reference. To obtain the typical gross exposed wall area, the average total exposed wall area of the 13 study buildings was calculated and divided by four to assume a square building. The impact of the building shape will be analyzed later in this section.

Table 7.2.1 Architectural Inputs for Typical Building Model.

	Typical Building Model *Based on 13 Buildings*			*Average of 39 Study Buildings*
Total Floor Area	121,922		ft²	*118,655*
Percent Area for Common Space	13%			
Number of Suites	110			*113*
Number of Storeys (above grade)	18			*18*
Height of Average Storey	8.7		ft	
Orientation from North	0		°	
Gross Exposed Wall Area, Wall 1	15580		ft²	
Gross Exposed Wall Area, Wall 2	15580		ft²	
Gross Exposed Wall Area, Wall 3	15580		ft²	
Gross Exposed Wall Area, Wall 4	15580		ft²	
Window Percentage, Wall 1	46%			*47%*
Window Percentage, Wall 2	46%			*47%*
Window Percentage, Wall 3	46%			*47%*
Window Percentage, Wall 4	46%			*47%*
Infiltration Rate (0.15 cfm/sf)	0.572		ACH	
	Pre	*Post*		
Overall Roof R-value	12.7	13.3	°F-ft²-hr/Btu	
Overall Wall R-value	3.6	5.5	°F-ft²-hr/Btu	
Overall Window U-value	0.70	0.51	Btu/°F-ft²-hr	
Window Solar Heat Gain Coefficient	0.67	0.39		

Mechanical Inputs

Table 7.2.2 shows the mechanical inputs for the typical building model. The mechanical system for the typical building was assumed to be the same as the majority of the 13 study buildings that were simulated.

- Space heat is provided by electric baseboard heaters within the suites.
- Ventilation air is heated at a gas fired rooftop make-up air unit and provided to the central corridors.
- Gas fireplaces are located throughout the building.
- Domestic hot water (DHW) is heated by a gas fired boiler.

Most of the mechanical input parameters were determined by averaging the input parameters for the 13 study buildings. The make-up air flow rate was set at 50 cfm per suite since ASHRAE Standard 62.1 (Ventilation for Acceptable Indoor Air Quality) requires 0.35 ACH for living spaces in MURBs, which equates to approximately 50 cfm for the typical building. The fireplace load was determined by calculating the average per suite load of the study buildings that had fireplaces in all suites, and multiplying this value by the number of suites in the typical building. Note the actual system efficiencies are different than the nominal efficiencies input into the program.

Actual efficiencies are calculated by the program and vary seasonally. The mechanical inputs did not change in the pre- and post-rehabilitation simulations.

Table 7.2.2 Mechanical Inputs for Typical Building Model.

System Type	No Direct Mechanical Ventilation / Central MAU	
Ventilation		
Minimum Outside Air	0.045	cfm/ft² floor area
Minimum Outside Air – total	*5,500*	*cfm*
Minimum Outside Air – per suite	*50.0*	*cfm/suite*
Overall Static Pressure	1.30	in. of water
Make-up Air Supply Temperature	68	°F
MAU / Central Air Handler	Furnace	
Furnace Heating Efficiency	77%	
Furnace Type	Single Stage	
In-Suite Space Heating		
Space Heating Equipment	Resistance	
Maximum Baseboard Capacity	3.0	Btu/ft²
Fireplaces	Included	
Fireplace Diversified Load	8,027	Mbtuh/yr
Fireplace Load – per suite	*73*	*Mbtuh/yr*
Auxiliaries		
Fan Efficiency	50%	
Domestic Hot Water		
Source	Fossil Fuel	
Heater Type	Modulating	
Supply Temperature	140	°F
Equipment Efficiency	77%	
Avg. Daily Peak Flow Rate	8.0	gpm
Electric Contribution to DHW (Heat Trace)	0%	
Space Conditions		
Heating Temperature Set-point (Day)	68	°F
Heating Temperature Setback (Night)	65	°F

Electrical Inputs

Table 7.2.3 shows the electrical inputs for the typical building energy model. All inputs were obtained by taking the average of the inputs for the 13 study buildings that were simulated, with the exception of the elevator load. The elevator load was assumed to be the base load (that is, elevators perform with normal automatic stand-by). The electrical inputs did not change in the pre- and post-rehabilitation simulations.

Table 7.2.3 Electrical Inputs for Typical Building Model.

Common Area Lighting Power Density	0.32	W/ft²
Suite Lighting Power Density	0.81	W/ft²
Plug Load Power Density	0.52	W/ft²
Peak Average Hourly Elevator Load	32	kW
Exterior Lighting & Miscellaneous Loads	36	kW

7.2.2 Energy Consumption of Pre- and Post- Typical Building Model

Energy consumption can be studied for both the typical building model and the average of the 13 study buildings. Beginning with the typical building model, the total energy density of the typical pre-rehabilitation building model is 206.3 kWh/m^2 and the typical post-rehabilitation building model is 199.5 kWh/m^2. The pre- to post-rehabilitation energy savings of the typical building model is 6.8 kWh/m^2 or 3.3%. The pre- to post- space heat savings of the typical building model is 6.7%.

Examining the average of the 13 study buildings, the average total pre-rehabilitation energy density is 213.2 kWh/m^2; however, two of these buildings (Building 39 and 41) did not undergo enclosure rehabilitations. The average pre-rehabilitation energy density of the 11 buildings that had an enclosure rehabilitation is 201.0 kWh/m^2. The average total post-rehabilitation energy is 195.7 kWh/m^2. The average percent savings of the 11 buildings that were rehabilitated is 5.3 kWh/m^2 or 2.6%. The average space heat savings of the 11 study buildings that were rehabilitated is 6.0%.

Distribution of Energy Consumption

The typical building model can be used to determine the distribution of total building energy consumption. Fig. 7.2.2.1 shows the annual pre-rehabilitation building energy consumption by component in kWh/m^2 and percentage of the total. Overall, 49% of energy is used for space and ventilation heating and 16% is used for DHW heating. Thirty-five percent is electricity for lighting, plug loads, appliances and other equipment.

Fig. 7.2.2.2 shows the annual post-rehabilitation building energy consumption by component in kWh/m^2 and percentage of total. Overall, 48% of energy is used for heating, 17% is used for DHW heating and 36% is used for electricity for lighting, plug loads, appliances and other equipment. Heating becomes a slightly lower portion in the post-rehabilitation scenario since the enclosure thermal performance was improved. Fireplaces account for a significant portion of space heating; fireplace consumption is discussed later in this section.

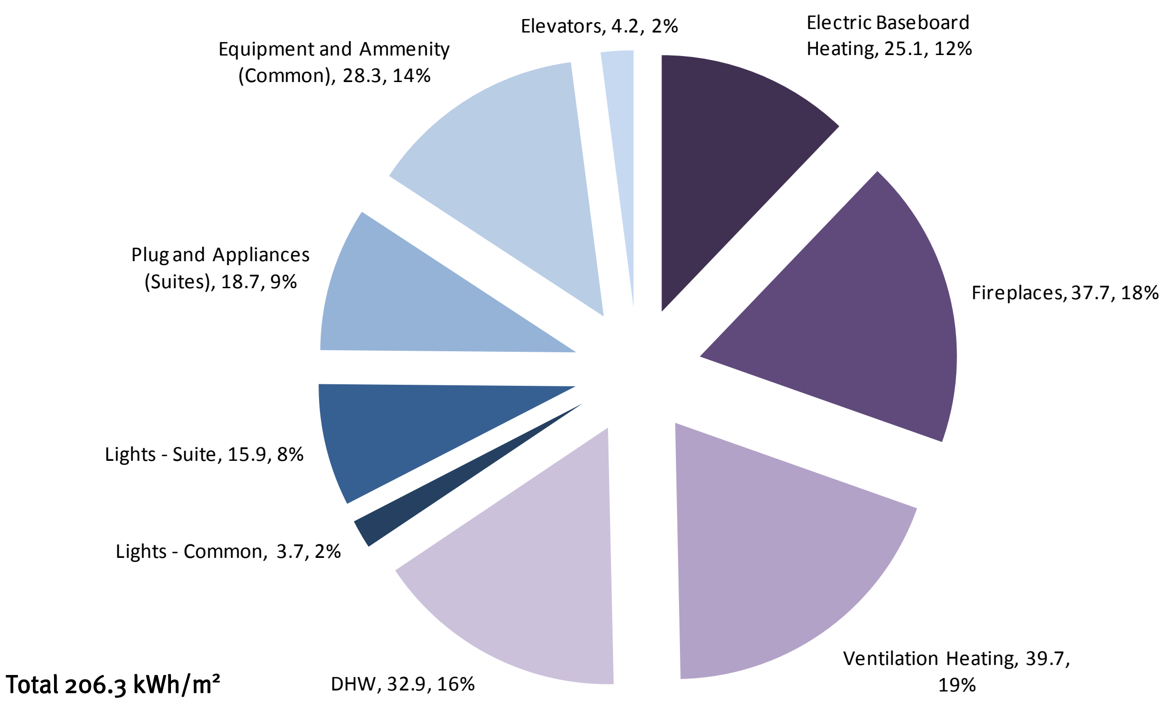


Fig. 7.2.2.1 Distribution of total pre-rehabilitation building energy consumption, kWh/m^2 and percentage of total.

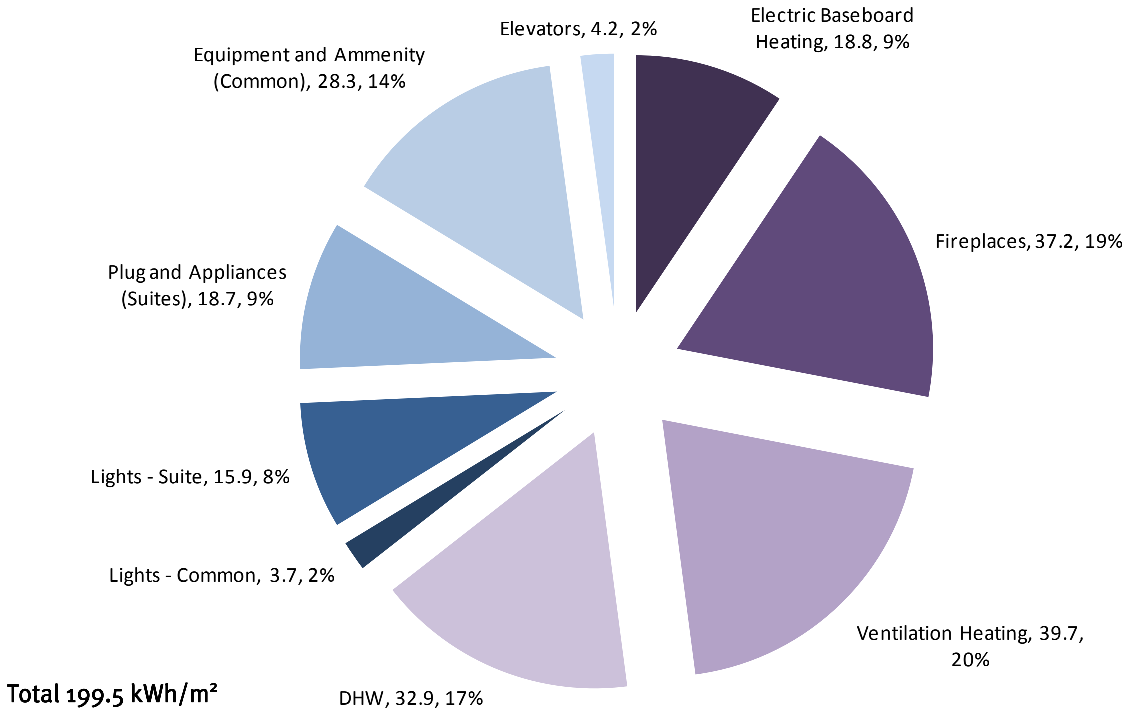


Fig. 7.2.2.2 Distribution of total post-rehabilitation building energy consumption, kWh/m² and percentage of total.

7.2.3 Typical Building Energy Simulations

The energy simulations that were performed for the 13 study buildings were simulated for the typical building in order to determine the standard or typical energy impact of each parameter. The results of the typical building energy simulations are also compared to the average results of the study buildings.

The Impact of Individual Enclosure Upgrades on Energy Consumption

Energy simulations were performed on the pre- and post-rehabilitation typical building model to determine the relative incremental impact of the thermal improvements made to the exterior walls and windows. Additional parametric simulations were also performed to show the potential for better insulated exterior walls and higher performance windows up-to and beyond current practice and building code requirements. Simulations are not shown for the impact of increasing roof insulation as it is relatively small, as shown previously.

Incremental building enclosure thermal improvements are not additive for energy reductions (i.e. one cannot simply add the individual energy savings from a window upgrade to the savings from wall upgrade together), because of depreciating returns on the additional insulating value. Upgrades must be considered in a package. This complicates the assessment returns to doing only a wall or only a window upgrade. The simulations here assume a fixed baseline configuration and present the relative change from that baseline.

The Impact of Wall Thermal Performance

Energy simulations were performed to assess the impact of modifying only the wall R-value on space heat energy consumption. Table 7.2.4 shows the R-values that were simulated by changing only the R-value in the calibrated pre- and post-rehabilitation simulations. The difference between the pre- and post- simulations is that the post scenarios include the upgraded roof R-value, window U-value and window SHGC.

Table 7.2.4 Summary of scenarios simulated for wall thermal performance.

	Pre R-Value [hr-ft^2-F/Btu]	Post R-Value [hr-ft^2-F/Btu]
Baseline	3.6	5.5
Excluding Balconies	4.0	6.6
Effective R10	10.0	10.0
ASHRAE Standard 90.1	15.6	15.6
ASHRAE Standard 189.1	18.2	18.2

Table 7.2.5 and Fig. 7.2.3.2 show the annual space heating energy consumption of each scenario that was simulated. Fig. 7.2.3.3 and Fig. 7.2.3.4 show the division of gas and electrical space heat consumption for the wall scenarios simulated. The baseline pre- and post- space heat consumption is 102.4 kWh/m^2 and 95.6 kWh/m^2, respectively. The rehabilitation enclosure upgrade alone reduced space heat energy consumption by 6.8 kWh/m^2. The scenario results show that an enclosure that meets the ASHRAE Standard 189.1 prescriptive requirement of R-18.2 effective walls would reduce space heat energy consumption by 6.9% in the post-rehabilitation building. The typical building simulation and the average savings of the study buildings shows that improving only wall thermal performance can result in up to about 8% reduction in space heat energy consumption.

Table 7.2.5 Impact of wall thermal performance on annual space heat consumption.

Wall	R-Value	Annual Space Heat Consumption		Typical Building Space Heat Savings from Baseline	Average Space Heat Savings of 11 Study Buildings
		kWh	kWh/m²/yr		
Pre-Rehabilitation					
Baseline	3.6	1,160,724	102.4	-	-
No Balconies	4.0	1,150,514	101.5	0.9%	0.8%
Effective R10	10.0	1,084,718	95.7	6.5%	5.4%
ASHRAE 90.1	15.6	1,062,344	93.8	8.5%	7.0%
ASHRAE 189.1	18.2	1,057,491	93.3	8.9%	7.4%
Post-Rehabilitation					
Baseline	5.5	1,083,323	95.6	-	-
No Balconies	6.6	1,066,778	94.1	1.5%	1.6%
Effective R10	10.0	1,036,562	91.5	4.3%	4.7%
ASHRAE 90.1	15.6	1,014,528	89.5	6.4%	7.0%
ASHRAE 189.1	18.2	1,008,708	89.0	6.9%	7.6%

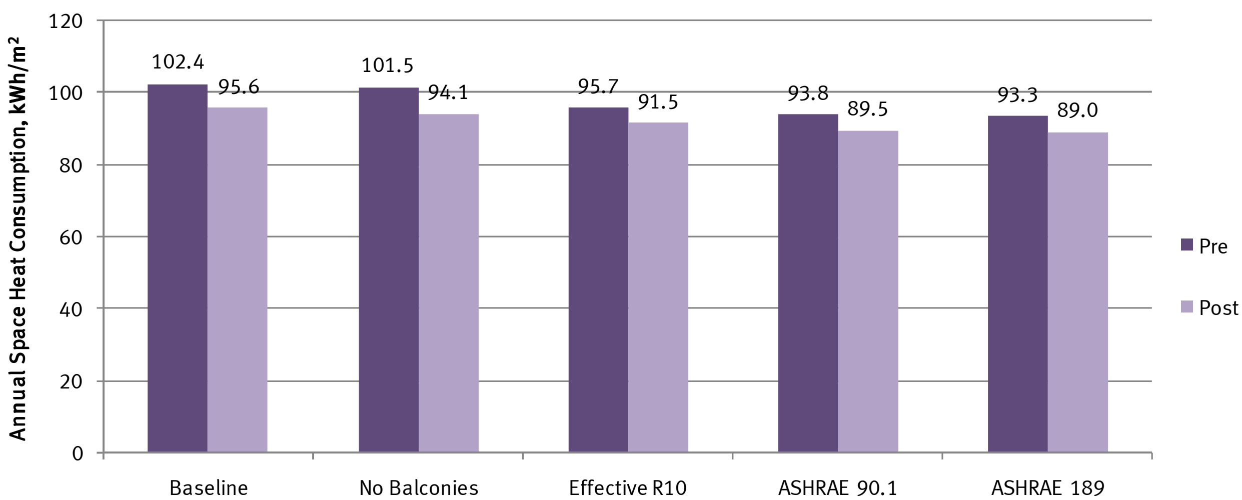


Fig. 7.2.3.2 Impact of wall thermal performance on annual space heat consumption (ventilation, fireplaces and electric baseboards).

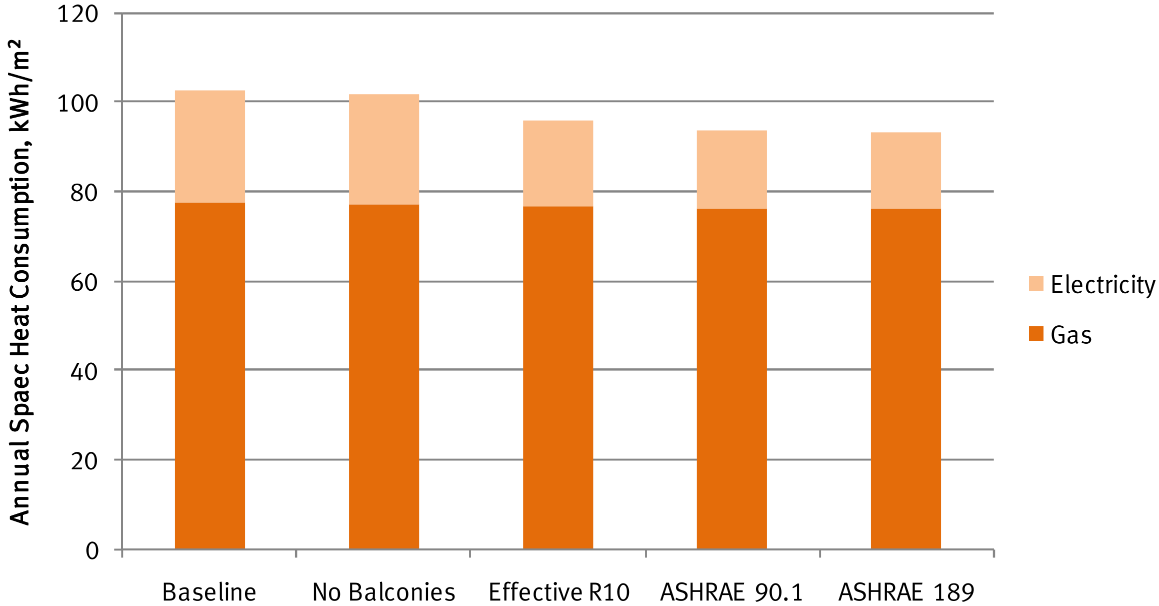


Fig. 7.2.3.3 Impact of wall thermal performance on pre-rehabilitation gas and electrical space heat.

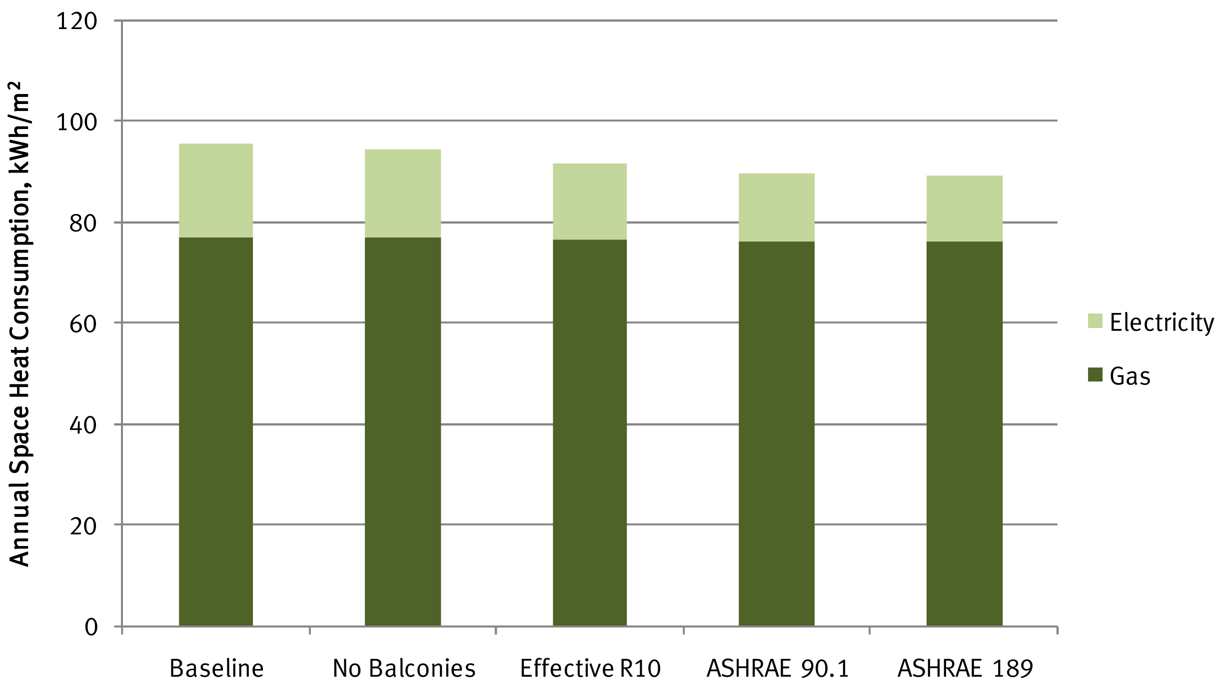


Fig. 7.2.3.4 Impact of wall thermal performance on post-rehabilitation gas and electrical space heat.

The Impact of Window Thermal Performance

Energy simulations were performed to assess the impact of modifying the window (and door) U-value and solar heat gain coefficient (SHGC) on space heat energy consumption. Table 7.2.6 shows the scenarios that were simulated by changing only the U-value and SHGC in the calibrated pre- and post-rehabilitation simulations. The difference between the pre- and post- simulations is that the post scenarios also include the improved wall and roof R-values. The U-values were chosen based on typical values for double and triple glazed windows with argon gas fill and thermally improved frames, such as vinyl or fibreglass frames. Windows that meet the *BC Energy Efficiency Act w*ere simulated, which requires a U-value of 0.45 hr-ft^2-F/Btu for metal frames.

Table 7.2.6 Summary of scenarios simulated for window thermal performance.

	U-Value [Btu/hr-ft^2-F]	SHGC
Baseline Pre	0.70	0.67
Baseline Post	0.51	0.39
Baseline Post with Pre SHGC	0.51	0.67
BC Energy Efficiency Act (metal frames)	0.45	0.40
BC Energy Efficiency Act (metal frames)	0.45	0.30
Double Glazed with Vinyl or Fibreglass Frame	0.27	0.40
Double Glazed with Vinyl or Fibreglass Frame	0.27	0.30
Triple Glazed with Vinyl or Fibreglass Frame	0.17	0.30
Triple Glazed with Vinyl or Fibreglass Frame	0.17	0.20

Table 7.2.7 and Fig. 7.2.3.5 show the annual space heating energy consumption of each scenario that was simulated. Fig. 7.2.3.6 and Fig. 7.2.3.7 show the division of gas and electrical space heat consumption for the window scenarios simulated. The baseline pre- and post- space heat consumption is 83.2 kWh/m^2 and 78.0 kWh/m^2, respectively. The simulation results show that windows that meet the *BC Energy Efficiency Act* standard for metal frames would reduce the post-rehabilitation space heating energy consumption by 3% (2.9 kWh/m^2/year) compared to the windows used for the rehabilitation work (which provide similar performance characteristics). Moving to double glazed with a non-metal frame would reduce post-rehabilitation space heating by 13% (12.2 kWh/m^2/year). Triple glazed windows with a non-metal frame would reduce post-rehabilitation space heating by 17% (16.2 kWh/m^2/year). The typical building simulation and the average savings of the study buildings shows that improving the window thermal performance can result in up to approximately 20% reduction in space heat energy consumption.

Table 7.2.7 Impact of window U-value and SHGC on annual space heat consumption.

Window	**Annual Space Heat Consumption**		**Typical Building Space Heat Savings from Baseline**	**Average Space Heat Savings of 11 Study Buildings**
	kWh	**kWh/m^2/yr**		
Pre-Rehabilitation				
Baseline	1,160,724	102.4	-	-
U = 0.45, SHGC = 0.4	1,101,819	97.2	5.1%	3.4%
U = 0.45, SHGC = 0.3	1,119,735	98.8	3.5%	1.6%
U = 0.27, SHGC = 0.4	1,003,798	88.6	13.5%	12.5%
U = 0.27, SHGC = 0.3	1,020,123	90.0	12.1%	10.7%
U = 0.17, SHGC = 0.3	959,642	84.7	17.3%	16.6%
U = 0.17, SHGC = 0.2	988,092	87.2	14.9%	13.4%
Post-Rehabilitation				
Baseline	1,083,323	95.6	-	-
U = 0.45, SHGC = 0.4	1,050,934	92.7	3.0%	2.9%
U = 0.45, SHGC = 0.3	1,069,536	94.4	1.3%	0.7%
U = 0.27, SHGC = 0.4	945,525	83.4	12.7%	13.9%
U = 0.27, SHGC = 0.3	960,889	84.8	11.3%	11.8%
U = 0.17, SHGC = 0.3	899,292	79.4	17.0%	18.8%
U = 0.17, SHGC = 0.2	922,848	81.4	14.8%	15.3%
Post U-Value with Pre SHGC	1,035,896	91.4	4.4%	5.1%

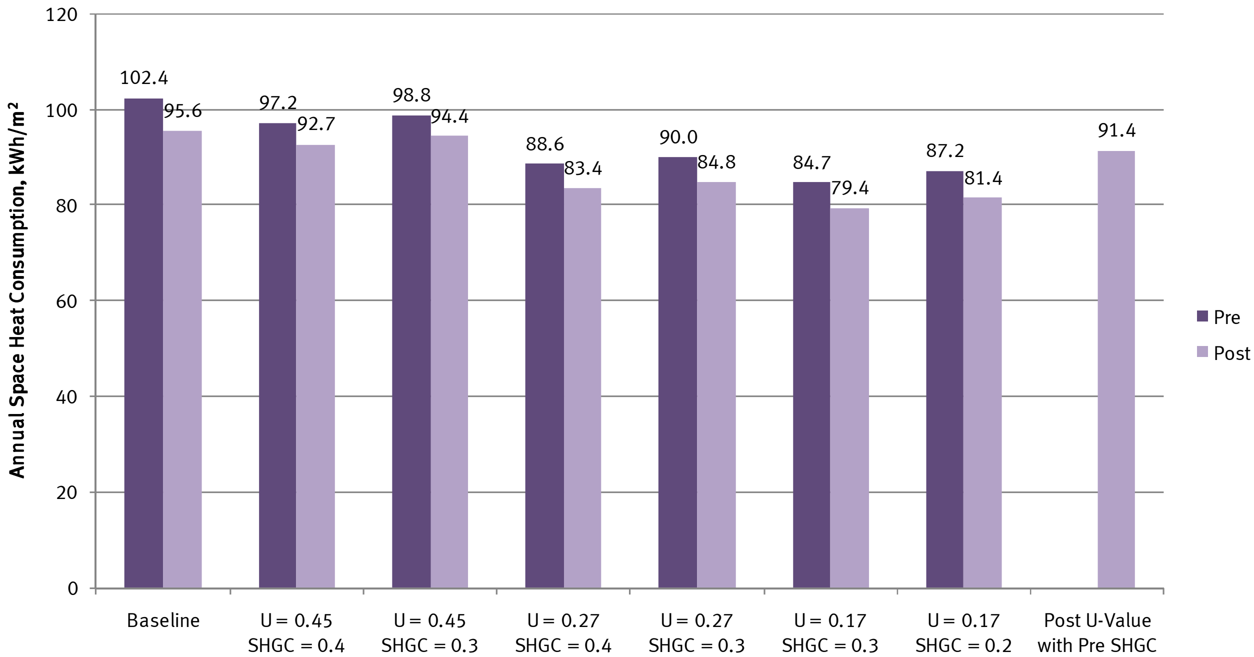


Fig. 7.2.3.5 Impact of window U-value and SHGC on annual space heat consumption.

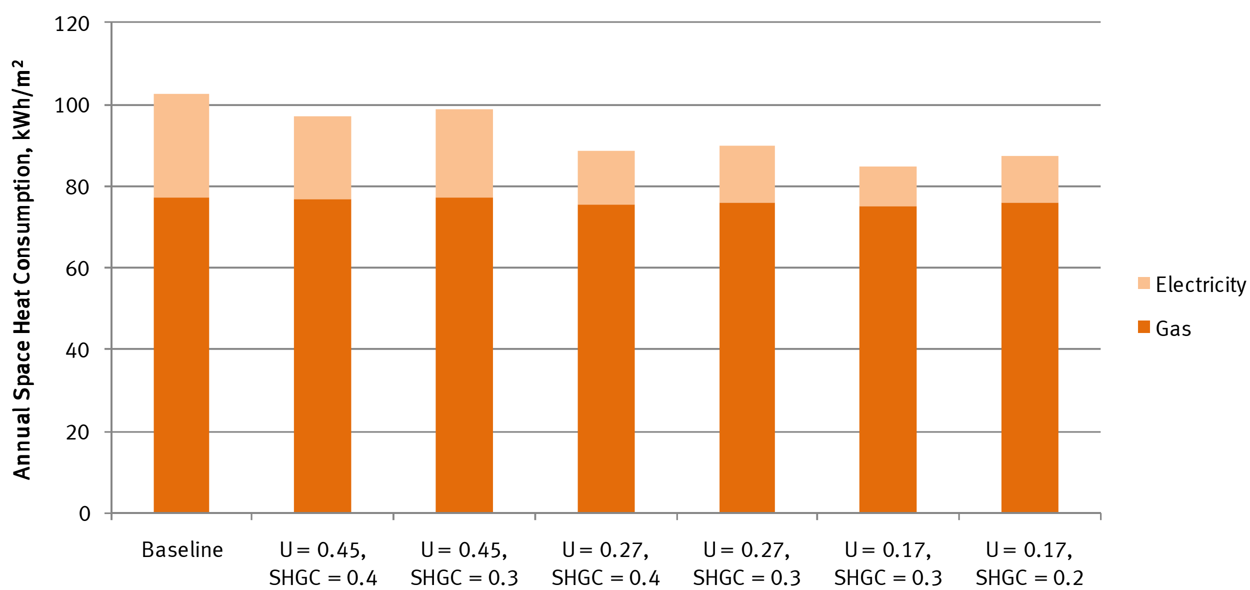


Fig. 7.2.3.6 Impact of window thermal performance on pre-rehabilitation gas and electrical space heat consumption.

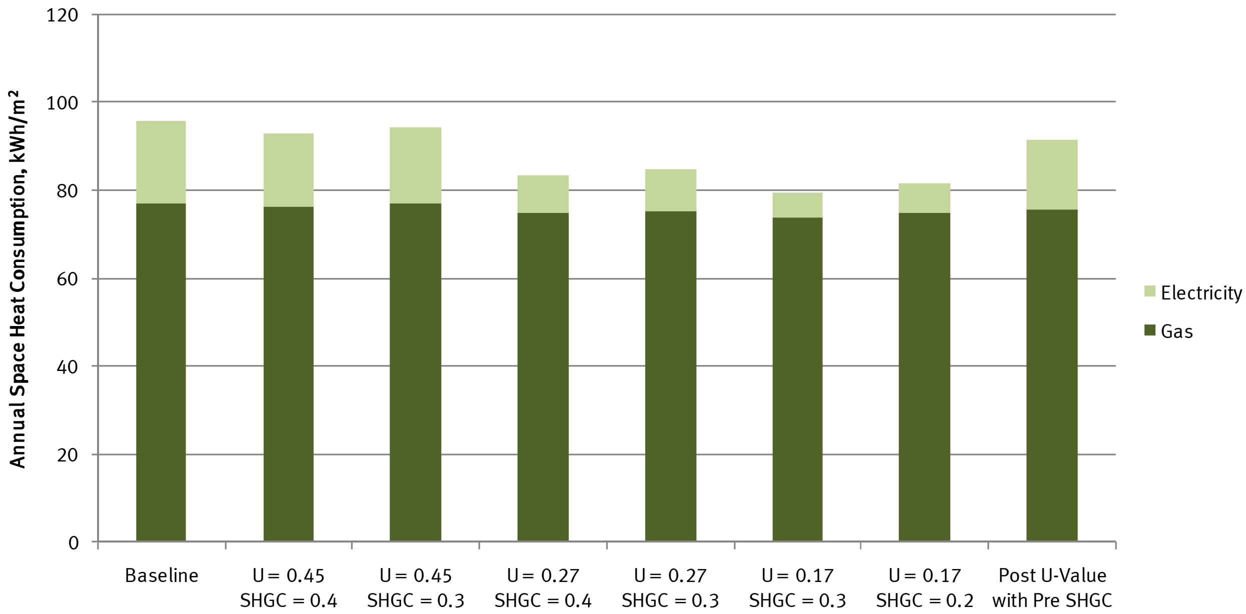


Fig. 7.2.3.7 Impact of window thermal performance on post-rehabilitation gas and electrical space heat consumption.

While reducing the U-value reduces annual space heating energy consumption, lowering the SHGC increases space heating and total building energy consumption since solar heat gain may offset some or all of the required space heat. The buildings in this study do not have mechanical cooling; if they did, lowering the SHGC would decrease cooling energy. Some suites may have plug-in air conditioners, in which case lowering the SHGC would reduce suite electrical consumption; however, this effect is not captured by the simulation and it is unknown how many (if any) suites have air conditioners. Regardless of annual energy consumption, a low SHGC may be important for occupant comfort in preventing overheating of the suites. A high SHGC should not be selected just because the simulation shows that it results in lower energy consumption.

The effect of varying only the SHGC is seen in the simulation of the baseline post-rehabilitation scenario with the pre-rehabilitation SHGC. The baseline post space heating energy consumption is 95.6 kWh/m^2/year, and the post U-Value with pre SHGC is 91.4 kWh/m^2/year. Increasing the post SHGC from 0.39 to 0.67 reduced annual space heating energy consumption by 4.2 kWh/m^2/year, or 4%. However, low-solar heat gain is typically preferred in the Lower Mainland to reduce overheating and offset the need for air-conditioning in MURBs. Changing the SHGC from 0.4 to 0.3 in the scenario with double glazed windows with a thermally improved frame (U = 0.27), post-rehabilitation space heating energy is increased from 88.6 kWh/m^2/year to 90.0 kWh/m^2/year, a difference of 1.4 kWh/m^2/year or 2%. Changing the SHGC from 0.3 to 0.2 in the scenario with triple glazed windows and a thermally improved frame (U = 0.17), post-rehabilitation space heating energy increases from 84.7 kWh/m^2/year to 87.2 kWh/m^2/year, a difference of 2.5 kWh/m^2/year or 3%. The effect of reducing the window U-value has a much greater impact on energy consumption than the SHGC.

Solar heat gain may be optimized through the use of exterior shading. Exterior shading strategies allow solar heat gain during heating seasons and block solar heat gain during cooling seasons. Exterior shading was not analyzed in this study.

The Impact of Airtightness and Air leakage on Energy Consumption

Table 7.2.8 presents the average air leakage rates (in cfm and ACH) for the typical building based for a range of typical airtightness characteristics.

Table 7.2.8 Airtightness Measurements and Potential Air leakage Rates for Typical Building.

Enclosure Airtightness	Representative of	Resulting Air leakage Rate for the Volume/Wall Ratio for Typical Building	
		cfm	ACH
0.02 cfm/ft² @ 5 Pa	Very Tight	1,246	0.076
0.05 cfm/ft² @ 5 Pa	Tight – Low Average	3,116	0.191
0.10 cfm/ft² @ 5 Pa	Tight – Average	6,232	0.381
0.15 cfm/ft² @ 5 Pa	Tight – High Average	9,348	0.572
0.20 cfm/ft² @ 5 Pa	Leaky	12,464	0.763
0.40 cfm/ft² @ 5 Pa	Very Leaky (4x the average) with some windows open	24,928	1.525

**Airtightness rates can be converted to 10 Pa equivalents by multiplying by 1.57. Correspondingly the cfm and ACH would increase by a factor of 1.57.*

Using the developed range of air-exchange rates for the typical building, energy simulations were performed to determine the potential impact of air leakage on space heat energy consumption. Energy simulations were performed for the pre- and post-rehabilitation building models and are presented in Table 7.2.9, Table 7.2.10 and Fig. 7.2.3.8. Fig. 7.2.3.9 and Fig. 7.2.3.10 show the impact of airtightness on pre- and post-rehabilitation gas and electrical space heat consumption, respectively.

Table 7.2.9 Pre-Rehabilitation Building Enclosure Energy Simulations of the Impact of Air leakage on Space Heating.

Enclosure Airtightness (cfm/ft²)	Annual Space Heat Consumption		Heat Required for Air-Leakage		Typical Building Percent Difference from Baseline (0.15 cfm/ft²)	Average Space Heat Savings of 11 Study Buildings
	kWh	kWh/m²/yr	kWh/m²/yr	% of Total Heat		
0*	1,095,715	96.7	-	-	5.6%	6.1%
0.02	1,105,879	97.6	0.9	0.9%	4.7%	5.2%
0.05	1,120,409	98.9	2.2	2.2%	3.5%	3.8%
0.1	1,140,404	100.6	3.9	3.9%	1.8%	1.7%
0.15**	1,160,724	102.4	5.7	5.6%	0.0%	-
0.2	1,175,547	103.7	7.0	6.8%	-1.3%	-1.3%
0.4	1,228,761	108.4	11.7	10.8%	-5.9%	-6.0%

* No air leakage case includes make-up air flow ** Simulated baseline

Table 7.2.10 Post-Rehabilitation Building Enclosure Energy Simulations of the Impact of Air leakage on Space Heating.

Enclosure Airtightness (cfm/ft²)	Annual Space Heat Consumption		Heat Required for Air- Leakage		Typical Building Percent Difference from Baseline (0.15 cfm/ft²)	Average Space Heat Savings of 9 Study Buildings
	kWh	kWh/m²/yr	kWh/m²/yr	% of Total Heat		
0*	992,953	87.6	-	-	8.3%	9.5%
0.02	1,006,342	88.8	1.2	1.3%	7.1%	8.0%
0.05	1,025,858	90.5	2.9	3.2%	5.3%	6.0%
0.1	1,054,124	93.0	5.4	5.8%	2.7%	2.8%
0.15**	1,083,323	95.6	8.0	8.3%	0.0%	-
0.2	1,106,786	97.7	10.0	10.3%	-2.2%	-2.1%
0.4	1,177,557	103.9	16.3	15.7%	-8.7%	-9.0%

* No air leakage case includes make-up air flow ** Simulated baseline

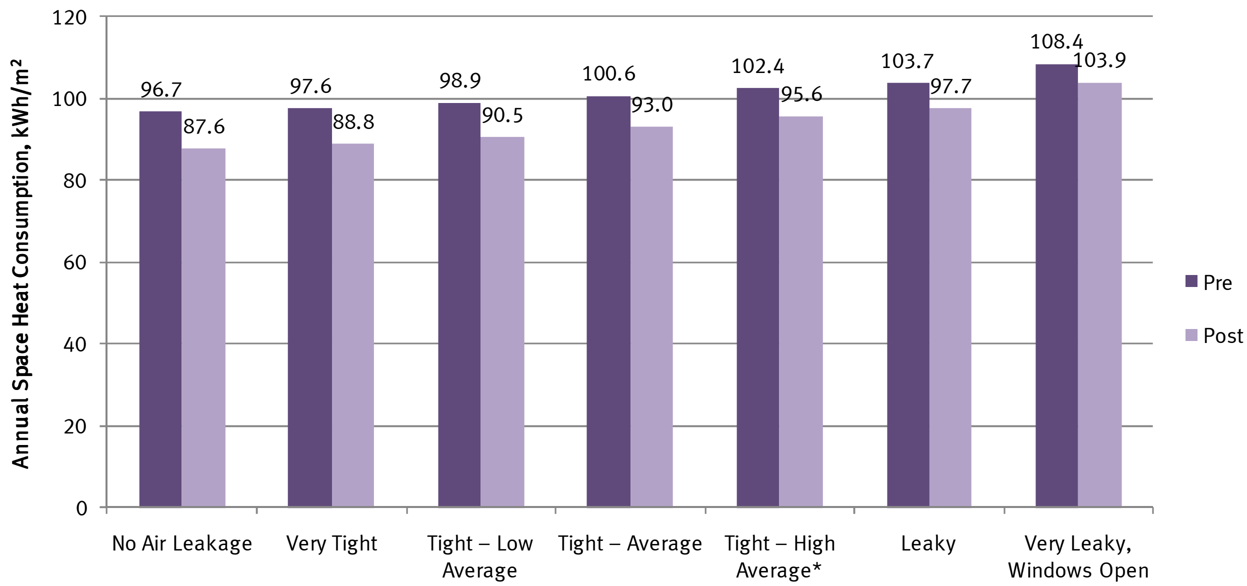


Fig. 7.2.3.8 Impact of airtightness on annual space heat consumption.

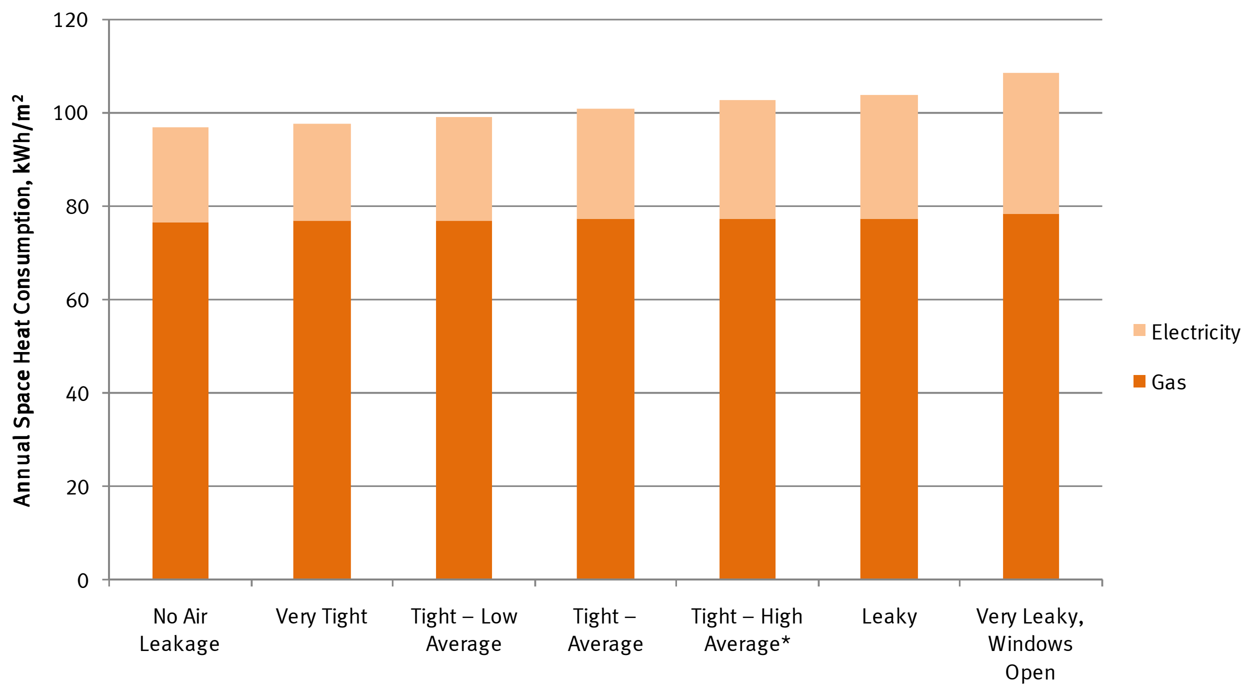


Fig. 7.2.3.9 Impact of airtightness on pre-rehabilitation annual gas and electrical space heat consumption.

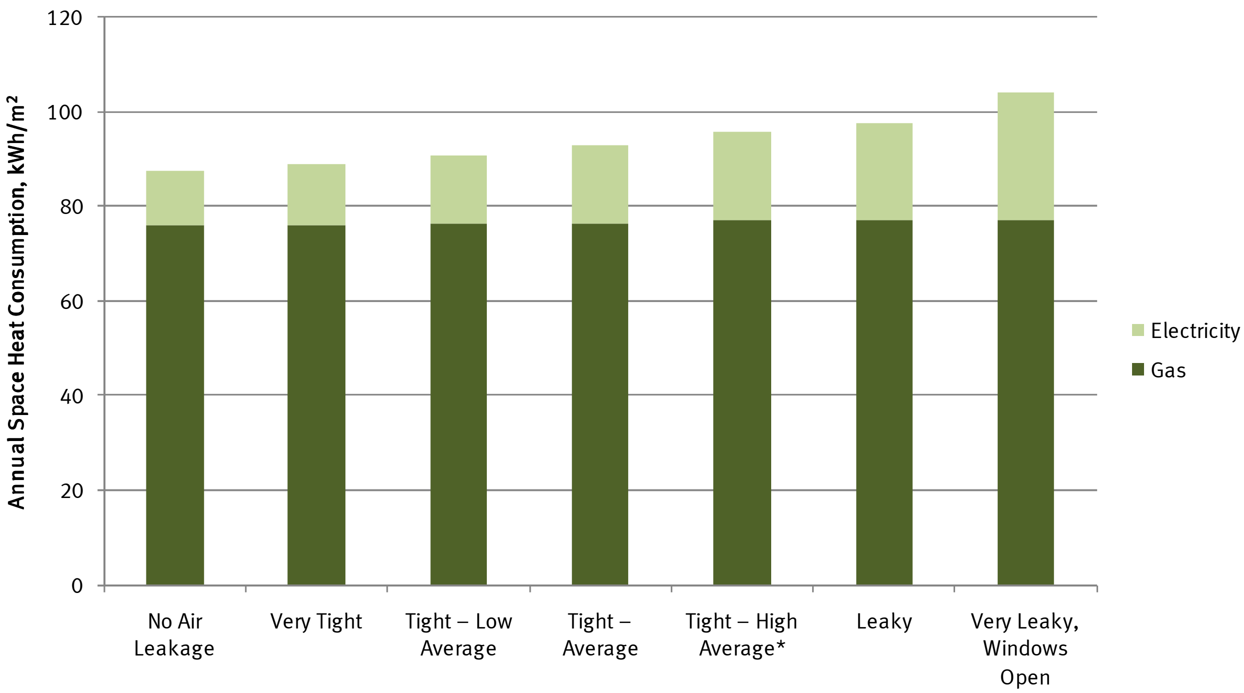


Fig. 7.2.3.10 Impact of airtightness on post-rehabilitation annual gas and electrical space heat consumption.

The energy simulations demonstrate the relative contribution of natural air leakage to space heat consumption for the typical building. In either the pre- or post-rehabilitation case, natural air leakage likely accounts for between 1% and 16% of the space heating load, depending on occupant behaviour and window operation. This shows the relative importance in keeping windows closed during heating periods and possible savings from doing so.

Distribution of Space Heat Loss

The post-rehabilitation space heat load distribution estimated by the energy simulation is shown in Fig. 7.2.3.11 for low, average and high air leakage rates. This analysis will improve the understanding of the relative contributions of the thermal resistance of the building enclosure (conduction) and air leakage (convection, both forced and natural) on space heat loss.

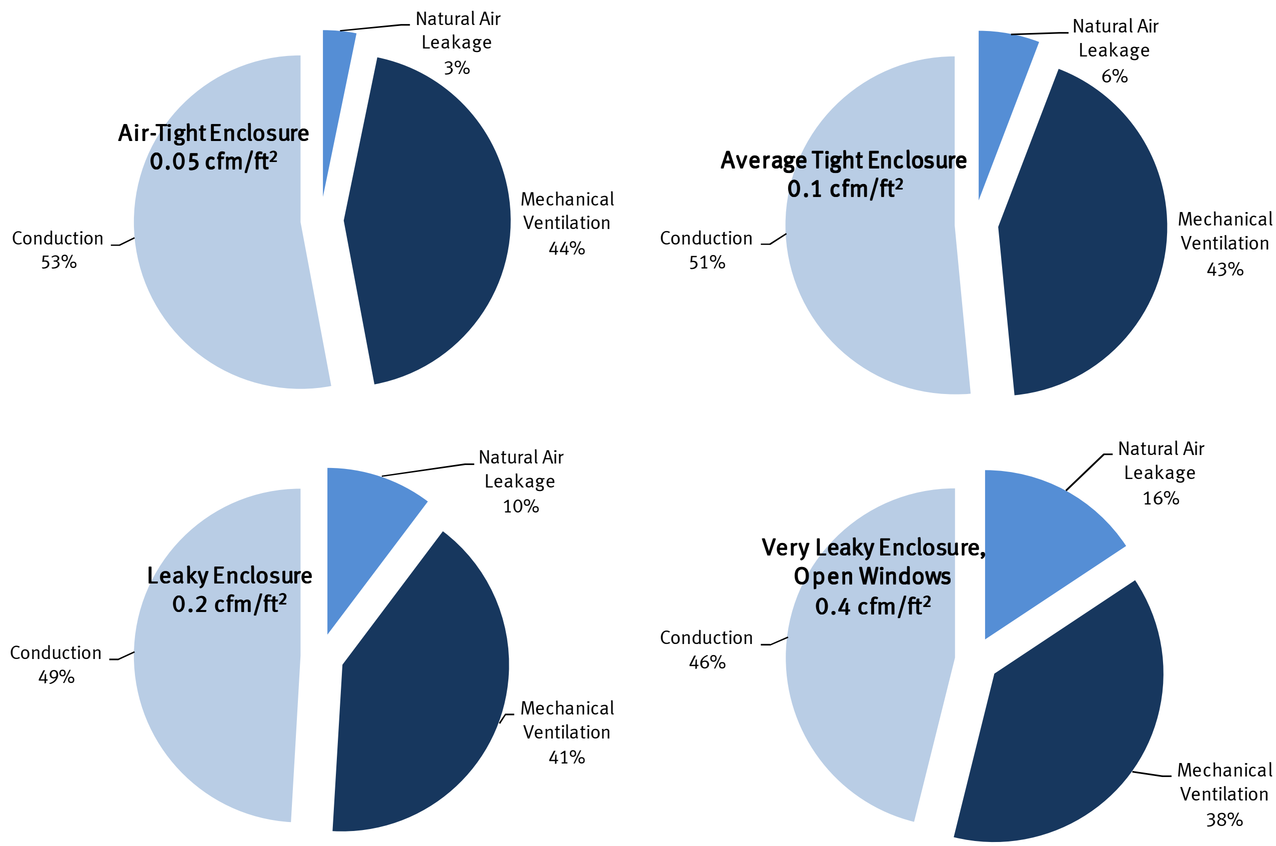


Fig. 7.2.3.11 Post-Rehabilitation Estimated Space Heat Loss Distribution for a Range of Potential Airtightness Levels.

Based on these results, it is shown that natural wind/stack pressure induced air leakage causes between 3% and 16% of the space heat loss depending on the airtightness of the building enclosure and the amount of windows open.

Energy Impacts from Mechanical Improvements and Adjustments

Mechanical upgrades and equipment adjustments have the potential to reduce input energy consumption of a building. Using the pre-rehabilitation calibrated energy model, mechanical system adjustments related to space heat were made to determine possible energy saving measures for MURBs. Other mechanical savings may be possible through lighting and plug load reductions, elevators, fan and pump upgrades, mechanical equipment upgrades and so on, however these are beyond the scope of this report.

The Impact of Make-Up Air Temperature Set-point Temperature

The make-up air supply set-point temperature has a significant impact on gas consumption. The typical building model used a make-up air temperature set-point of 20°C (68°F) as this is what the majority of the study buildings used. Corridor temperatures do not need to be maintained at 20°C, and a temperature of 16 to 18°C (60 to 64°F) would significantly reduce energy consumption (typical of design assumptions). Table 7.2.11 and Fig. 7.2.3.12 compare the effect of varying the set-point temperature for the make-up air unit using the pre-rehabilitation energy model.

Table 7.2.11 Energy Savings Potential for Make-Up Air Temperature Set-points.

Set-Point Temperature	Space Heat Consumption, kWh	Typical Building % Savings From Baseline (68°F)	Average Space Heat Savings of 11 Study Buildings
74°F (23°C)	1,305,742	-12.5%	-15.6%
72°F (22°C)	1,257,056	-8.3%	-10.3%
70°F (21°C)	1,207,901	-4.1%	-5.1%
68°F (20°C)*	1,160,724	-	-
66°F (19°C)	1,117,976	3.7%	4.7%
64°F (18°C)	1,080,820	6.9%	9.2%
62°F (17°C)	1,048,414	9.7%	13.2%
60°F (16°C)	1,019,915	12.1%	16.9%
55°F (13°C)	959,896	17.3%	24.4%

*Simulated baseline

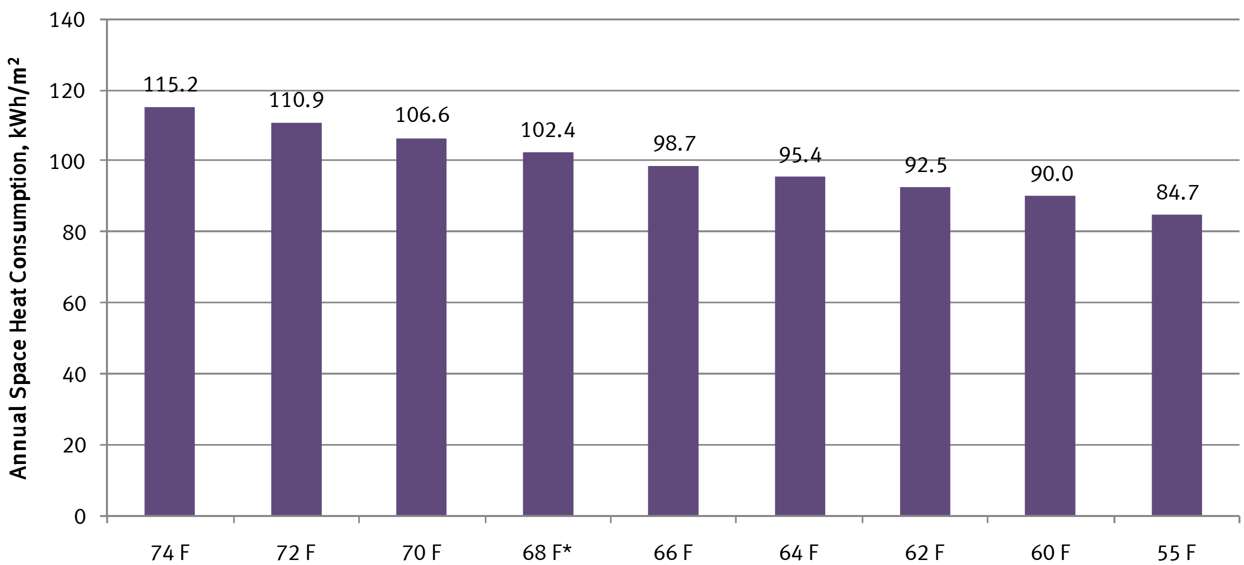


Fig. 7.2.3.12 Space Heat Energy Consumption of Make-up Air Temperature Set-points.

Lowering the make-up air temperature set-point to 16°C (60°F) reduces space heat consumption by 12%. Although decreasing make-up air temperature will reduce heating energy for make-up air, suite space heating energy will go up slightly. Fig. 7.2.3.13 shows the division of gas and electrical consumption for the make-up air temperatures simulated. As shown, the decrease in make-up air heating energy is much greater than the increase in suite electrical heating energy, but the net effect is a reduction in space heat energy and total energy consumption for the building.

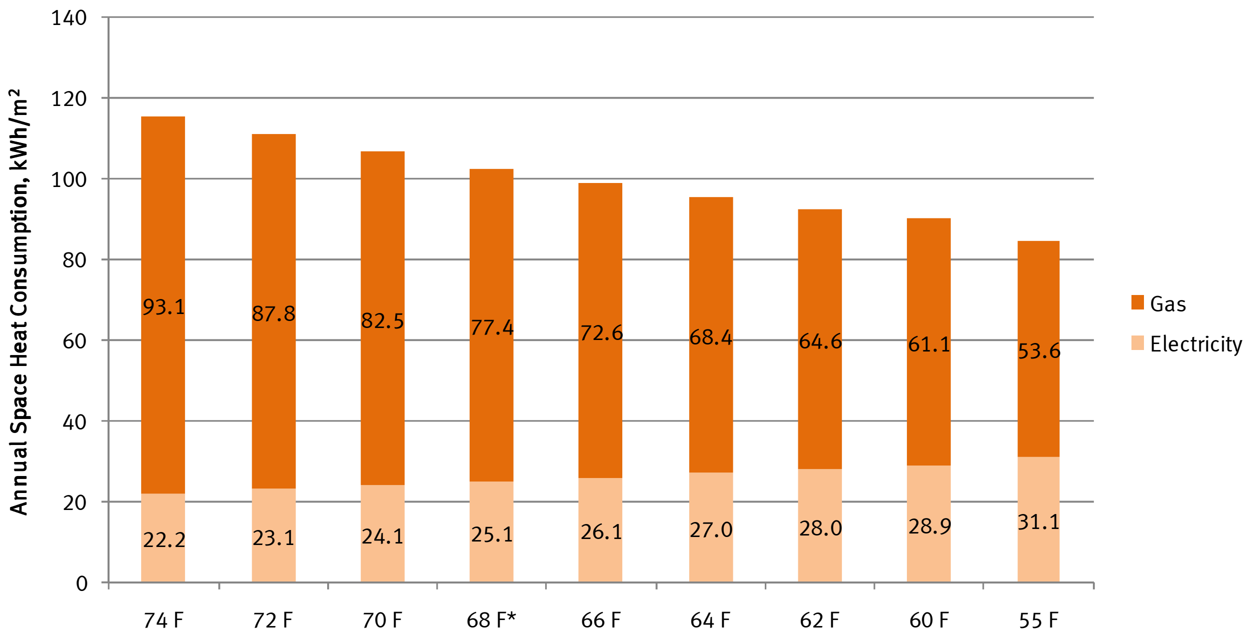


Fig. 7.2.3.13 Space Heat Gas and Electrical Consumption of Make-up Air Temperature Set-points.

Significant gas energy savings may be realized by reducing the make-up air set-point; however, reducing the temperature will also affect occupant comfort and move energy consumption to the suites. Occupants may complain of cold drafts and may block off door undercuts (and hence ventilation air) when corridor temperatures drop too low. Seasonal adjustments (i.e. to turn off the heat during the summer months) or night-time setbacks to temperature will further reduce make-up air energy consumption.

The Impact of Make-Up Air Flow Rate

The make-up air unit at the typical building is sized to deliver 5,500 cfm of air (based on 50 cfm per suite), or 0.045 cfm/ft^2. The flow rate was adjusted in the pre-rehabilitation simulation to determine the energy impact of higher or lower airflow rates. Based on the study buildings, more modern make-up air units typically deliver approximately 110 cfm per suite to the corridors (up to 170 cfm per suite). Space heat consumption for various airflow rates is shown in Table 7.2.12 and Fig. 7.2.3.14. Fig. 7.2.3.15 shows the division of gas and electrical space heating consumption for the simulated make-up air flow rates.

This analysis was performed for theoretical purposes only and assumes that the flow rate from the corridor reaches each suite (and that each suite has a minimum level of ventilation for health). The ventilation rate of the make-up air unit should only ever be reduced if it can be shown that every suite in the building (not the corridors) is being over ventilated above ASHRAE 62 recommendations.

Table 7.2.12 Energy Savings Potential for Make-up Air Flow Rate.

Air Flow Rate (cfm/ft^2)	Representative of	Space Heat Consumption, kWh	Typical Building % Savings From Baseline	Average Space Heat Savings of 11 Study Buildings
0.045	100% of Nominal (50 cfm/suite)*	1,160,724	-	-
0.043	95% of Nominal (48 cfm/suite)	1,142,123	1.6%	2.1%
0.041	90% of Nominal (45 cfm/suite)	1,123,623	3.2%	4.5%
0.038	85% of Nominal (43 cfm/suite)	1,096,210	5.6%	6.9%
0.036	80% of Nominal (40 cfm/suite)	1,077,882	7.1%	9.4%
0.034	75% of Nominal (38 cfm/suite)	1,059,803	8.7%	11.5%
0.032	70% of Nominal (35 cfm/suite)	1,041,964	10.2%	13.8%
0.029	65% of Nominal (33 cfm/suite)	1,015,719	12.5%	16.1%
0.027	60% of Nominal (30 cfm/suite)	998,417	14.0%	18.4%
0	No make-up air (0 cfm/suite)	803,307	30.8%	42.3%
0.100	Typical modern air flow rate (110 cfm/suite)	1,688,347	-45.5%	-61.9%

*Simulated baseline

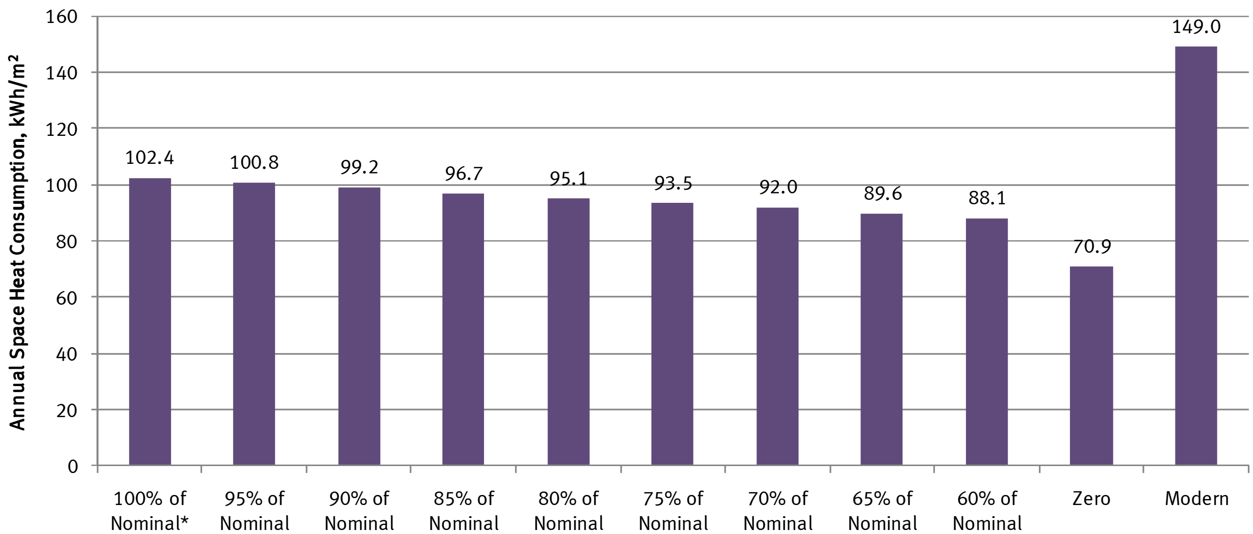


Fig. 7.2.3.14 Space Heat Energy Consumption of Make-up Air Flow Rate.

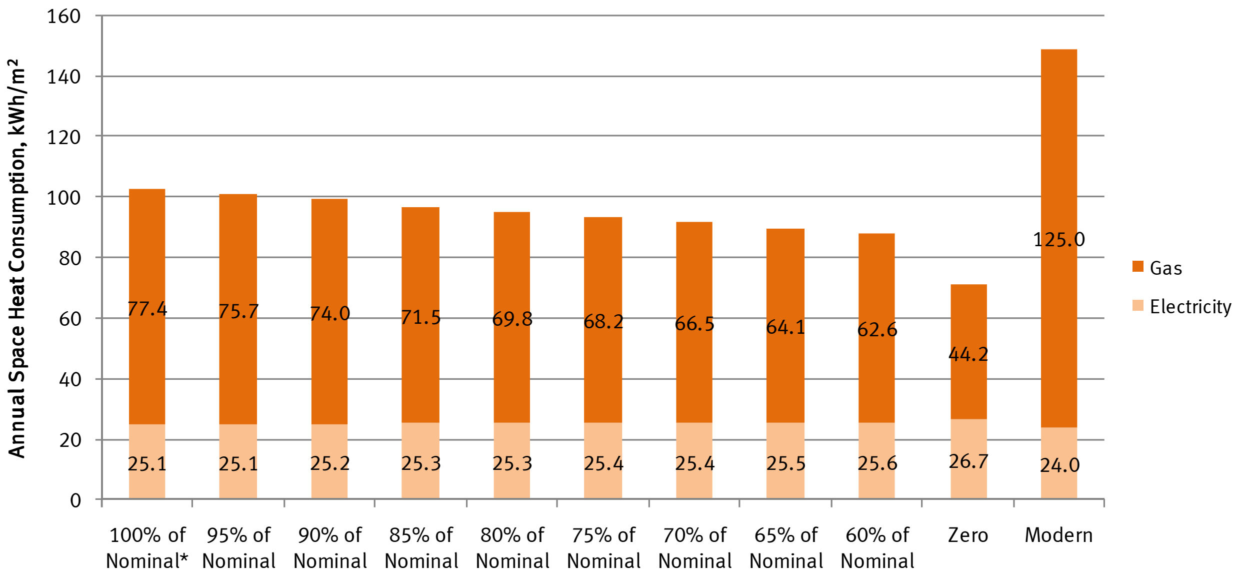


Fig. 7.2.3.15 Gas and Electrical Space Heat Energy Consumption of Make-up Air Flow Rate.

The make-up air flow rate can have a significant impact on energy consumption. The simulations show that reducing the flow rate by 40% reduces energy consumption by 14%. However, based on observations at the study buildings, only a portion of the make-up air flow is typically delivered to the suites as a result of air flow through shafts, blocked suite entry door undercuts, and other factors.

Therefore, reducing the flow rates at make-up air units without confirmation of the actual delivery of air to the various rooms in the suites could impact occupant health, as well as adversely affect the performance of the building enclosure assemblies and other building systems (for example increase the condensation potential on windows).

Increasing the make-up air flow rate to corridors to a rate more representative of modern buildings increases energy consumption by 46%. Improvements are needed the pressurized corridor approach of ventilation in order to ensure adequate airflow reaches the suites (and is not lost in the distribution process).

The Impact of Heat Recovery Ventilation

Most large commercial buildings utilize central exhaust heat recovery systems. ASHRAE 90.1-2007 requires at least 50% heat recovery for fan systems with both a design supply air capacity of 5,000 cfm or greater and a minimum outdoor air supply of 70% or greater of the design supply quantity air (ASHRAE 90.1-2007 6.5.6.1). Make-up air systems are not required to have heat recovery per Exception 6.5.6.1.i, which states that heat recovery is not required where the largest exhaust source is less than 75% of the design outdoor airflow. Make-up air systems do not have central exhaust; exhaust occurs through intermittent bathroom and kitchen fans as well as through incidental penetrations in the enclosure. The new ASHRAE Standard 189.1-2009 requires at least 60% energy recovery for systems with greater than 4000 cfm and 80% outdoor air in the Vancouver climate zone (5C), with no exception for systems without exhaust (ASHRAE Standard 189.1-2009 7.4.3.8). Under this new standard MURB make-up air systems will be required to have ventilation heat recovery.

The buildings in the study currently have no capability for central exhaust heat recovery as exhaust air is intermittently occupant controlled and is expelled at each suite through the exterior wall; there is no return ductwork. Exhaust air heat recovery could be implemented in existing buildings in two ways. First, return ductwork could be installed to remove air from the suites and exhaust it through a rooftop heat recovery unit. Second, in-suite heat recovery ventilators (HRVs) could be installed at each suite to provide individual ventilation to each unit. Either of these options could be applied to new buildings as well.

A simulation was performed for the hypothetical situation that at the typical building where the exhaust air was recovered and run through a central HRV, or in-suite HRVs were installed. Spreadsheet calculations were performed for the in-suite HRV scenario as this could not be simulated using the program. Table 7.2.13 and Fig. 7.2.3.16 show the simulation results for various heat recovery scenarios with the pre-rehabilitation building. Fig. 7.2.3.17 shows the division of gas and electrical consumption for the heat recovery scenarios. Central HRV units are capable of heat recovery efficiencies upwards of 90% while smaller units that would be installed in-suite are limited to efficiencies of about 80%.

Table 7.2.13 Energy Savings Potential for Ventilation Heat Recovery.

Scenario	Space Heat Consumption, kWh	Typical Building % Savings From Baseline	Average Space Heat Savings of 11 Study Buildings
Baseline Pre (no heat recovery)	1160724	-	-
50% Central HRV	979,499	15.6%	20.7%
70% Central HRV	914,143	21.2%	28.7%
90% Central HRV	853,761	26.4%	36.1%
50% In-Suite HRV	1,010,460	12.9%	19.4%
70% In-Suite HRV	927,599	20.1%	29.0%
80% In-Suite HRV	886,168	23.7%	33.8%

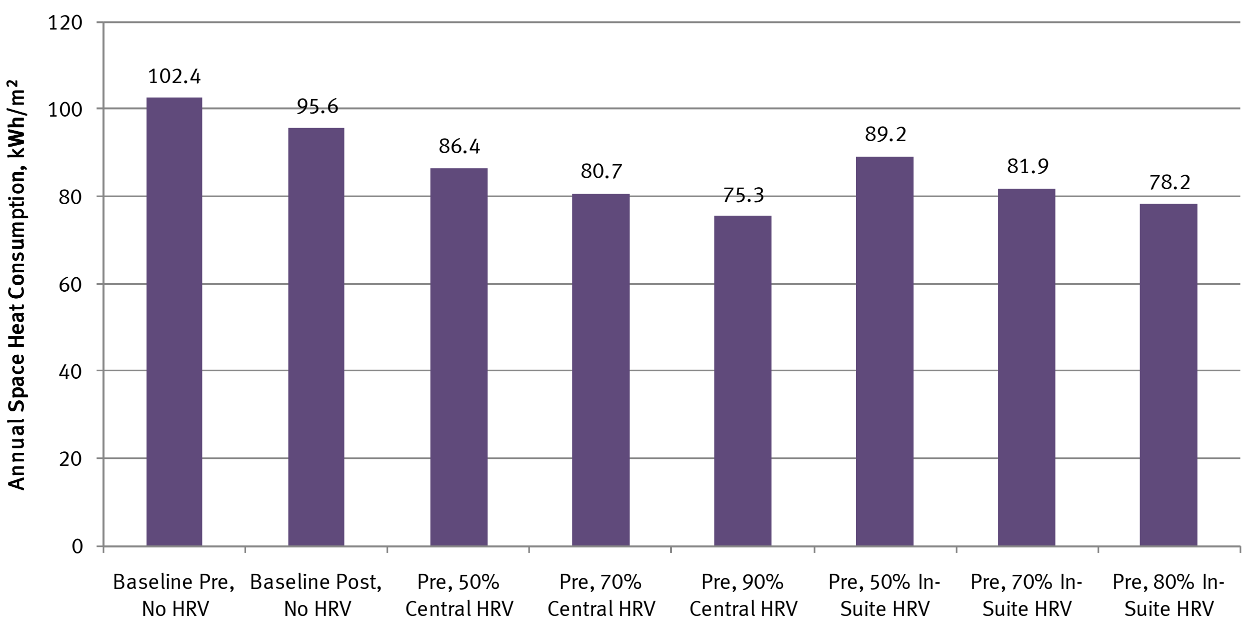


Fig. 7.2.3.16 Space Heat Energy Consumption of Heat Recovery Ventilation.

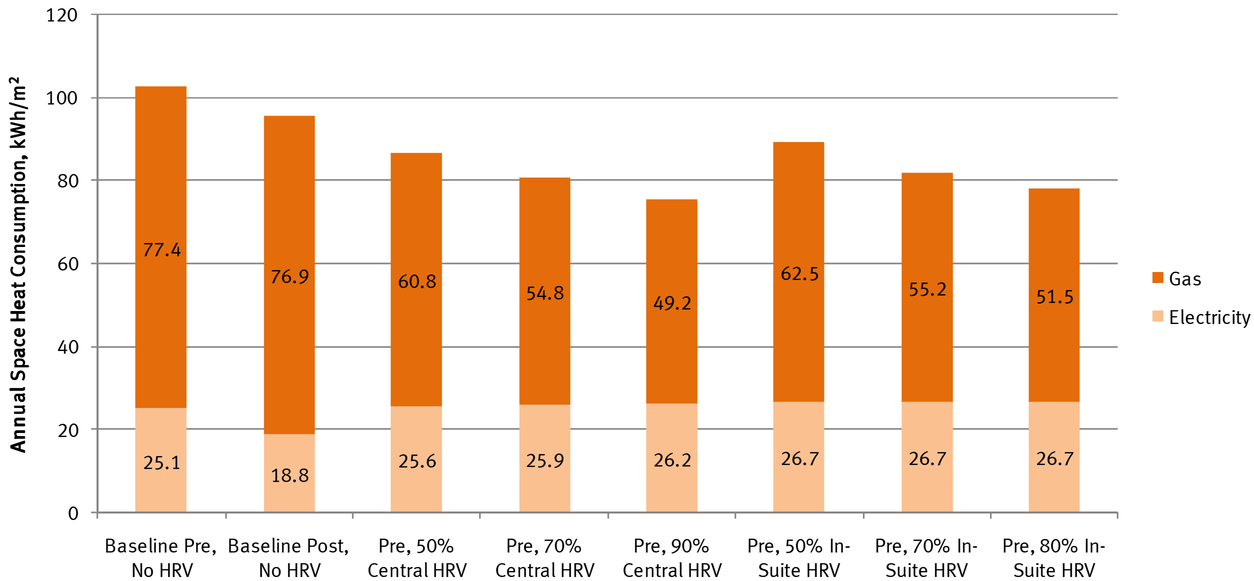


Fig. 7.2.3.17 Gas and Electric Space Heat Energy Consumption of Heat Recovery Ventilation.

A 90% efficient central HRV reduces annual space heat energy consumption by 26%. An 80% efficient in-suite HRV reduces energy consumption by 24% per year. Heat recovery may significantly reduce energy consumption but may be challenging in rehabilitation scenarios.

The Impact of Combining Energy Efficiency Measures

The energy efficiency measures analysed thus far are not additive, as discussed previously. That is, one cannot add the individual energy reduction of improving the wall and window thermal performance, reducing air leakage, and so on, to obtain a total energy savings. These effects need to be combined in a separate simulation.

Two scenarios were simulated to determine the overall effect of increasing the wall R-value, decreasing the window U-value, improving airtightness, lowering the corridor make-up air temperature and adding heat recovery to ventilation make-up air. The simulation results are compared to the pre- and post-rehabilitation simulation results. Table 7.2.14 shows the combinations of energy efficiency measures that were simulated, with the pre- and post-rehabilitation simulation inputs for reference. Table 7.2.15 and Fig. 7.2.3.18 show the simulation results for the improved scenarios. Fig. 7.2.3.19 shows the total annual energy consumption for the improved scenarios, divided into gas and electrical components.

Table 7.2.14 Combination Energy Efficiency Measures Simulated.

Scenario	Simulation Inputs
Baseline Post	⇢ Walls effective R-5.5 ⇢ Windows double glazed, air fill, low-e, aluminum frame; U = 0.51, SC = 0.45 ⇢ Airtightness “Tight – High Average”, 0.15 cfm/ft^2 ⇢ Make-up air temperature set-point 68ºF ⇢ No heat recovery
“Good”	⇢ Walls effective R-10 ⇢ Windows double glazed, argon fill, low-e, low conductive frame; U = 0.27, SC = 0.35 ⇢ Airtightness “Tight – Low Average”, 0.05 cfm/ft^2 ⇢ Make-up air temperature set-point 64ºF ⇢ No heat recovery
“Best”	⇢ Walls effective R-18.2 ⇢ Windows triple glazed, argon fill, low-e, low conductive frame; U = 0.17, SC = 0.23 ⇢ Airtightness “Very Tight”, 0.02 cfm/ft^2 ⇢ Make-up air temperature set-point 60ºF ⇢ 80% Heat Recovery

Table 7.2.15 Energy Savings Potential for Improved Buildings.

Scenario	Space Heat Consumption, kWh	Typical Building % Savings From Baseline	Average Space Heat Savings of 11 Study Buildings
Baseline Pre	1,160,724	-	-
Baseline Post	1,083,323	6.7%	6.0%
“Good”	763,778	34.2%	36.0%
“Best”	509,632	56.1%	70.5%

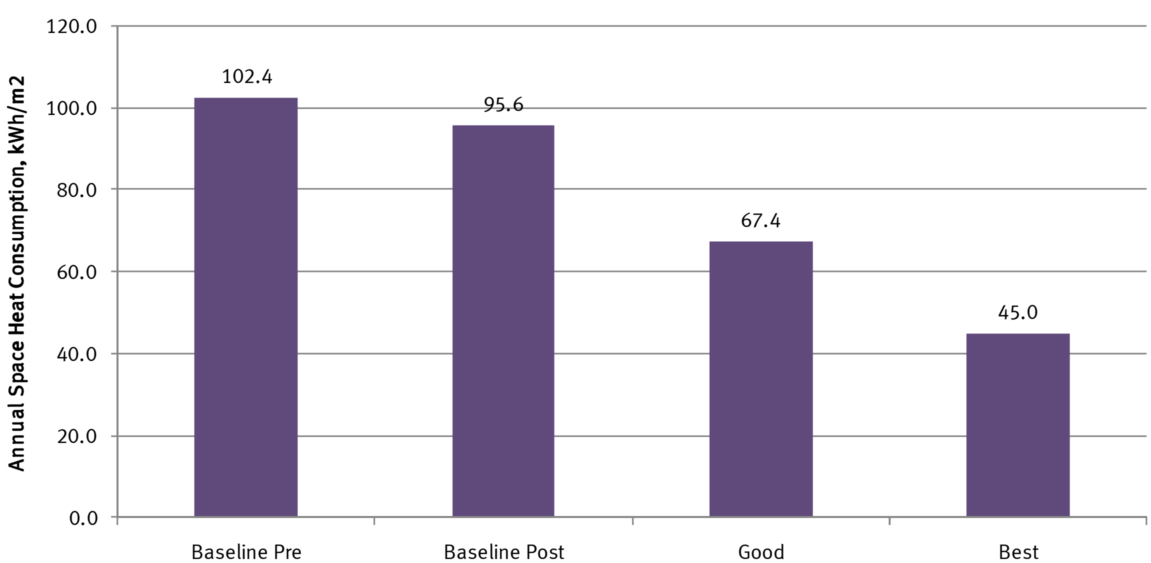


Fig. 7.2.3.18 Space Heat Energy Consumption of Improved Buildings.

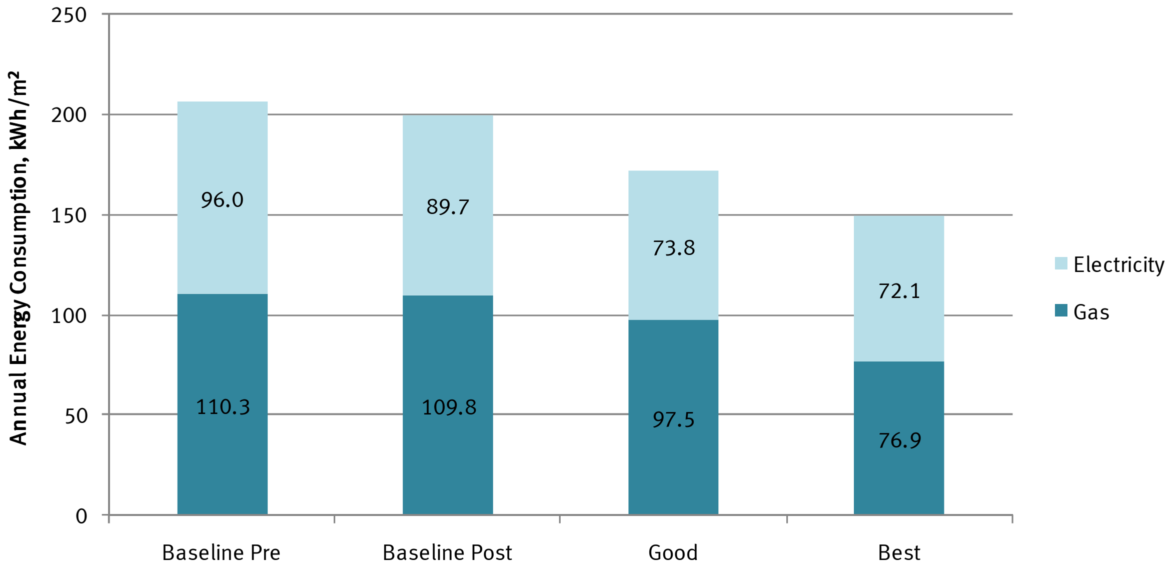


Fig. 7.2.3.19 Total Annual Energy Consumption of Improved Buildings.

The simulations with multiple energy efficiency measures show that significant energy savings may be realized by combining the measures discussed in this report. The "best" scenario shows a space heat reduction of 56%, consuming 45 kWh/m^2/year for space heat. The total building energy consumption for this building is 149 kWh/m^2/year, without addressing mechanical equipment upgrades and lighting and plug loads. Significant energy savings may be realized through enclosure and make-up air improvements. These findings are based on simulation only, and further research is needed to confirm actual savings.

Fig. 7.2.3.20 shows the distribution of energy consumption for the "best" scenario. The plot shows that ventilation and electric baseboard space heating are now a small portion of total energy consumption. Fireplaces are still a significant portion of total energy consumption; however, the simulation does not account for the fact that occupants may use their fireplaces less often due to the improved enclosure (the "good" and "best" scenarios are simulated without fireplaces in the following section, "The Impact of Fireplaces"). Electrical consumption accounts for 48% of total energy consumption, a much greater portion than in the baseline scenarios.

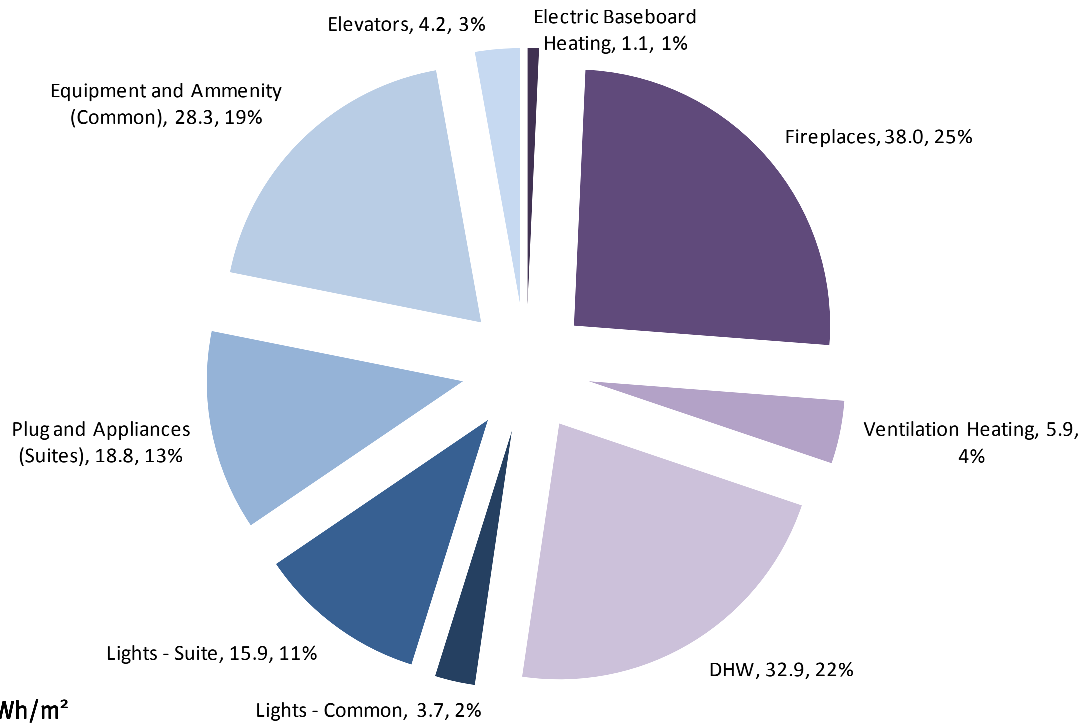


Fig. 7.2.3.20 Distribution of total energy consumption for "best" scenario, kWh/m^2 and percentage.

7.2.4 Additional Analysis on Typical Building Energy Model

Further simulations were performed using the established typical building model in order to further study energy consumption in multi-unit residential buildings.

The Impact of Fireplaces

Fireplaces account for 18% of total building energy consumption in the typical building, or 36% of space heating (37.5 kWh/m^2). Fireplaces contribute to space heating so removing fireplaces should increase the electric space heating consumption. Fig. 7.2.4.1 shows the gas and electric space heat consumption with and without fireplaces. Removing fireplaces from the simulation reduces gas consumption by 37.5 kWh/m^2 and increases electrical consumption by 4 kWh/m^2 over the course of a year. The total space heating reduction from removing fireplaces is 32.6%. Gas fireplaces are not efficient space heating systems but they may have other benefits such as occupant comfort and aesthetics.

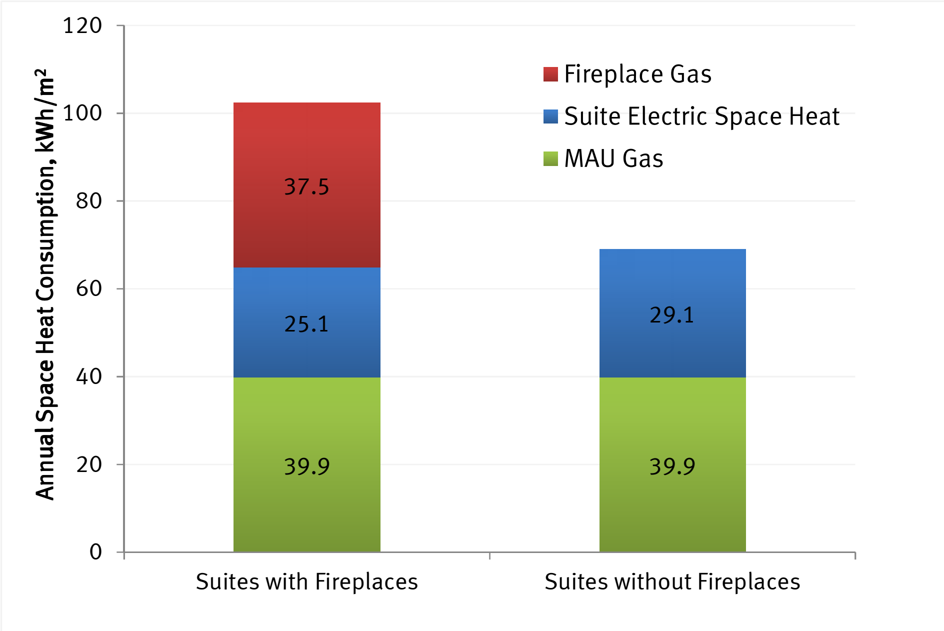


Fig. 7.2.4.1 Gas and electric space heat consumption with and without fireplaces.

Fig. 7.2.4.2 shows the distribution of energy consumption in the post-rehabilitation typical building simulations with and without fireplaces. The case without fireplaces has higher electric baseboard heating consumption but lower total energy consumption.

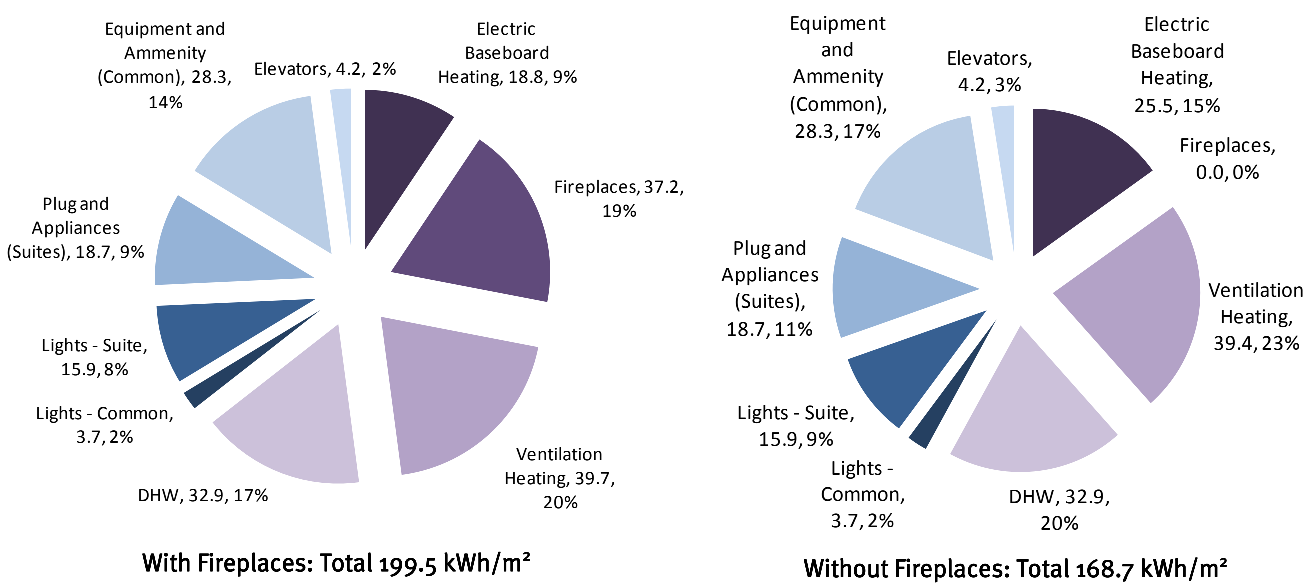


Fig. 7.2.4.2 Distribution of energy consumption for post-rehabilitation typical building model with and without fireplaces.

It is clear that fireplaces are not an efficient means of space heating, and consume a significant portion of energy in MURBs. Two simulations were completed to determine the energy consumption of the "good" and "best" scenarios previously simulated but without fireplaces. Fig. 7.2.4.3 and Fig. 7.2.4.4 show the simulation results, as well as the previous "good" and "best" simulation results (with fireplaces) for comparison. Fig. 7.2.4.4 shows the distribution of energy consumption for the "best" scenario without fireplaces.

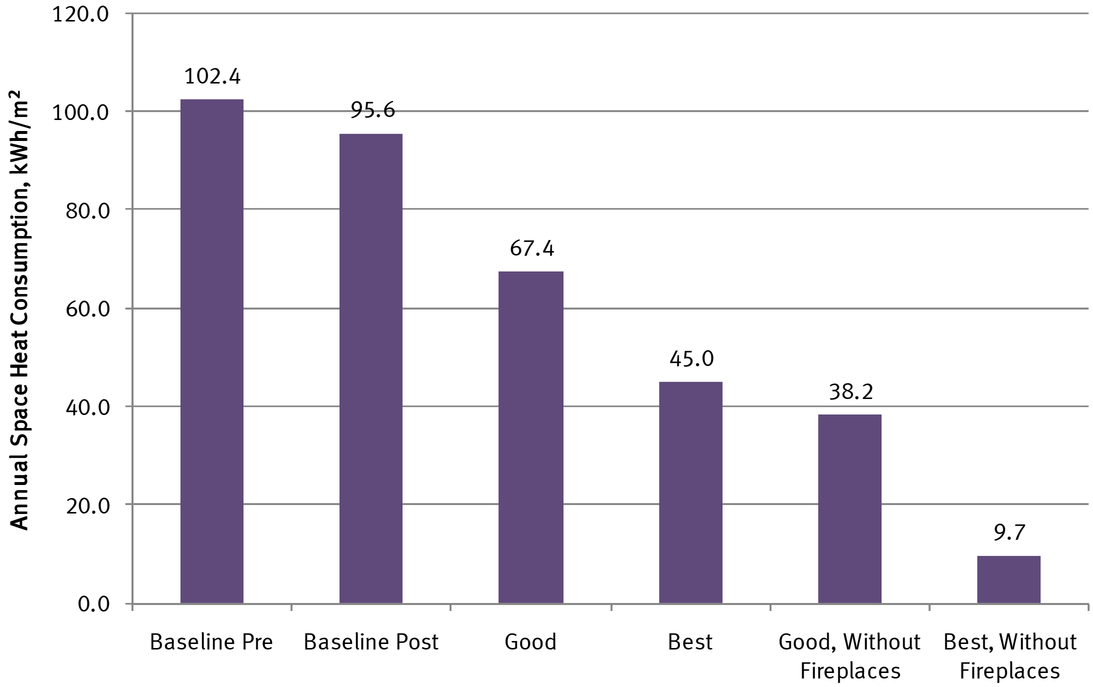


Fig. 7.2.4.3 Space heat consumption of “good” and “best” scenarios, with and without fireplaces.

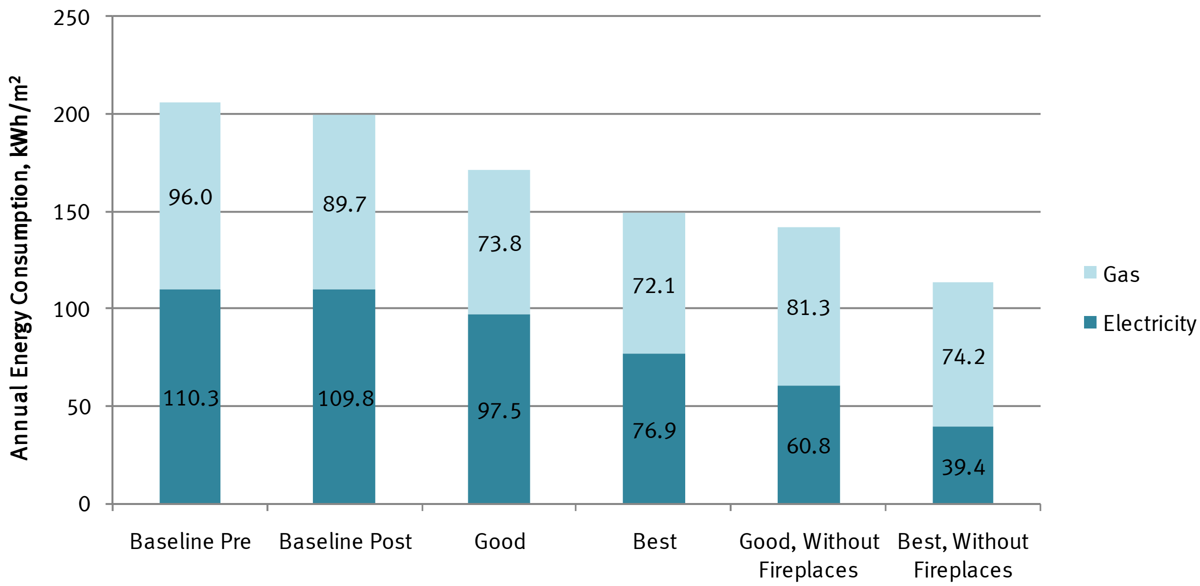


Fig. 7.2.4.4 Total energy consumption of “good” and “best” scenarios, with and without fireplaces.

To summarise, Fig. 7.2.4.5 shows the annual space heat consumption of the “good” and “best” scenarios simulated without fireplaces. In a low energy building these should be the true “good” and “best” scenarios.

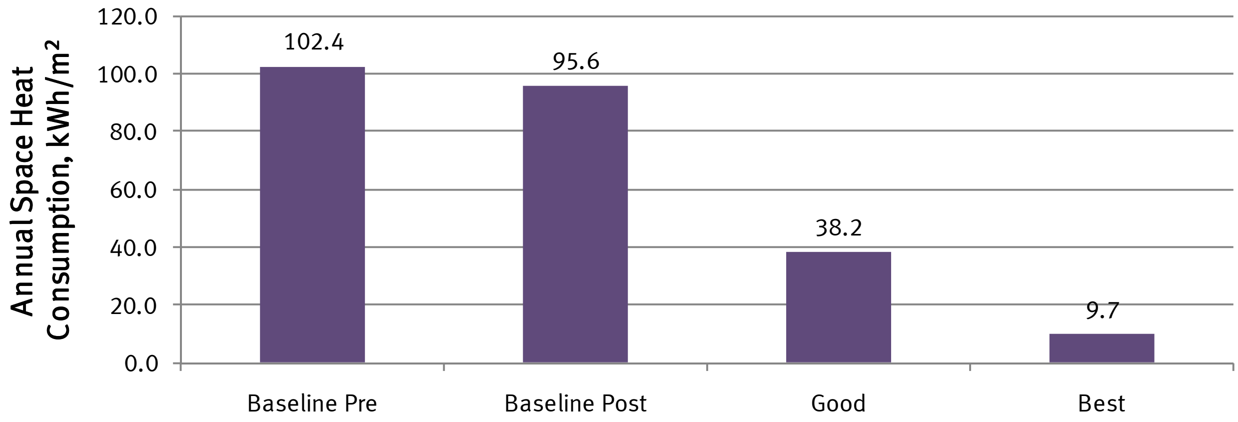


Fig. 7.2.4.5 Total energy consumption of "good" and "best" scenarios, without fireplaces.

The simulations without fireplaces show significantly lower energy consumption. The "best" scenario consumes a total of 113.6 kWh/m^2 per year. Of this, only 9% is used for heating, while 29% is DHW and 62% is electrical. This simulation shows that it is possible to reduce space heating loads significantly in MURBs.

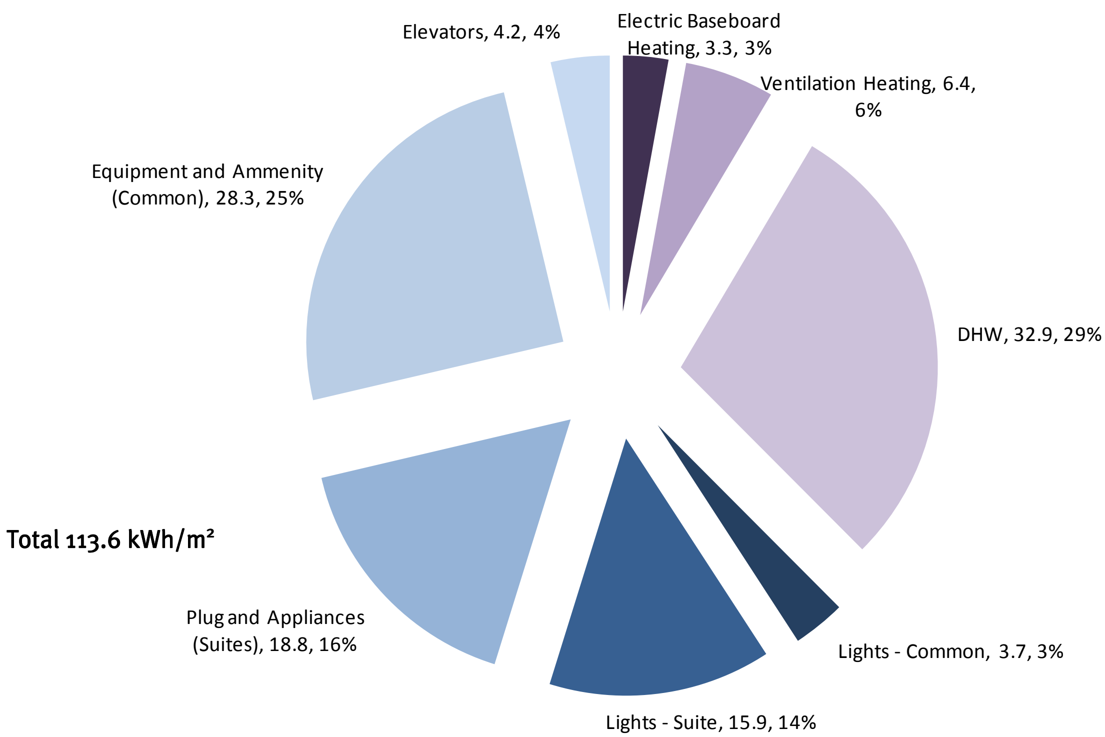


Fig. 7.2.4.6 Distribution of energy consumption for "best" scenario without fireplaces.

The simulations show that fireplaces consume a significant amount of energy but are not an efficient means of space heating. A number of simulations were re-run using the post-rehabilitation typical building model with zero fireplace consumption to determine the impact of enclosure and mechanical changes on a building without fireplaces. Analysis was completed for the wall R-value, window U-value and SHGC, air leakage rate and MUA flow rate in a building without fireplaces.

Table 7.2.16, Fig. 7.2.4.7 and Fig. 7.2.4.8 show the annual space heat energy consumption with different wall R-values for the post-rehabilitation typical building without fireplaces. The percentage space heat savings are slightly higher for the building without fireplaces but the absolute reductions in space heat consumption are slightly higher in the building with fireplaces. The reduction in annual space heat consumption due to increasing the wall R-value is close in the buildings with and without fireplaces.

Table 7.2.16 Impact of wall thermal performance on annual space heat consumption in post-rehabilitation typical building without fireplaces.

Wall	R-Value	Annual Space Heat Consumption		Space Heat Savings from Baseline	Typical Building with Fireplaces	
		kWh	kWh/m²/yr		Space Heat Consumption, kWh/m²/yr	Space Heat Savings
Baseline	5.5	734,874	64.9	-	95.6	-
No Balconies	6.6	722,830	63.8	1.6%	94.1	1.5%
Effective R10	10.0	699,574	61.7	4.8%	91.5	4.3%
ASHRAE 90.1	15.6	675,335	59.6	8.1%	89.5	6.4%
ASHRAE 189.1	18.2	670,414	59.2	8.8%	89.0	6.9%

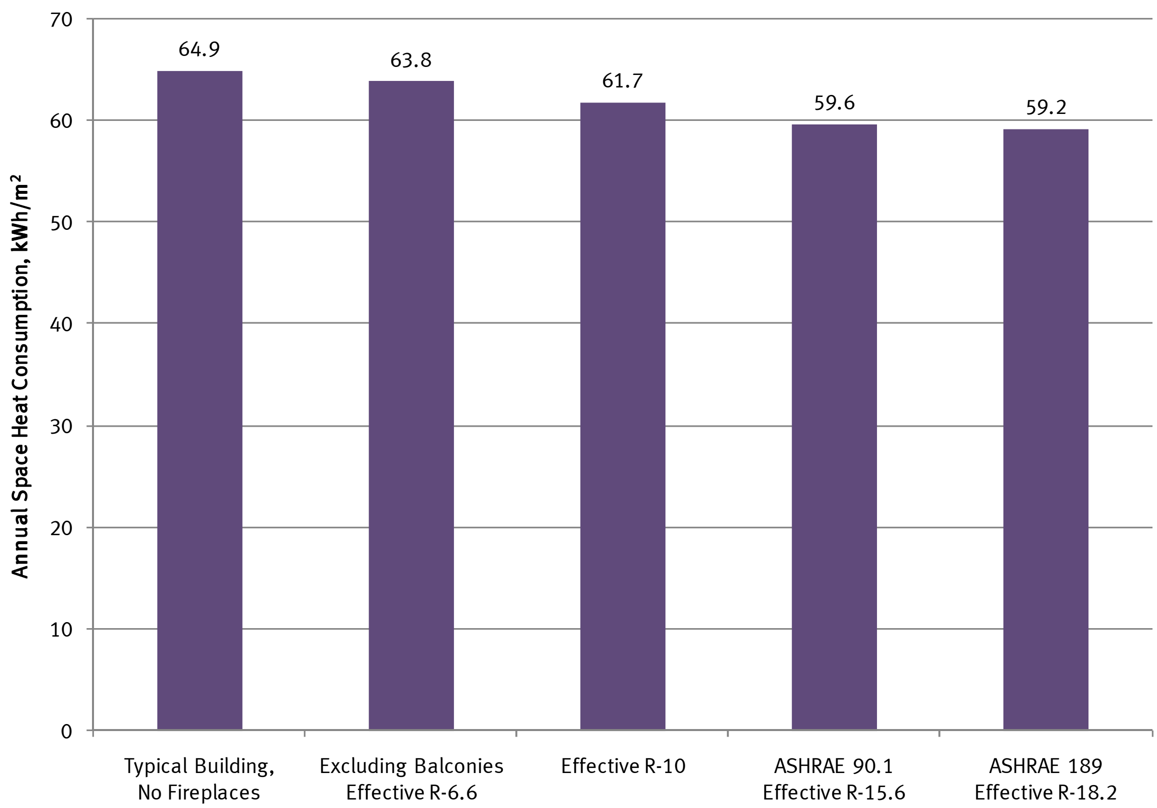


Fig. 7.2.4.7 Impact of wall thermal performance on annual space heat consumption in building without fireplaces.

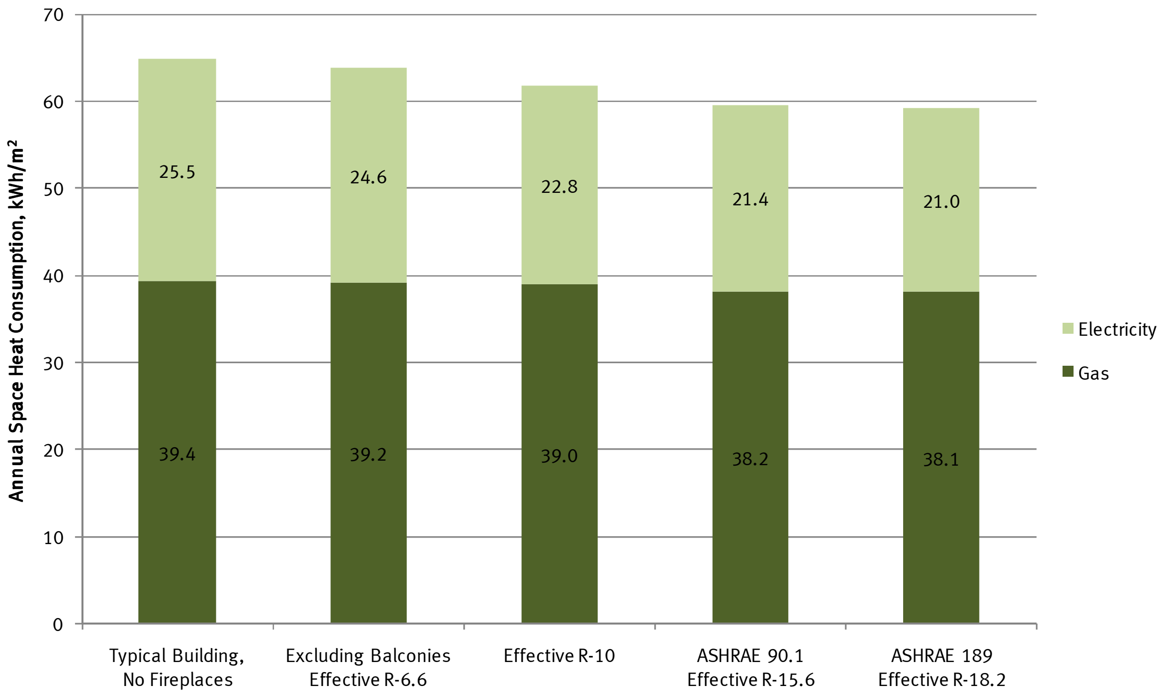


Fig. 7.2.4.8 Impact of wall thermal performance on post-rehabilitation gas and electricity space heat.

Table 7.2.17, Fig. 7.2.4.9 and Fig. 7.2.4.10 show the annual space heat energy consumption with different window U-values and SHGC's for the post-rehabilitation typical building without fireplaces. The change in space heat consumption is close for the buildings with and without fireplaces.

Table 7.2.17 Impact of window thermal performance on annual space heat consumption in post-rehabilitation typical building without fireplaces.

Window	Annual Space Heat Consumption		Space Heat Savings from Baseline	Typical Building with Fireplaces	
	kWh	kWh/m²/yr		Space Heat Consumption, kWh/m²/yr	Space Heat Savings
Baseline	734,874	64.9	-	95.6	-
U = 0.45, SHGC = 0.4	716,801	63.3	2.5%	92.7	3.0%
U = 0.45, SHGC = 0.3	738,699	65.2	-0.5%	94.4	1.3%
U = 0.27, SHGC = 0.4	622,409	54.9	15.3%	83.4	12.7%
U = 0.27, SHGC = 0.3	643,171	56.8	12.5%	84.8	11.3%
U = 0.17, SHGC = 0.3	572,645	50.5	22.1%	79.4	17.0%
U = 0.17, SHGC = 0.2	604,599	53.4	17.7%	81.4	14.8%

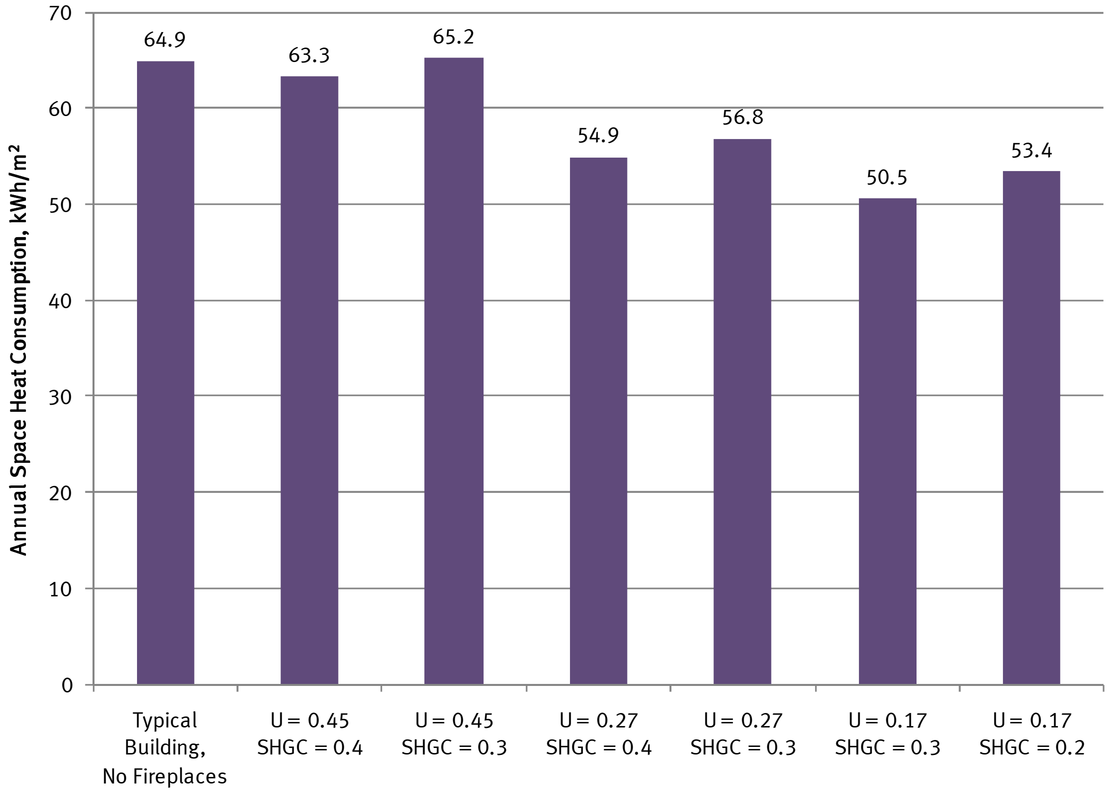


Fig. 7.2.4.9 Impact of window thermal performance on annual space heat consumption in building without fireplaces.

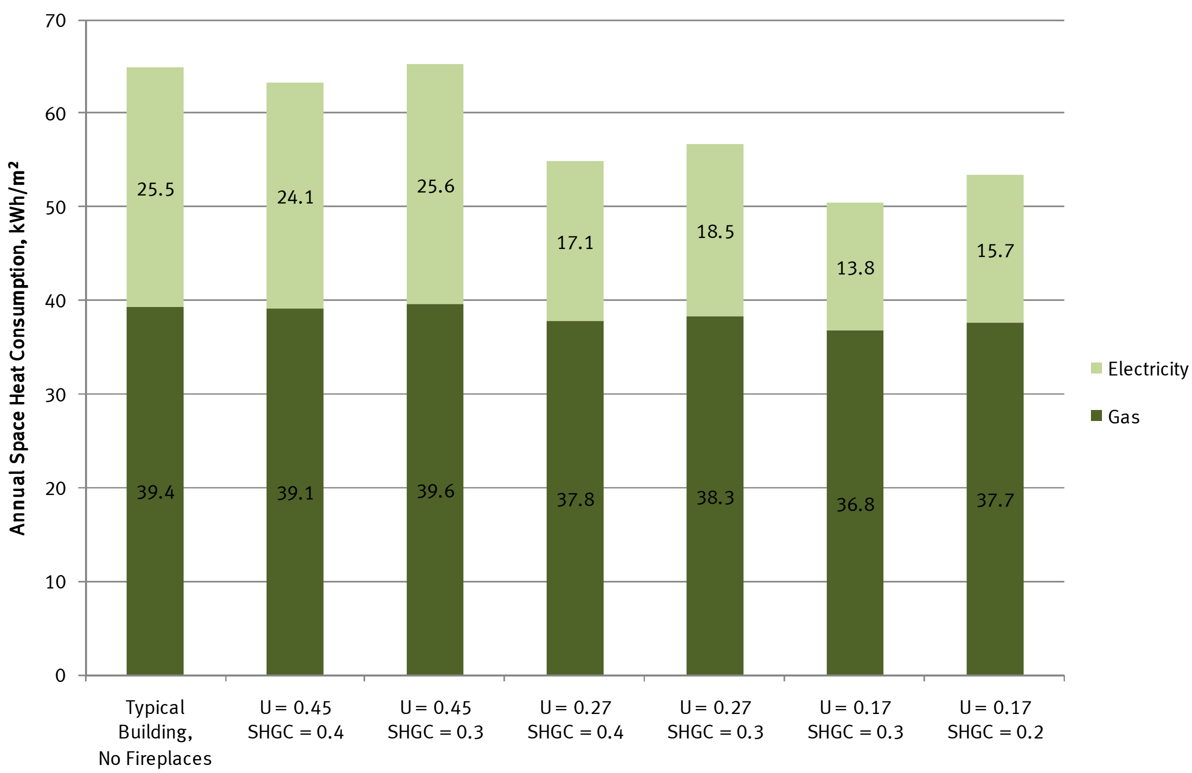


Fig. 7.2.4.10 Impact of window thermal performance on post-rehabilitation gas and electricity space heat.

Table 7.2.18, Fig. 7.2.4.11 and Fig. 7.2.4.12 show the annual space heat energy consumption with different enclosure air leakage rates. The percentage space heat savings are slightly higher for the building without fireplaces but the absolute reductions in space heat consumption are slightly higher in the building with fireplaces. The change in annual space heat consumption due to changing the enclosure airtightness is close in the buildings with and without fireplaces.

Table 7.2.18 Post-Rehabilitation Building Enclosure Energy Simulations of the Impact of Air leakage on Space Heating in Typical Building without Fireplaces.

Enclosure Airtightness (cfm/ft²)	Annual Space Heat Consumption		Percent Difference from Baseline (0.15 cfm/ft²)	Typical Building with Fireplaces	
	kWh	kWh/m²/yr		Space Heat Consumption, kWh/m²/yr	Space Heat Savings
0*	660924	58.3	10.1%	87.6	8.3%
0.02	672704	59.4	8.5%	88.8	7.1%
0.05	686962	60.6	6.5%	90.5	5.3%
0.1	712431	62.9	3.1%	93.0	2.7%
0.15**	734874	64.9	-	95.6	-
0.2	747749	66.0	-1.8%	97.7	-2.2%
0.4	798438	70.5	-8.6%	103.9	-8.7%

* No air leakage case includes make-up air flow ** Simulated baseline

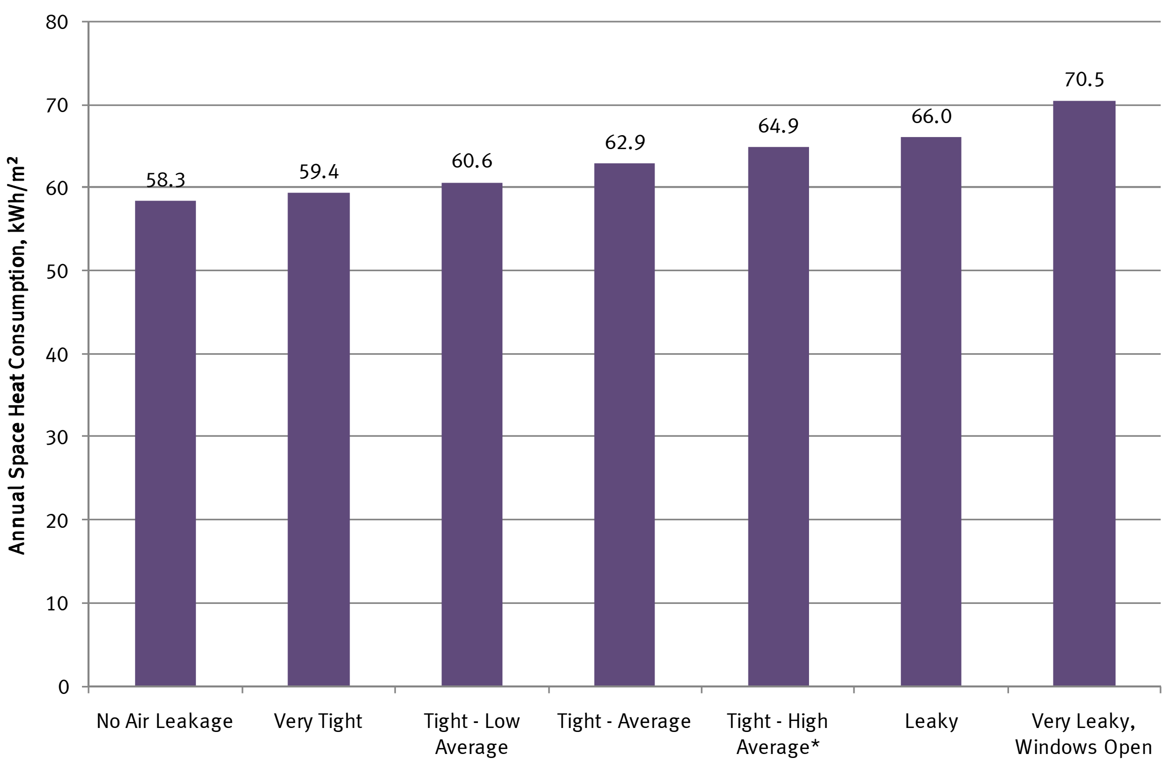


Fig. 7.2.4.11 Impact of airtightness on annual space heat consumption in building without fireplaces.

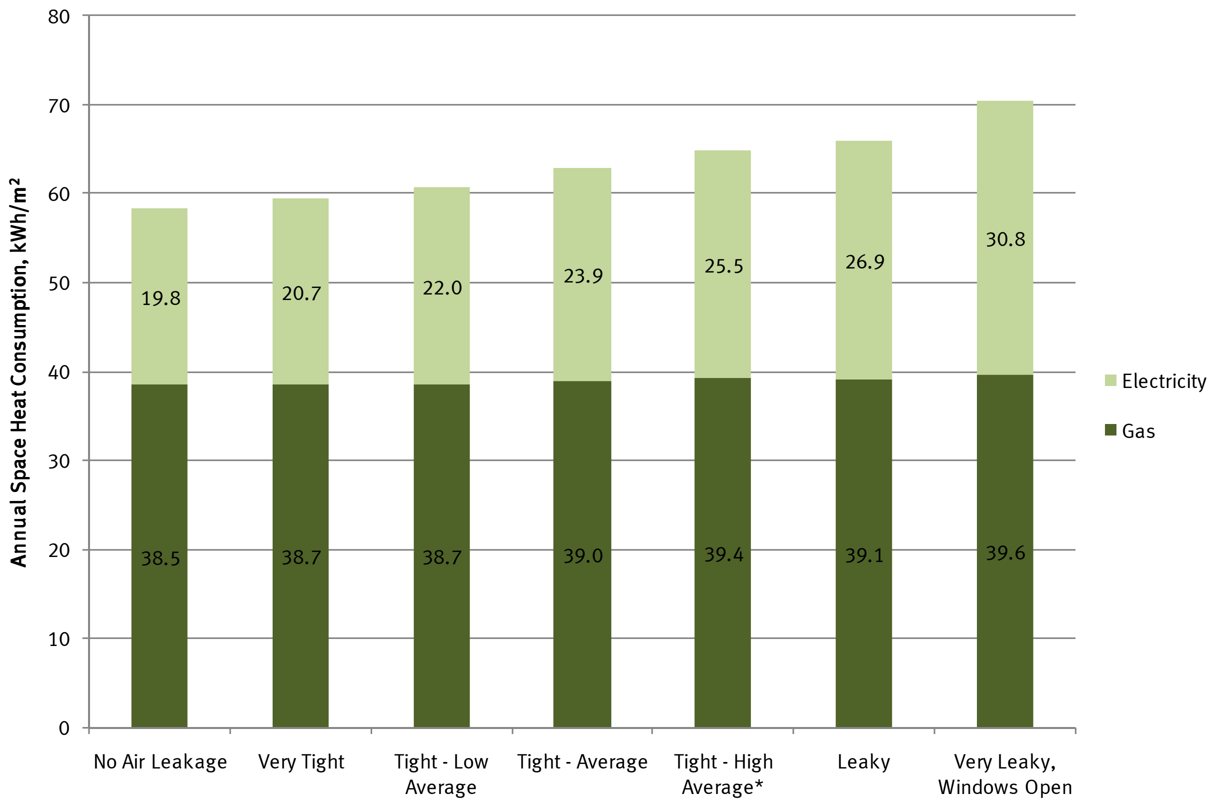


Fig. 7.2.4.12 Impact of airtightness on post-rehabilitation gas and electricity space heat consumption.

Table 7.2.19, Fig. 7.2.4.13 and Fig. 7.2.4.14 show the annual space heat consumption with different make-up air flow rates in the post-rehabilitation typical building simulation without fireplaces. The make-up air simulations were only completed in the building with fireplaces using the pre-rehabilitation enclosure, so direct comparison of the savings is not possible. However, the percent savings in the post-rehabilitation simulations without fireplaces are close to the percent savings in the pre-rehabilitation case with fireplaces.

Table 7.2.19 Impact of make-up air flow rate on annual space heat consumption in post-rehabilitation typical building without fireplaces.

Air Flow Rate (cfm/ft²)	Representative of	Space Heat Consumption		Space Heat Savings from Baseline
		kWh	kWh/m²/yr	
0.045	100% of Nominal (50 cfm/suite)*	734,874	64.9	-
0.043	95% of Nominal (48 cfm/suite)	716,096	63.2	2.6%
0.041	90% of Nominal (45 cfm/suite)	697,339	61.5	5.1%
0.038	85% of Nominal (43 cfm/suite)	669,477	59.1	8.9%
0.036	80% of Nominal (40 cfm/suite)	651,002	57.5	11.4%
0.034	75% of Nominal (38 cfm/suite)	632,813	55.8	13.9%
0.032	70% of Nominal (35 cfm/suite)	614,760	54.3	16.3%
0.029	65% of Nominal (33 cfm/suite)	588,111	51.9	20.0%
0.027	60% of Nominal (30 cfm/suite)	570,704	50.4	22.3%
0	No make-up air (0 cfm/suite)	372,347	32.9	49.3%
0.100	Typical modern air flow rate (110 cfm/suite)	1,267,236	111.8	-72.4%

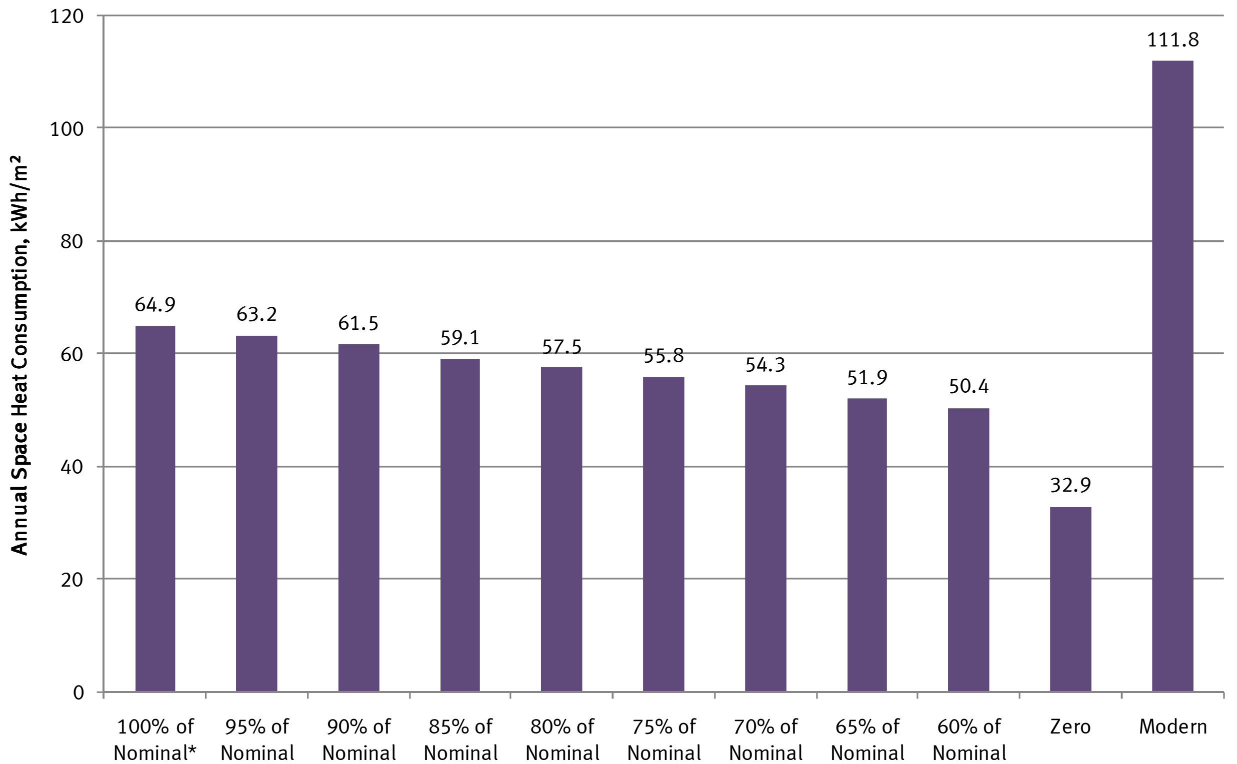


Fig. 7.2.4.13 Impact of make-up air flow rate on annual space heat consumption in building without fireplaces.

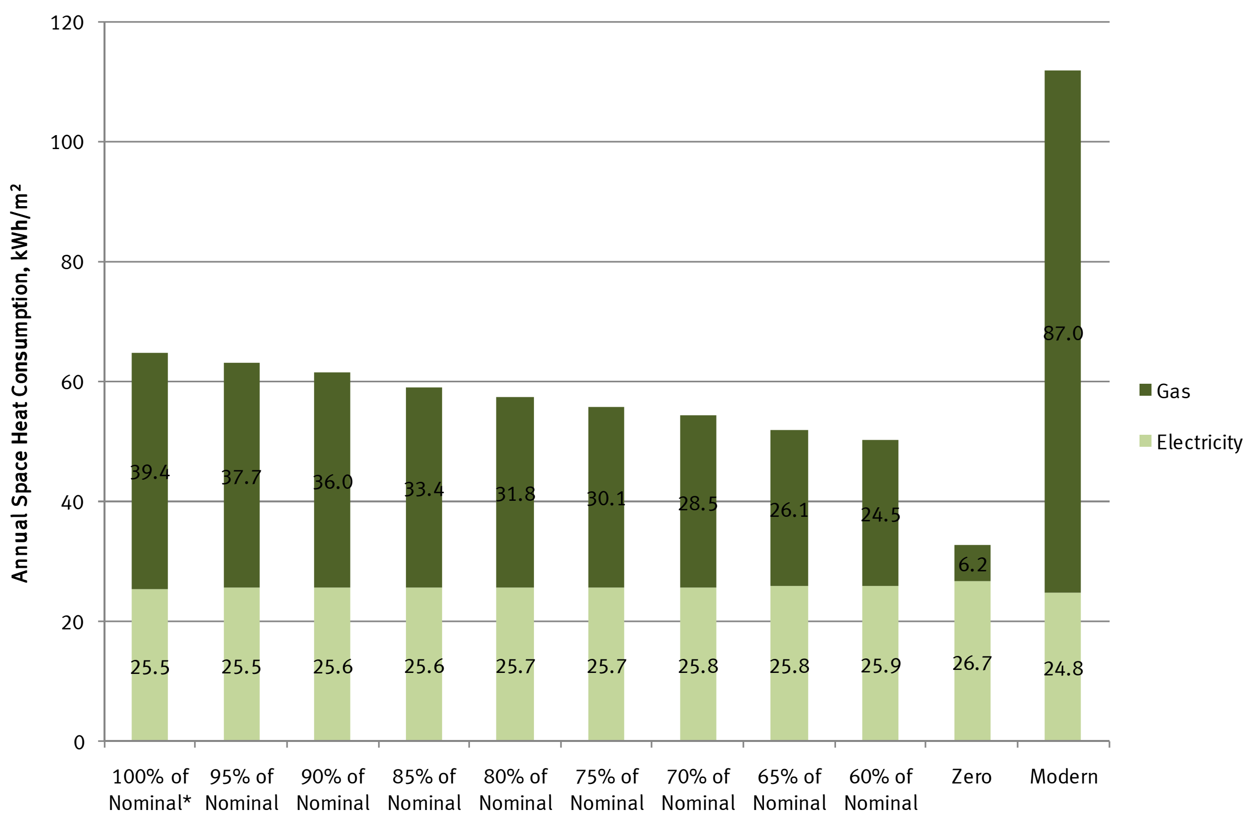


Fig. 7.2.4.14 Impact of make-up air flow rate on post-rehabilitation gas and electricity space heat consumption.

The Impact of Shape and Orientation

Energy simulations were performed to assess the impact of modifying the building shape from square to rectangle, and changing the orientation. Table 7.2.20 shows the modified gross exposed wall areas for each elevation used to simulate this scenario.

Table 7.2.20 Simulated square and rectangular gross exposed wall area.

Window to Wall Ratio	Square	Rectangular
First Wall	15,580	10,387
Second Wall	15,580	20,774
Third Wall	15,580	10,387
Fourth Wall	15,580	20,774
Total	**62,320**	**62,322**

Table 7.2.21 and Fig. 7.2.4.15 show the annual space heating energy consumption of each scenario that was simulated. Fig. 7.2.4.16 and Fig. 7.2.4.17 show the gas and electrical consumption of the scenarios that were simulated. The baseline pre- and post- space heat consumption is 102.4 kWh/m^2 and 95.6 kWh/m^2, respectively. The simulation results show that changing the shape and orientation has a very small effect on space heat energy consumption. In the pre-rehabilitation scenario space heating energy is 0.1% lower for the rectangular buildings. The post-rehabilitation scenarios show slightly greater space heat savings, 0.5% for a N-S facing building and 0.7% for an E-W facing building. The results show that shape and orientation savings are negligible for the current typical building simulation. However, the simulation does not include for cooling, and space heating typically occurs in the evening, or during the winter months when solar heat gains are minimal. The results also suggest that as enclosure performance is improved, shape and orientation may have a greater effect on space heat consumption.

Table 7.2.21 Impact of shape and orientation on annual space heat consumption.

Window to Wall Ratio	Annual Space Heat Consumption		Typical Building Space Heat Savings from Baseline
	kWh	kWh/m^2/yr	
Pre-Rehabilitation			
Baseline Pre (square)	1,160,724	102.4	-
Rectangular, long axis facing N-S	1,159,562	102.3	0.1%
Rectangular, long axis facing E-W	1,159,454	102.3	0.1%
Post-Rehabilitation			
Baseline Post (square)	1,083,323	95.6	-
Rectangular, long axis facing N-S	1,078,166	95.2	0.5%
Rectangular, long axis facing E-W	1,075,303	94.9	0.7%

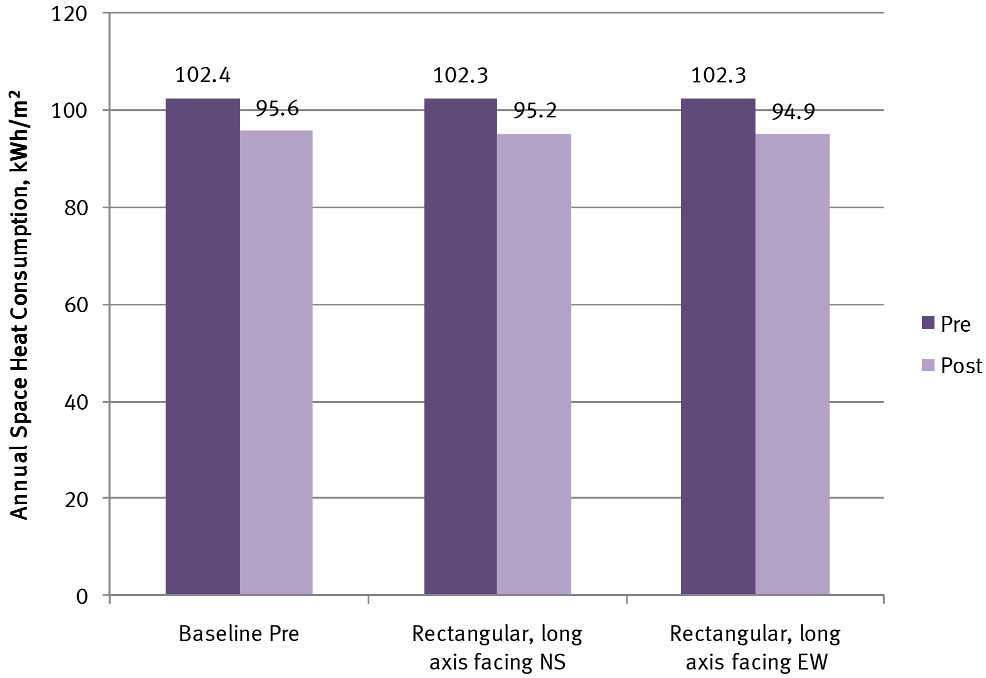


Fig. 7.2.4.15 Impact of shape and orientation on annual space heat consumption (ventilation and electric baseboards).

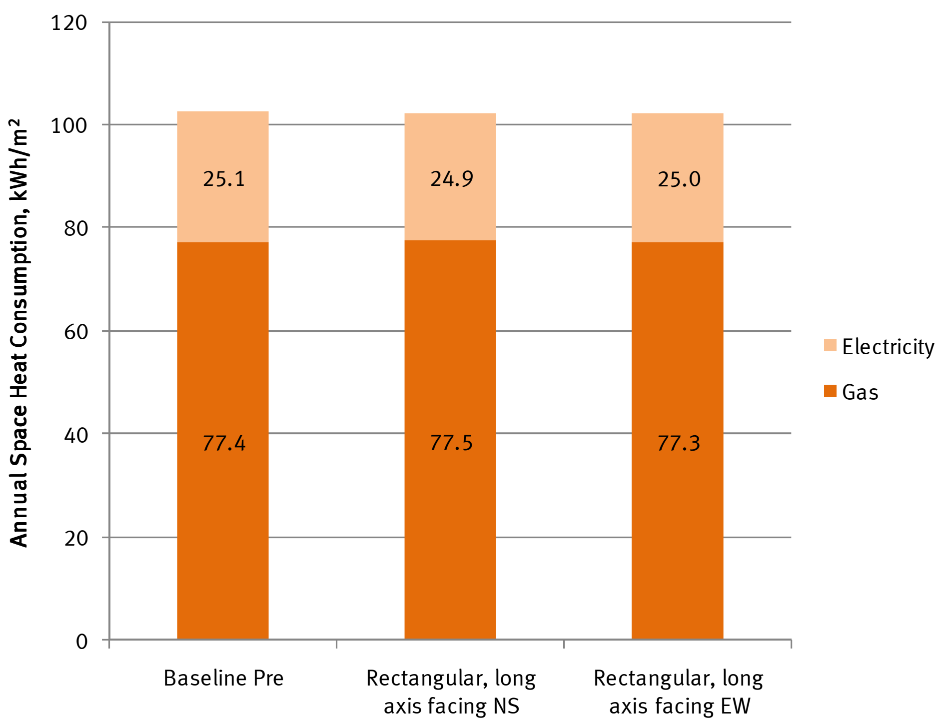


Fig. 7.2.4.16 Gas and electric space heat consumption for pre-rehabilitation building shape and orientation simulations.

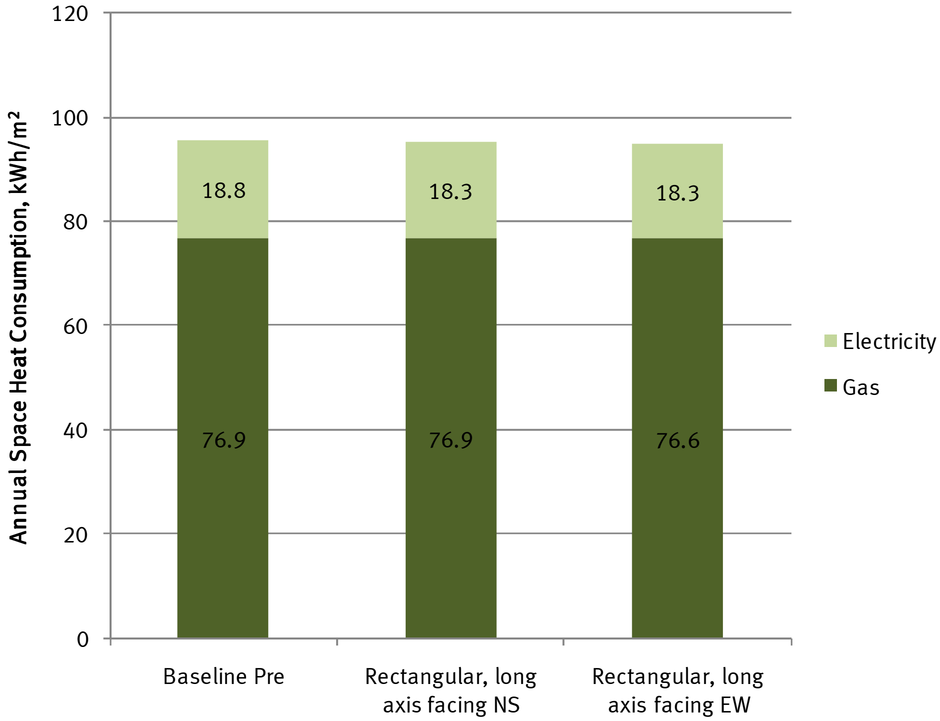


Fig. 7.2.4.17 Gas and electric space heat consumption for post-rehabilitation building shape and orientation simulations.

The Impact of Window to Wall Ratio

Energy simulations were performed to assess the impact of modifying only the window to wall ratio on space heat energy consumption. Window to wall ratios between 20% and 90% were simulated in 10% increments. Table 7.2.22 shows the overall effective R-value for each window to wall ratio scenario that was simulated with the pre- and post-rehabilitation wall R-values, calculated using area weighting. The difference between the pre- and post- simulations are that the post scenarios include the upgraded roof R-value, window U-value and window SHGC.

Table 7.2.22 Overall effective enclosure R-values for different window to wall ratios.

Window to Wall Ratio	Pre-Rehabilitation Effective R-Value	Post-Rehabilitation Effective R-Value
Baseline (46%)	2.1	3.0
20%	2.8	4.0
30%	2.5	3.6
40%	2.2	3.2
50%	2.0	2.9
60%	1.9	2.6
70%	1.7	2.4
80%	1.6	2.3
90%	1.5	2.1

Table 7.2.23 and Fig. 7.2.4.18 show the annual space heating energy consumption of each scenario that was simulated. Fig. 7.2.4.19 and Fig. 7.2.4.20 show the gas and electrical consumption for the pre- and post-rehabilitation window to wall ratio simulations, respectively. The baseline pre- and post- space heat consumption is 102.4 kWh/m^2 and 95.6 kWh/m^2, respectively. The scenario results show that reducing the window to wall ratio to 20% lowers space heat consumption by 2.5% in the pre-rehabilitation building and 5.1% in the post-rehabilitation building. Increasing the window to wall ratio to 90% raises space heat consumption by 1.8% in the

pre-rehabilitation building and 5.7% in the post-rehabilitation building. The window to wall ratio has a greater impact in the post-rehabilitation simulations since the post-rehabilitation U-value is better (lower).

Table 7.2.23 Impact of window to wall ratio on annual space heat consumption.

Window to Wall Ratio	Annual Space Heat Consumption		Typical Building Space Heat Savings from Baseline
	kWh	kWh/m²/yr	
Pre-Rehabilitation			
Baseline Pre (46%)	1,160,724	102.4	-
20%	1,131,499	99.9	2.5%
30%	1,144,803	101.0	1.4%
40%	1,155,542	102.0	0.4%
50%	1,163,880	102.7	-0.3%
60%	1,169,916	103.2	-0.8%
70%	1,176,895	103.9	-1.4%
80%	1,179,793	104.1	-1.6%
90%	1,182,002	104.3	-1.8%
Post-Rehabilitation			
Baseline Post (46%)	1,083,323	95.6	-
20%	1,027,630	90.7	5.1%
30%	1,051,696	92.8	2.9%
40%	1,072,205	94.6	1.0%
50%	1,090,491	96.2	-0.7%
60%	1,106,489	97.7	-2.1%
70%	1,120,183	98.9	-3.4%
80%	1,132,116	99.9	-4.5%
90%	1,144,582	101.0	-5.7%

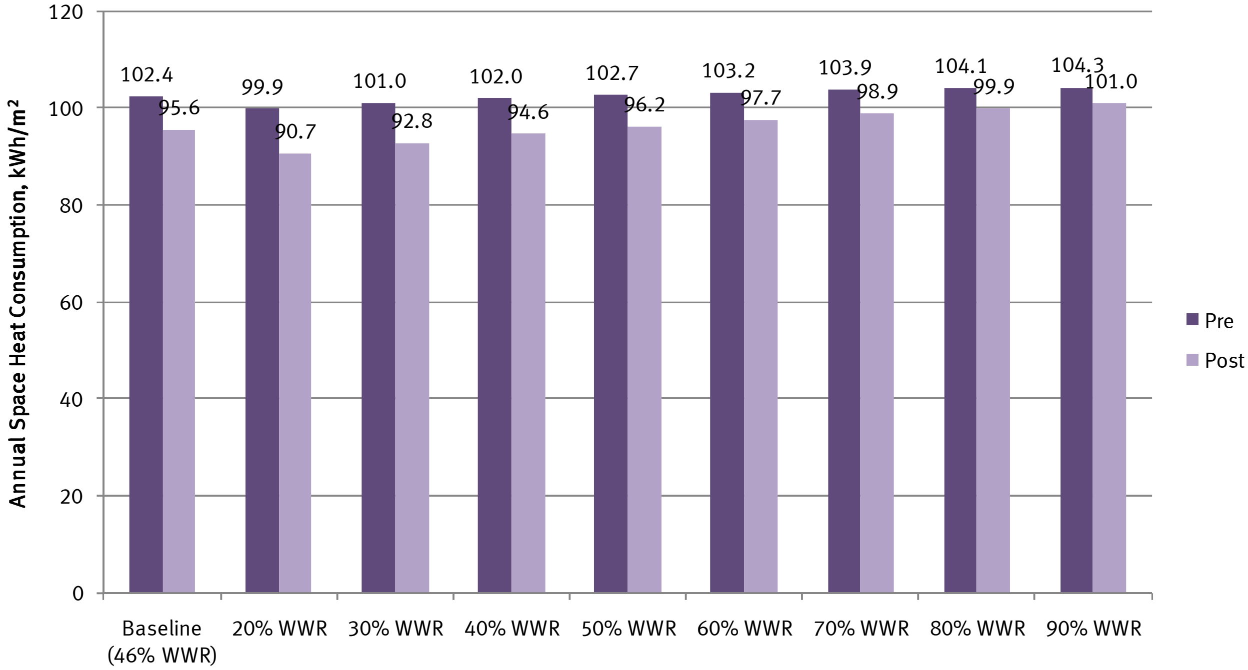


Fig. 7.2.4.18 Impact of window to wall ratio on annual space heat consumption (ventilation and electric baseboards).

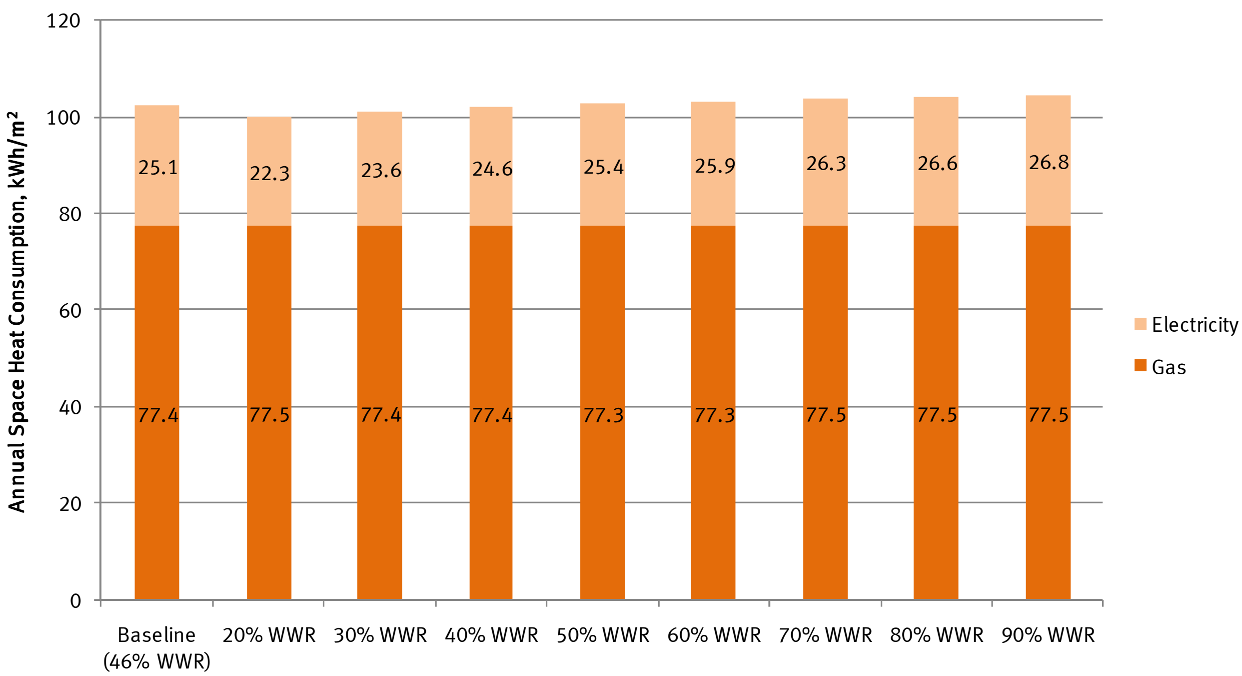


Fig. 7.2.4.19 Gas and electrical consumption for pre-rehabilitation window to wall ratio simulations.

Fig. 7.2.4.20 Gas and electrical consumption for post-rehabilitation window to wall ratio simulations.

To show the impact of varying the window to wall ratio when the building has a higher performance enclosure, the window to wall ratio was varied in the "good" scenario that was established in the previous section. This building was simulated with an overall enclosure R-value of R-10, windows with a U-value of 0.27 and a solar heat gain coefficient of 0.3, a low airtightness of 0.05 cfm/sf (0.191 ACH) and a make-up air temperature of 64°F (18°C). Simulations were completed with and without fireplaces to determine the energy impact on the electrical space heat consumption.

Table 7.2.24, Fig. 7.2.4.21 and Fig. 7.2.4.22 show the simulation results. These results show a clear relationship between window to wall ratio and heating energy consumption. A 20% window to wall ratio in the scenario without fireplaces has 7.2% lower space heat consumption, while a 90% window to wall ratio in the scenario without fireplaces has a 10% greater space heat consumption.

Table 7.2.24 Impact of window to wall ratio on annual space heat consumption for a "good" building.

Window to Wall Ratio	Annual Space Heat Consumption		Typical Building Space Heat Savings from Baseline
	kWh	kWh/m²/yr	
"Good" Simulation, With Fireplaces			
Baseline (46%)	763,778	67.4	-
20%	736,026	65.0	3.6%
30%	745,548	65.8	2.4%
40%	756,994	66.8	0.9%
50%	768,421	67.8	-0.6%
60%	780,237	68.9	-2.2%
70%	792,151	69.9	-3.7%
80%	803,766	70.9	-5.2%
90%	815,020	71.9	-6.7%
"Good" Simulation, Without Fireplaces			
Baseline (46%)	433,194	38.2	-
20%	401,917	35.5	7.2%
30%	414,350	36.6	4.4%
40%	426,389	37.6	1.6%
50%	437,623	38.6	-1.0%
60%	448,251	39.6	-3.5%
70%	458,128	40.4	-5.8%
80%	467,146	41.2	-7.8%
90%	475,487	42.0	-9.8%

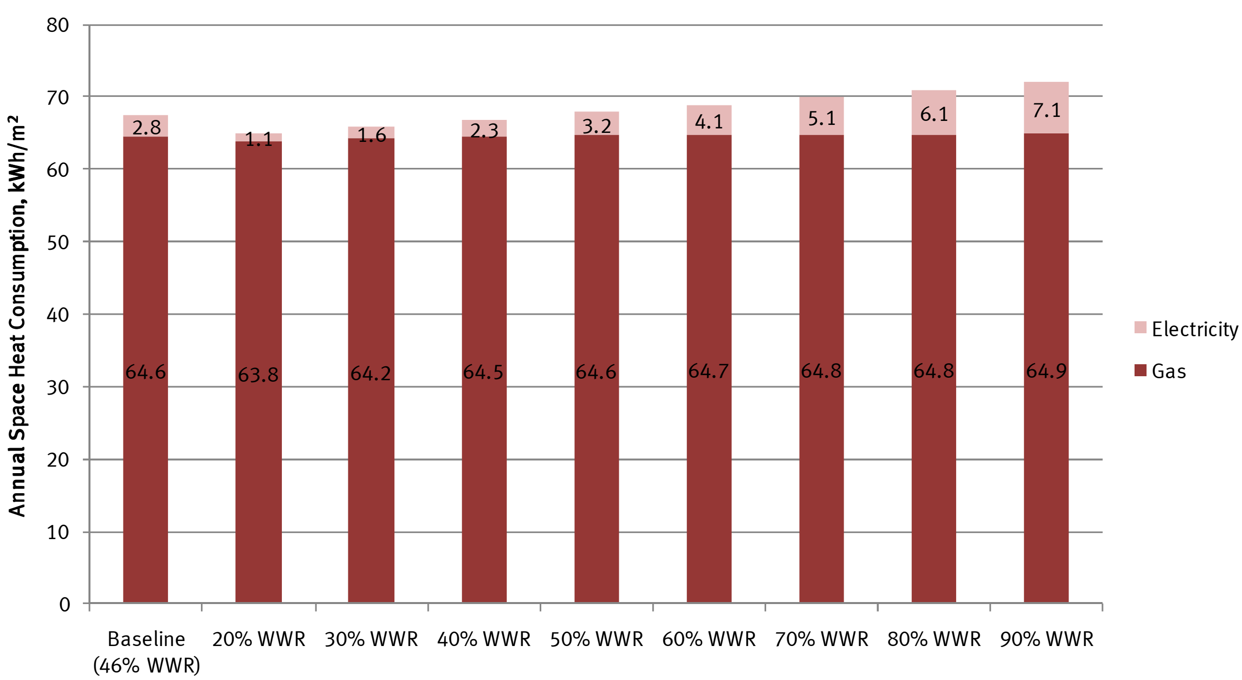


Fig. 7.2.4.21 Space heat energy consumption of "good" scenario with fireplaces, varying the window to wall ratio.

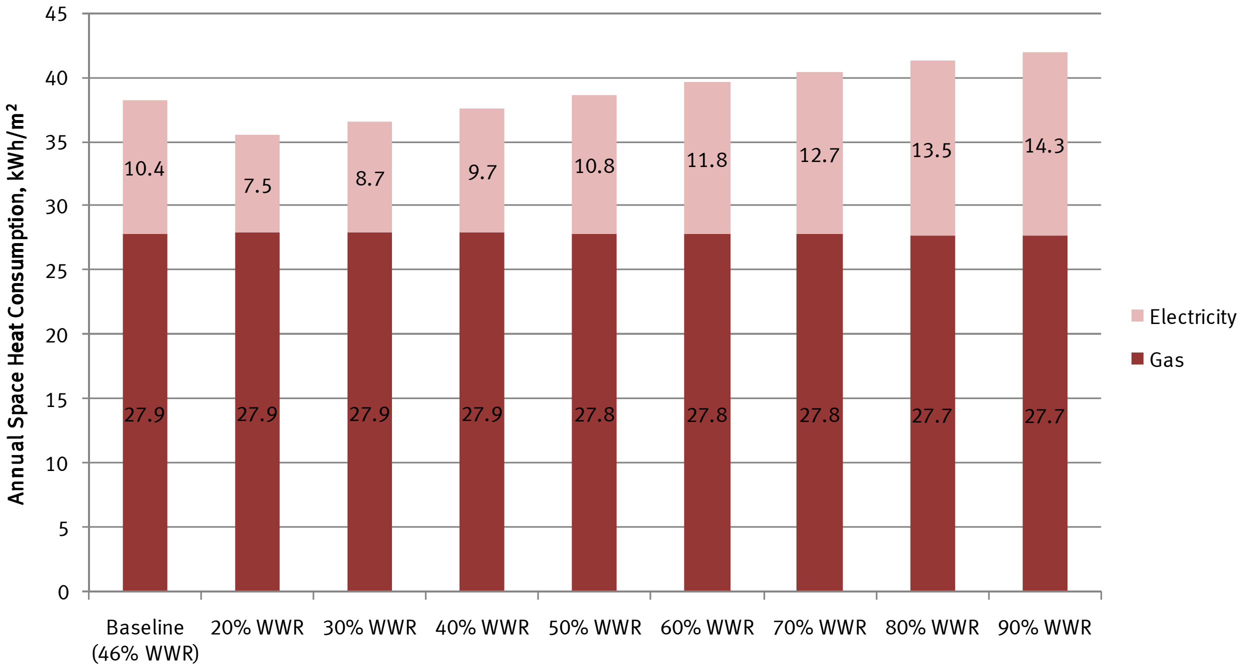


Fig. 7.2.4.22 Space heat energy consumption of "good" scenario without fireplaces, varying the window to wall ratio.

The Impact of Varying Make-Up Air Flow Rate with Airtightness

Air flows and stack pressure throughout a MURB over the course of a year are complex and not well understood. It is hypothesized that changing the airtightness of the building may impact the make-up air flow rate due to pressure changes within the primary make-up air duct. This may create better or worse than expected energy performance when the airtightness is increased or decreased.

A series of simulations were performed where the make-up air flow rate decreases as airtightness decreases. It was assumed that at a leaky rate the make-up air system operates at 100% of its rated air flow capacity, and at a tight rate, the make-up air system operates at 80% of its rated air flow capacity. Values in between were scaled linearly using the leaky and tight endpoints. Further research is needed to set these parameters.

Fig. 7.2.4.23 shows the resulting space heat energy consumption of the simulations. For reference, Fig. 7.2.4.24 shows the original plot of varying airtightness while make-up air flow rate remains constant. The simulations show that if make-up air flow rate does change with airtightness, greater than expected energy savings result from improving airtightness (but also less ventilation air flow is delivered). If the building becomes more leaky, for example if windows are often left open, energy consumption will increase beyond the expected air leakage increase due to a higher make-up air flow rate.

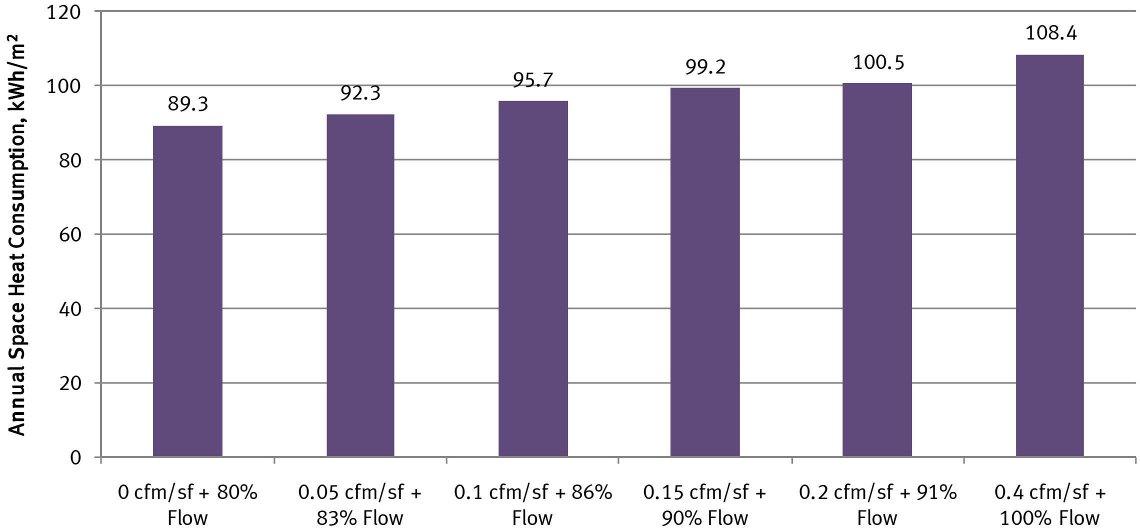


Fig. 7.2.4.23 Space heat energy consumption of varying make-up air flow rate with airtightness.

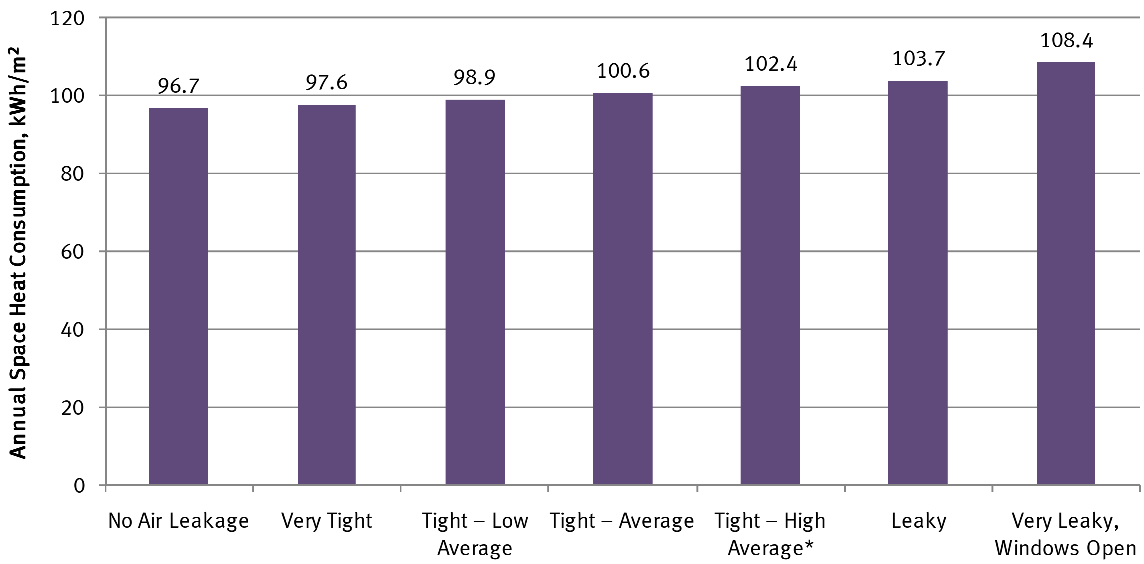


Fig. 7.2.4.24 Space heat energy consumption of varying airtightness while make-up air remains constant.

Further research is necessary to determine the effect of airtightness on make-up air flow.

The Impact of Geographic Location

The typical pre-rehabilitation simulation was run for cities across Canada to determine the energy impact of geographic location on the archetypical MURB. It is known that MURBs may be constructed differently and have different HVAC systems in colder climates, however, the analysis was performed to show the mildness of the Vancouver climate analysis and energy consumption potential within other climate zones.

In addition to Vancouver, the simulation was run for Calgary, Edmonton, Winnipeg, Toronto, Ottawa, Montreal, Halifax, St. John's and Whitehorse. Table 7.2.25 and Fig. 7.2.4.25 shows the resulting space heat energy consumption for other Canadian cities, and Fig. 7.2.4.26 shows the total annual energy consumption. Being in the most temperate climate, Vancouver has the lowest space heat consumption of the cities simulated. The next highest space heat consumption from Vancouver is Toronto, which has 18% (18.5 kWh/m^2) higher space heat consumption than Vancouver. The city with the highest consumption, Whitehorse, has 56% (57.5 kWh/m^2) higher space heat consumption than Vancouver.

Table 7.2.25 Space Heat Energy Savings Potential for Simulated Pre-Rehabilitation Buildings Across Canada.

Location	Space Heat Consumption, kWh	Space Heat Consumption, kWh/m^2	% Space Heat Difference from Vancouver
Vancouver	1,160,724	102.4	-
Calgary	1,490,020	131.5	+28.4%
Edmonton	1,591,570	140.5	+37.1%
Winnipeg	1,640,181	144.8	+41.3%
Toronto	1,369,412	120.9	+18.0%
Ottawa	1,462,666	129.1	+26.0%
Montreal	1,466,274	129.4	+26.3%
Halifax	1,409,500	124.4	+21.4%
Whitehorse	1,812,174	159.9	+56.1%

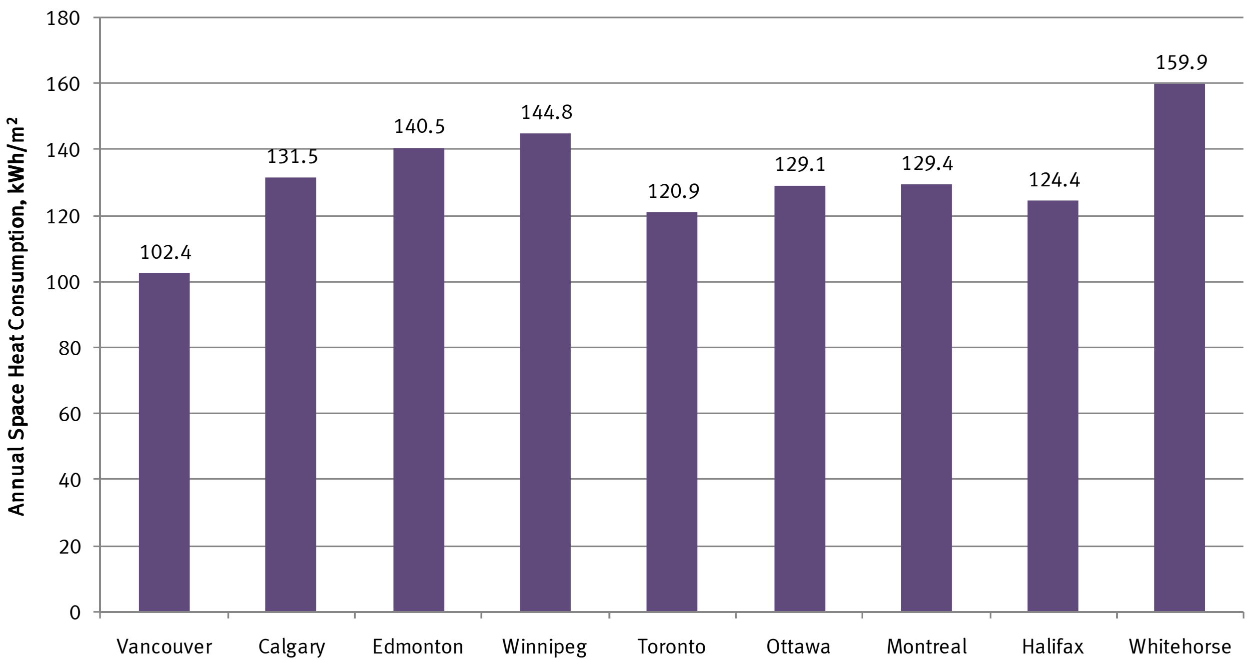


Fig. 7.2.4.25 Space heat consumption for locations across Canada.

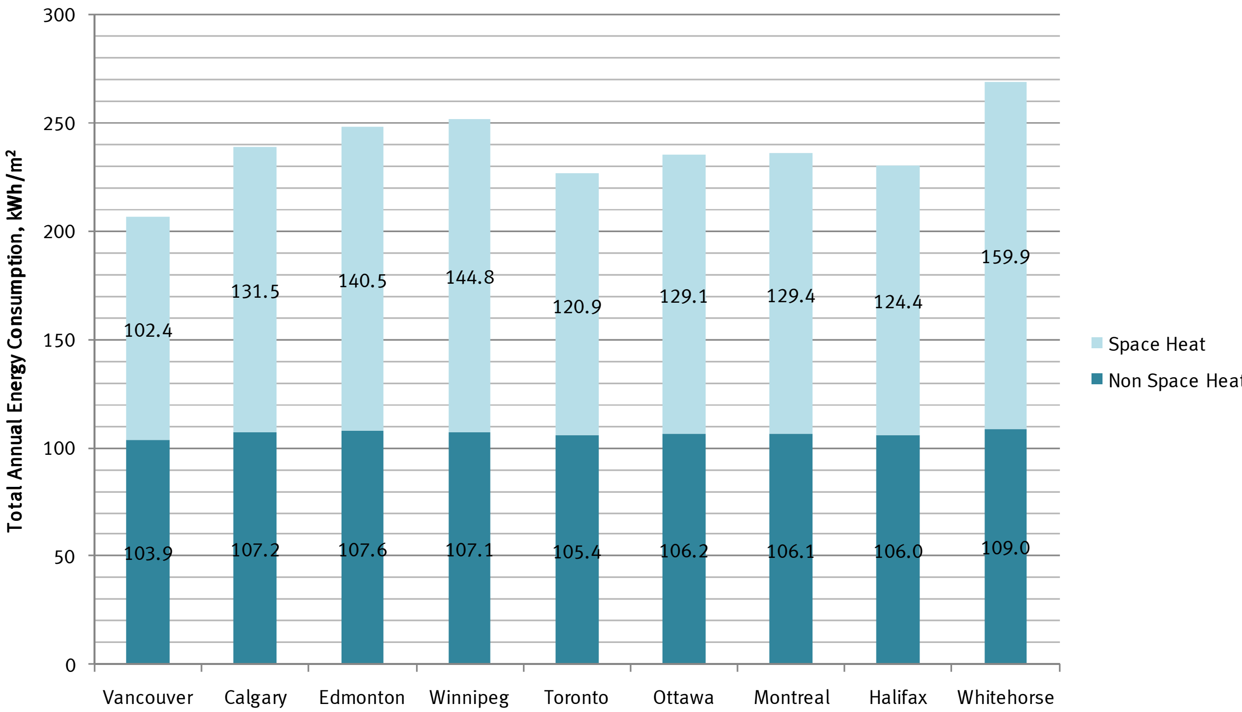


Fig. 7.2.4.26 Total annual energy consumption for locations across Canada (for simulated buildings without cooling).

The Impact of Hydronic versus Electric Space Heating

There are two common suite space heating systems in existing MURBs: hydronic radiators and electric baseboards. Of the 13 study buildings that were simulated, one building had hydronic radiators and the remaining twelve buildings had electric baseboards. The typical building was simulated with hydronic radiators and electric baseboards to view the difference in energy consumption between the two systems. The systems were assumed to have the same baseboard heating output capacity (3.0 Btu/sf). Two hydronic scenarios were simulated: one using a boiler efficiency typical of older, existing systems and one using a high efficiency boiler typical of new installations. The boiler efficiency for the old hydronic system was assumed to be the same as the efficiency of the boiler in the typical building (77%), and the efficiency of the new system was assumed to be a 95% efficient condensing boiler. The actual efficiency varies seasonally and is calculated by the program.

Fig. 7.2.4.27 shows the gas and electrical consumption for the three systems. The suite space heating consumption (not including gas make-up air) of the electric system is 29.1 kWh/m^2 while the consumption of the old gas system is 38.7 kWh/m^2 and the consumption of the new gas system is 29.9 kWh/m^2. The electric system consumes 9.6 kWh/m^2 less energy than an existing hydronic system. A modern efficient hydronic system consumes 0.8 kWh/m^2 more energy than the electric baseboard system.

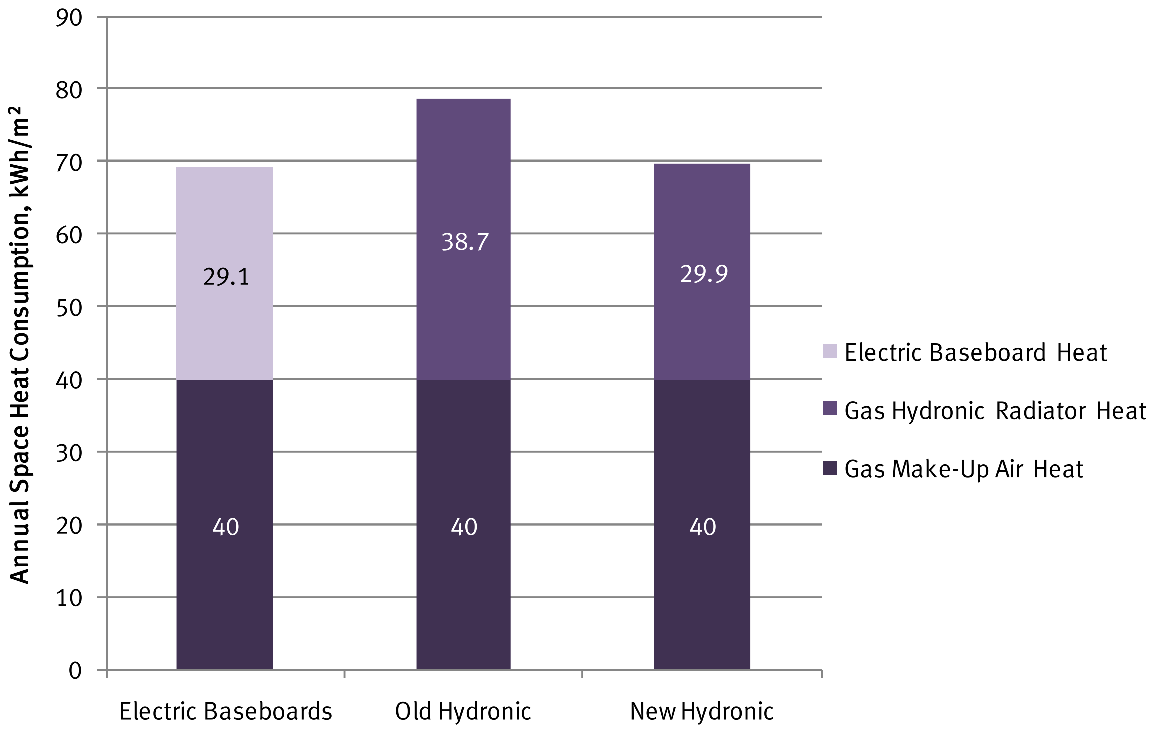


Fig. 7.2.4.27 Space heat energy consumption for gas and electric heating systems.

An important factor in comparing gas and electrical consumption is site and source energy. The energy consumption values discussed in this study are all site energy; that is, energy consumed at the building. Source energy is the actual energy consumption required to deliver the required site energy to the building. Source energy includes energy lost in production and transmission.

The ratio of site to source energy is different for gas and electricity. The average ratio of source energy to site energy for natural gas is 1.09 (Deru and Torcellini 2007). In other words, 1.09 GJ of energy is required to deliver 1 GJ of gas at the building. Electrical site to source ratios vary for different geographical areas, depending on how the electricity is produced. In British Columbia, the majority of electricity is hydroelectric, which has a low source to site ratio. Other methods of electricity generation include nuclear, coal, fossil fuels, and renewables (such as solar, wind, and tidal power). The average electricity source to site ratio for British Columbia is 1.11. The United States average electricity source to site ratio is 3.315.

Table 7.2.26 shows the corresponding source energy for the electric and hydronic space heating (including only the in-suite space heating portion, and not the make-up air heating). In British Columbia, electric baseboard heating consumes nearly the same amount of source energy as an efficient hydronic heating system. However, source energy calculated using the United States average source to site ratio shows that gas heating has a much lower energy impact than electric heating in many regions.

Table 7.2.26 Site and source energy for electric and gas heated buildings.

Scenario	Site In-Suite Space Heat Consumption, kWh/m²	BC Source In-Suite Space Heat Consumption, kWh/m²	US Average Source In-Suite Space Heat Consumption, kWh/m²
Electric Baseboards	29.1	32.3	96.6
Old Hydronic Radiators	38.7	42.2	42.2
New Hydronic Radiators	29.9	32.6	32.6

Modern Buildings

The typical building was intended to be representative of the existing stock of mid- to high-rise MURBs. This is slightly different from a typical new MURB that would be designed and constructed in the Lower Mainland. New MURBs tend to be larger than the typical building model, and have slightly better enclosure thermal performance, even with a higher glazing ratio. A typical modern building model was established. This model uses the average post-rehabilitation wall R-value, the average post-rehabilitation window U-value and SHGC (average of double glazed aluminum windows with low-e coating). The floor area, number of suites, and exposed wall area were determined by taking the typical gross suite area and scaling to 30 storeys, more representative of new, higher buildings in Vancouver. The make-up air flow rate was assumed to be the same as in Building 39, 0.1 cfm/sf (equivalent to 126 cfm/suite). The fireplace load per suite remained the same but the total building fireplace load increased since there are more suites in the modern building. Table 7.2.27 shows the inputs for the modern building model that are different from the original typical building model.

Table 7.2.27 Typical modern building simulation inputs.

Total Floor Area	193,720	ft²
Number of Suites	154	
Number of Storeys (above grade)	30	
Gross Exposed Wall Area, Wall 1	24,360	ft²
Gross Exposed Wall Area, Wall 2	24,360	ft²
Gross Exposed Wall Area, Wall 3	24,360	ft²
Gross Exposed Wall Area, Wall 4	24,360	ft²
Window Percentage, Wall 1	50%	
Window Percentage, Wall 2	50%	
Window Percentage, Wall 3	50%	
Window Percentage, Wall 4	50%	
Overall Wall R-Value	5.5	°F-ft²-hr/Btu
Overall Window U-Value	0.47	Btu/°F-ft²-hr
Window Shading Coefficient	0.37	
Minimum Outside Air	0.1	cfm/ft²
Minimum Outside Air – Per Suite	*126*	*cfm/suite*
Fireplace Diversified Load	11,242	Mbtuh/yr
Fireplace Load – per suite	*73*	*Mbtuh/yr*

Fig. 7.2.4.28 shows the annual space heat consumption for the typical modern building simulation, compared to the previous typical pre- and post-rehabilitation simulations. Fig. 7.2.4.29 shows the total annual energy consumption for the modern building simulation. The modern building has 37.7 kWh/m² higher space heating consumption than the typical existing pre-rehabilitation building. This increase is largely due to the significantly higher make-up air flow rate simulated in the modern building. Fig. 7.2.4.30 shows the distribution of energy consumption in the modern building simulation. Ventilation heating accounts 39% of total building energy consumption, a much higher portion than the 19% ventilation heating in the typical existing building.

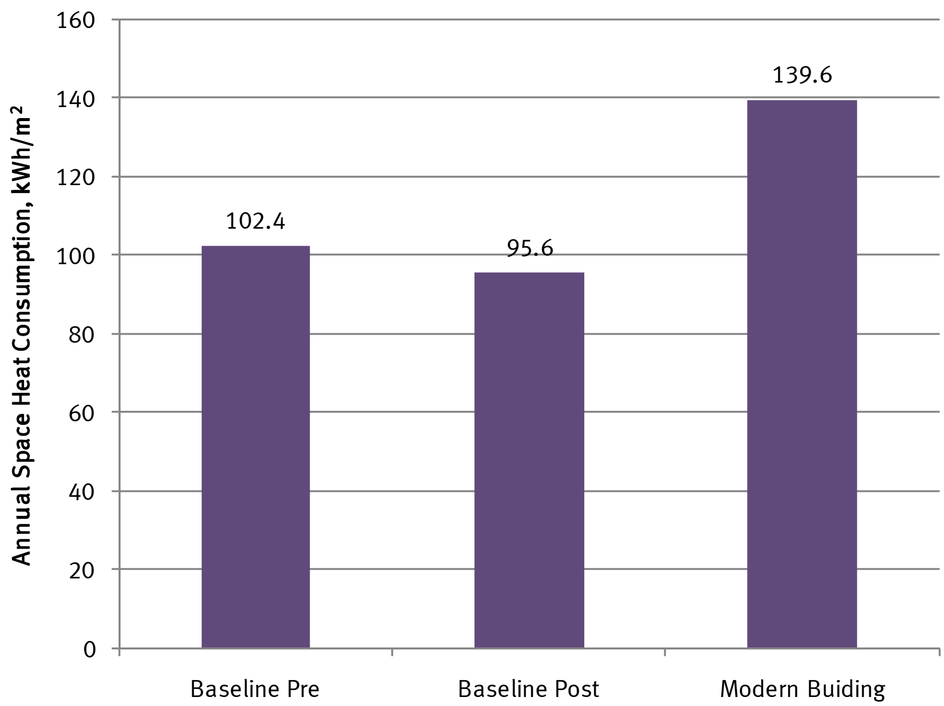


Fig. 7.2.4.28 Space heat energy consumption for typical modern building.

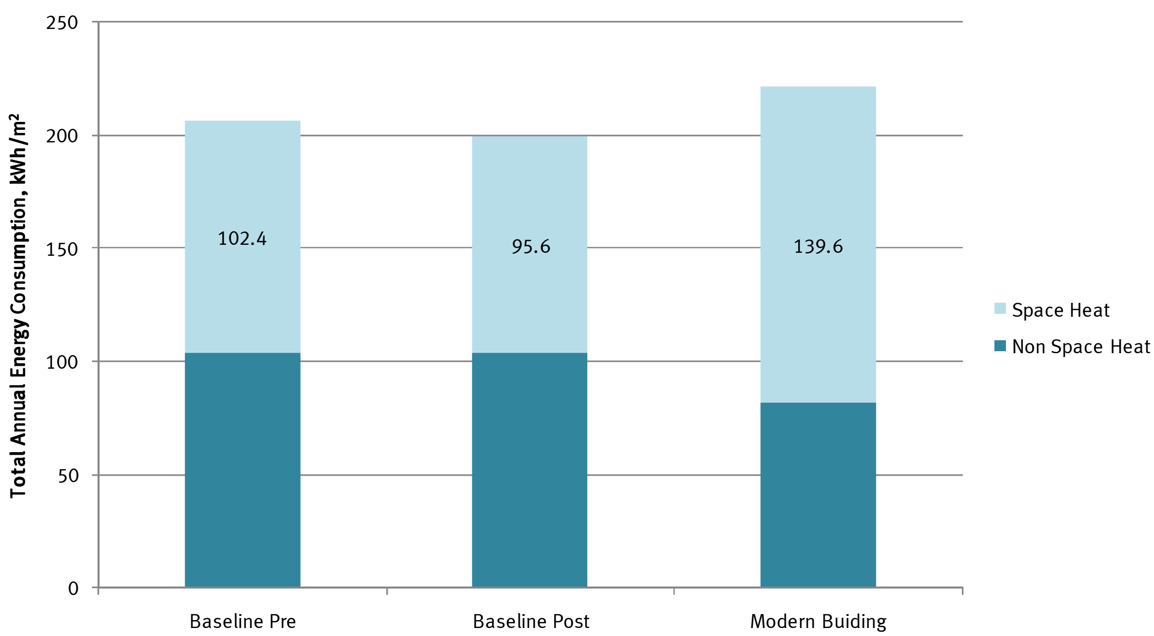


Fig. 7.2.4.29 Total annual energy consumption for typical modern building.

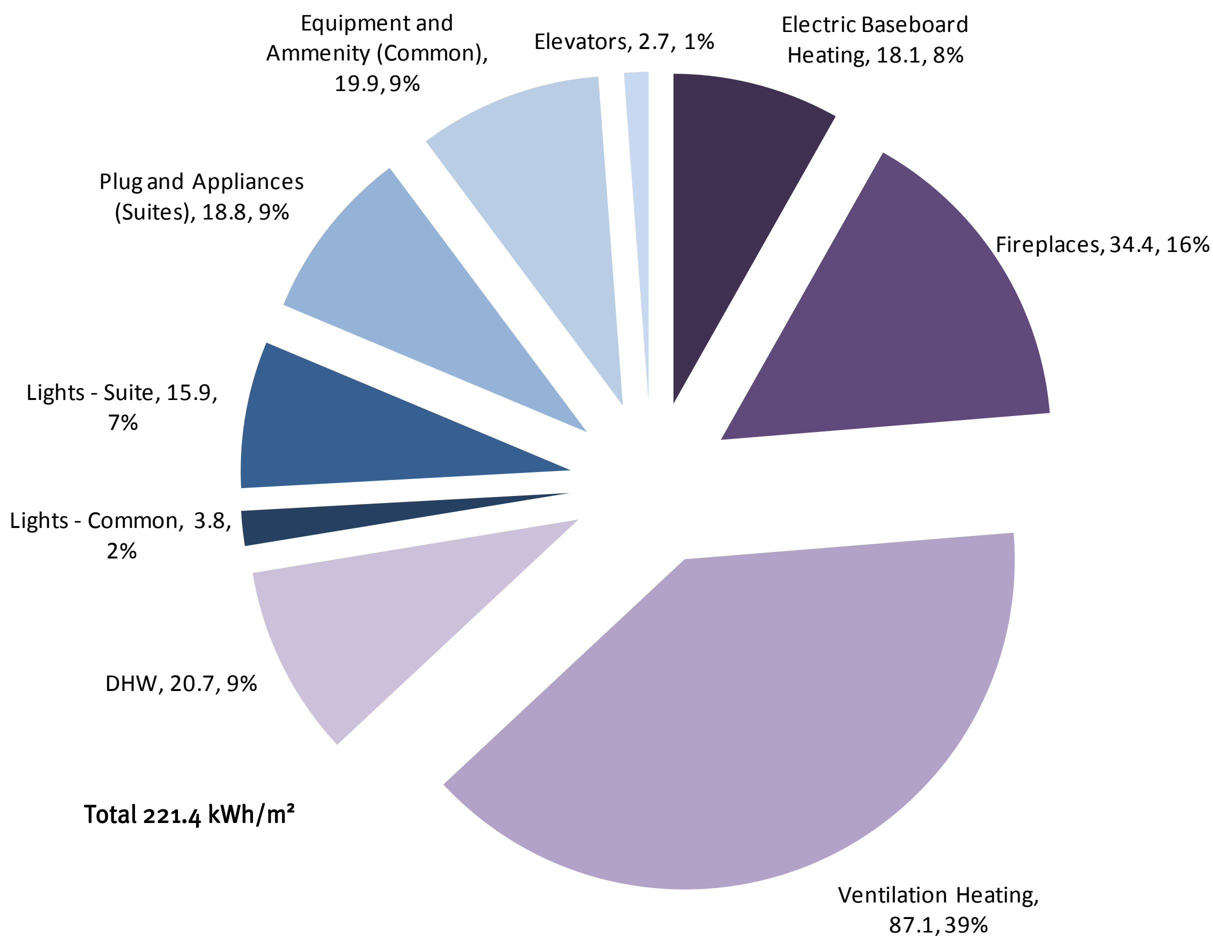


Fig. 7.2.4.30 Distribution of total building energy consumption, kWh/m^2 and percentage of total for modern building.

Impact of Non-Heating Loads on Space Heat Energy Consumption

Internal gains such as lights, plug loads, and DHW pipe losses help offset the space heating load. Simulations were run with these loads removed to see the impact they have on space heating consumption. Fig. 7.2.4.31 and Fig. 7.2.4.32 show the space heat consumption when internal gains are removed. It appears either the program does not account for internal gains from DHW pipe losses, or these losses are insignificant, since the simulation with no DHW resulted in the same energy consumption as the baseline simulation. Removing lights and plug loads from the building increases space heat consumption by 4% (4.6 kWh/m^2). Removing make-up air results in a significant gas savings with only a small increase in electric (in-suite space heating) consumption.

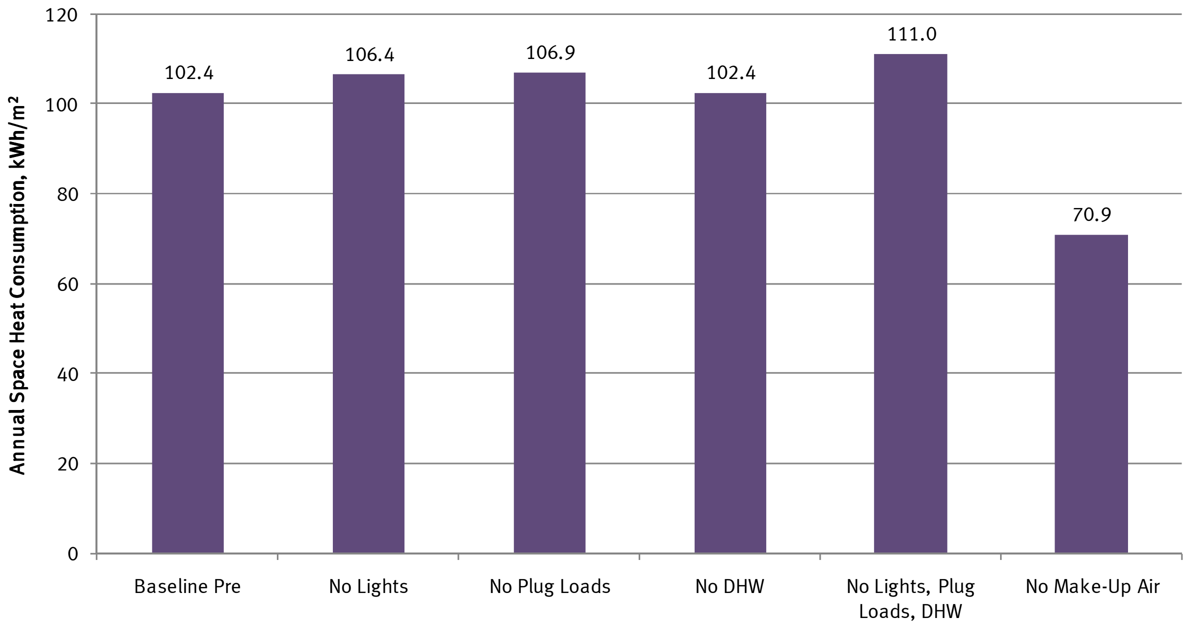


Fig. 7.2.4.31 Space heat consumption when internal gains are removed.

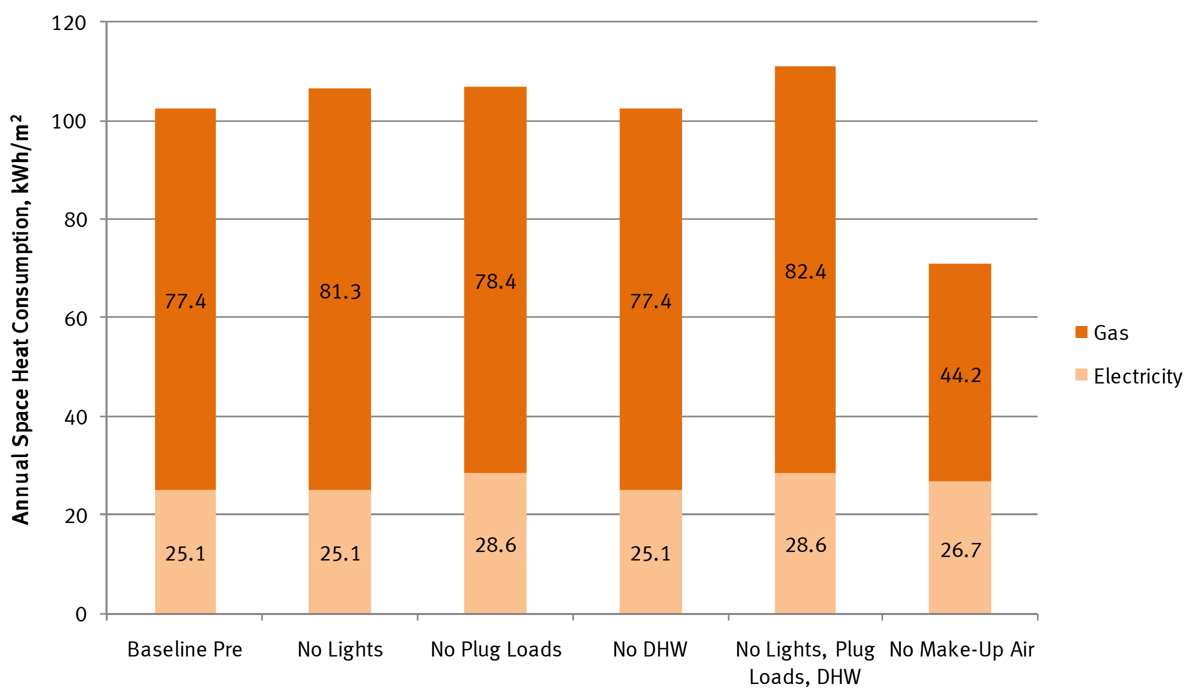


Fig. 7.2.4.32 Gas and electric space heat consumption when internal gains are removed.

The Distribution of Space Heat Loss in Thermally Improved Buildings

The space heat load distribution was simulated for the "good" and "best" building scenarios without fireplaces, with low, average and high air leakage rates. The results of these simulations are shown in Fig. 7.2.4.33 ("good") and Fig. 7.2.4.34 ("best"). These simulations show that an energy efficient building with heat recovery has a more even distribution of conduction, air leakage and ventilation contributing to heating.

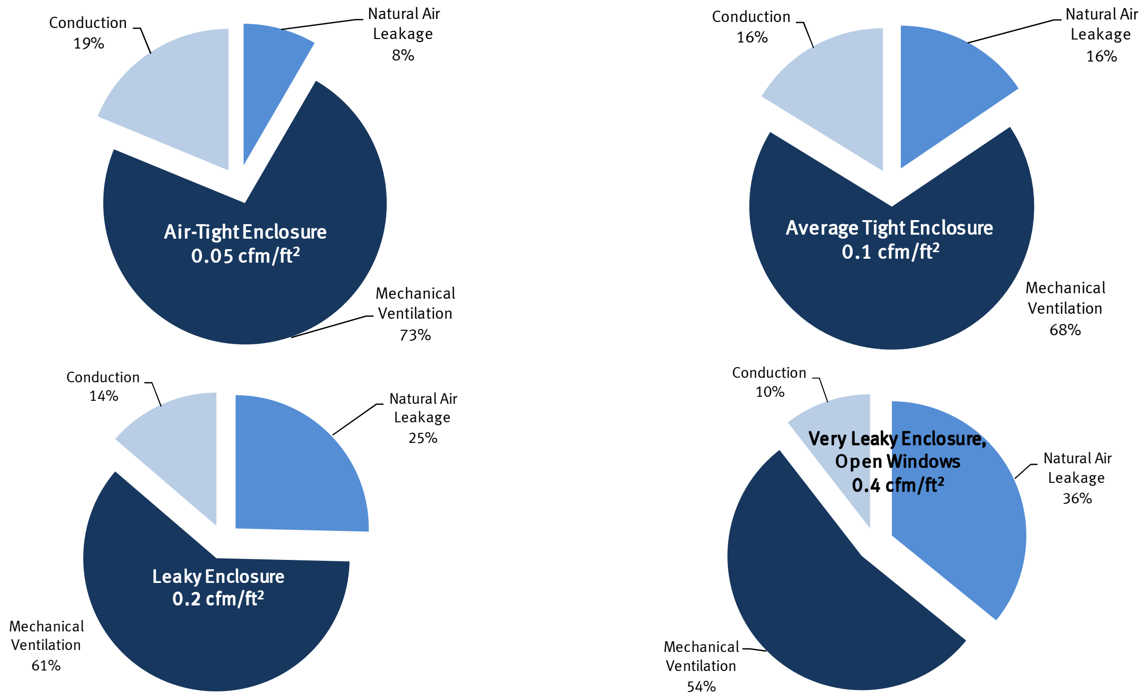


Fig. 7.2.4.33 Estimated Space Heat Loss Distribution for a Range of Potential Airtightness Levels in “good” scenario.

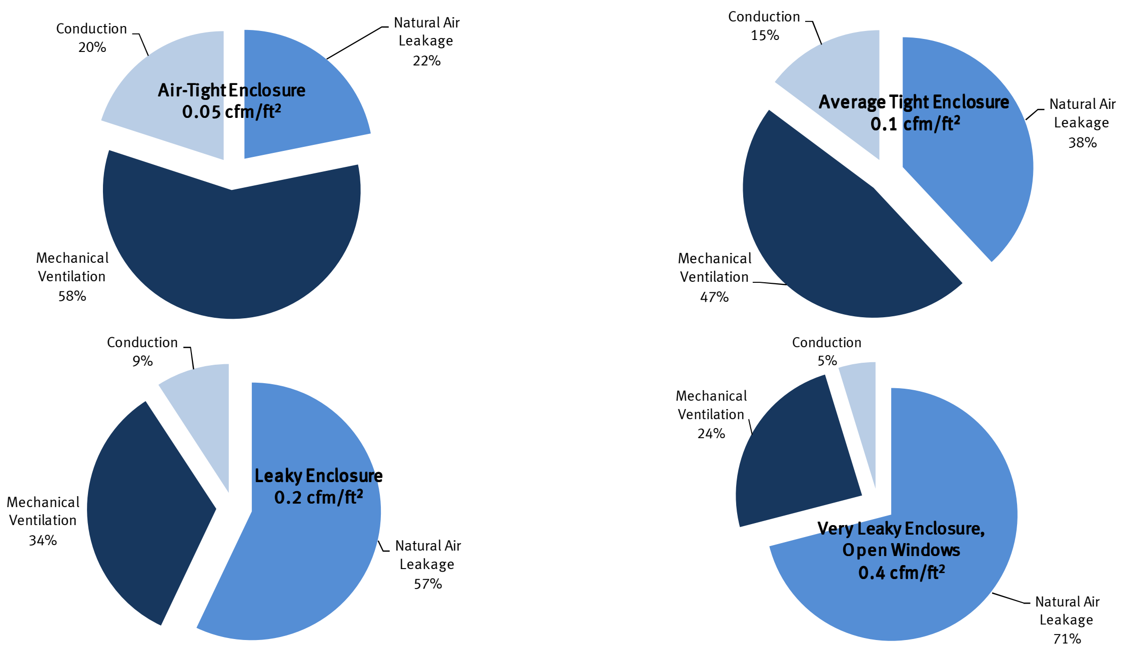


Fig. 7.2.4.34 Estimated Space Heat Loss Distribution for a Range of Potential Airtightness Levels in “best” scenario.

Owner and Strata Energy Consumption

In many MURBs, energy bills are paid partly by the individual suite owners and partly by the Strata Corporation. Suite owners typically pay directly for their suite electrical consumption, while the Strata pays for common electrical consumption and all gas consumption. The Strata-paid energy is paid by the owners as part of their condo fees.

Fig. 7.2.4.35 shows the division of owner and strata total building energy consumption in the typical building simulation; the strata is responsible for 76% of energy consumption while owners are responsible for 29%. Fig. 7.2.4.36 and Fig. 7.2.4.37 show the distribution of consumption within the owner and strata energy, respectively.

Fig. 7.2.4.38 shows the division of owner and strata total building energy consumption in the "best" building simulation; the division is similar for the typical case with strata responsible for 67% of energy consumption while owners are responsible for 33%. Fig. 7.2.4.39 and Fig. 7.2.4.40 show the distribution of consumption within the owner and strata energy, respectively.

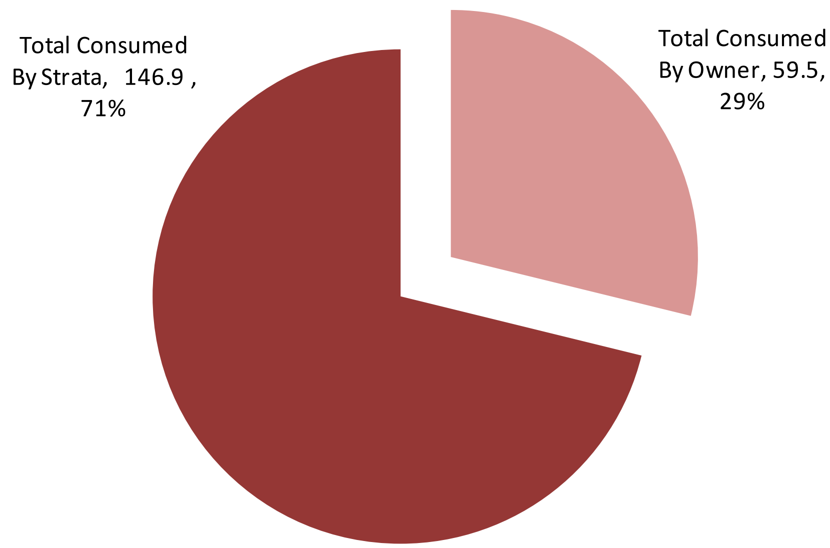


Fig. 7.2.4.35 Distribution of total building energy consumption, between strata and owners, kWh/m^2 and percentage of total in typical building model.

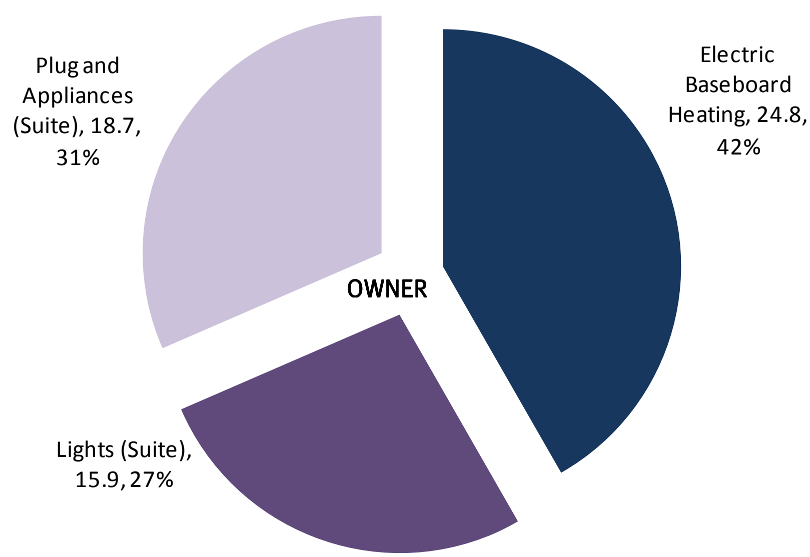


Fig. 7.2.4.36 Distribution of owner building energy consumption, kWh/m^2 and percentage of total in typical building model.

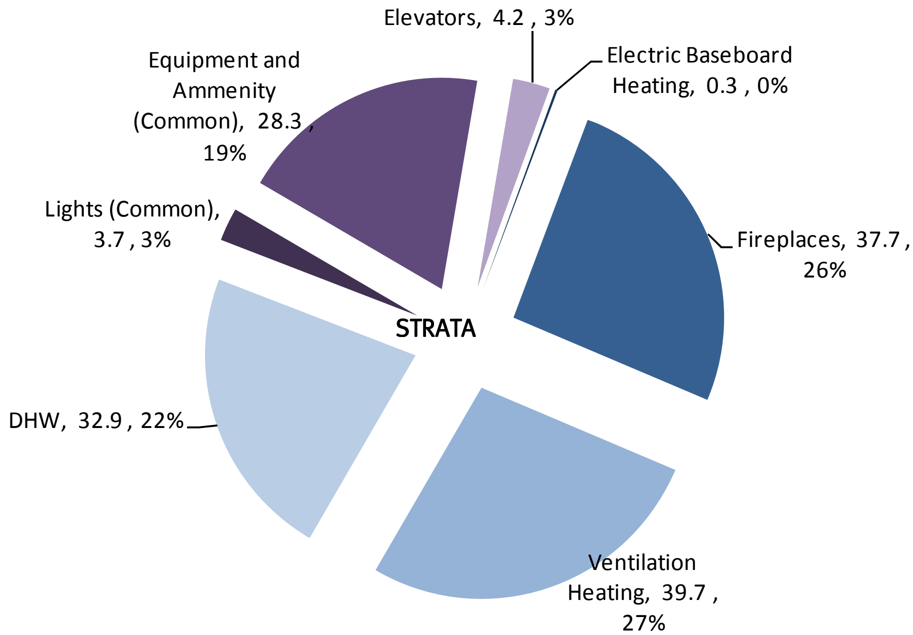


Fig. 7.2.4.37 Distribution of strata building energy consumption, kWh/m² and percentage of total in typical building model.

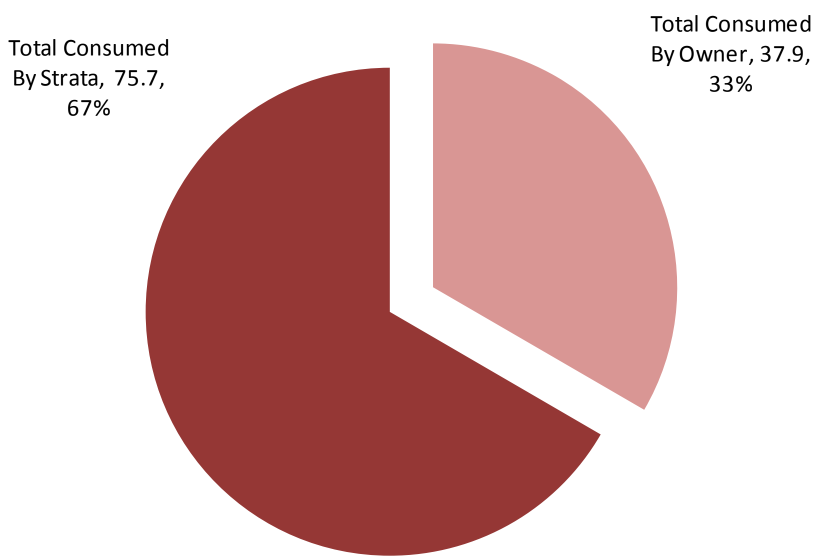


Fig. 7.2.4.38 Distribution of total building energy consumption, between strata and owners, kWh/m² and percentage of total in "best" building simulation.

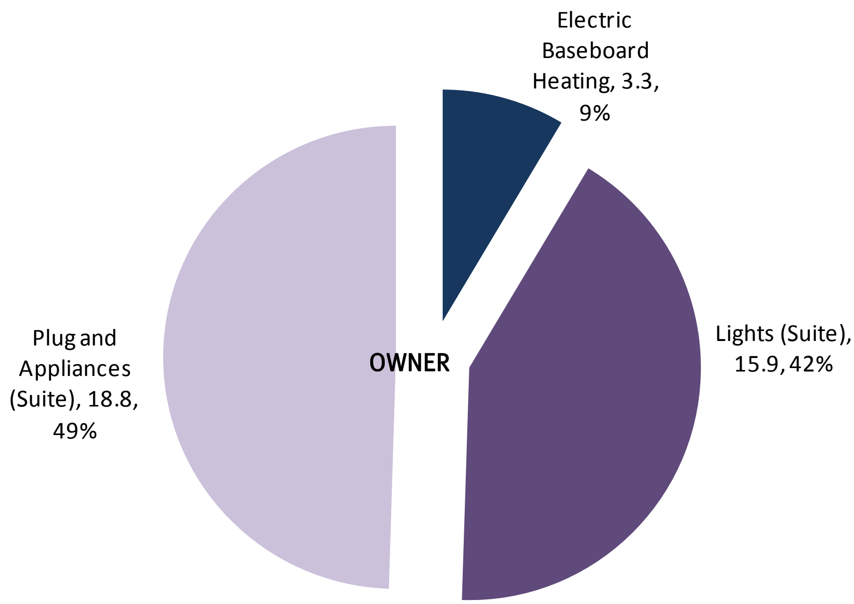


Fig. 7.2.4.39 Distribution of owner building energy consumption, kWh/m^2 and percentage of total in "best" building simulation.

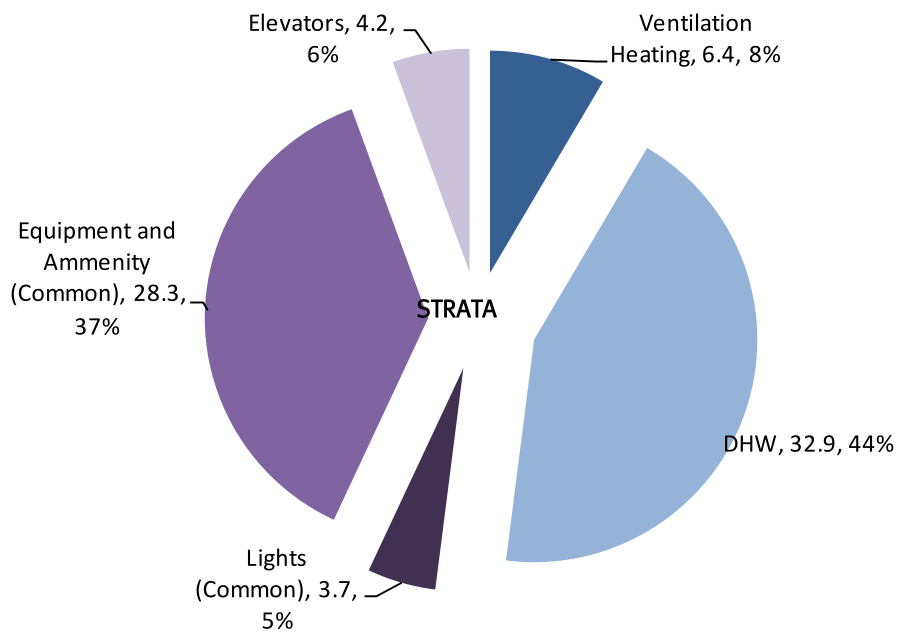


Fig. 7.2.4.40 Distribution of strata building energy consumption, kWh/m^2 and percentage of total in "best" building simulation.

Solar Thermal Domestic Hot Water

To further reduce energy consumption in the building, solar thermal collectors could be installed on the roof to provide solar-heated domestic hot water. A brief analysis was completed to determine the potential energy savings available from solar DHW.

RETScreen was used to determine the amount of solar DHW that could be provided to the typical building. The RETScreen simulation used Sunda Solar Thermal evacuated tube collectors, model Seido 5-16 AS/AB (available in BC through Canadian Solar Technologies). Using the roof area of the typical building and the dimensions of the collectors, the roof can hold about 120 collectors tilted at an angle of 30 degrees. Using weather data for

Vancouver and assuming the collectors face due south, RETScreen predicts 162.7 MWh in heating delivered annually. This represents 44% of the total DHW energy consumption simulated by FAST (total annual DHW energy is 373.3 kWh).

Fig. 7.2.4.41 shows the distribution of energy consumption for the "best" scenario building with solar DHW and without fireplaces. Fig. 7.2.4.42 shows the total annual energy consumption for a number of the simulations, including the "best" scenario with solar DHW and without fireplaces. Note that 44% of the DHW energy is from solar, while the remainder is still gas heated. Equipment and amenity electrical consumption increases by 0.5 kWh/m^2 per year due to the pump power required for the solar DHW system (very small compared to the savings in DHW gas heating consumption).

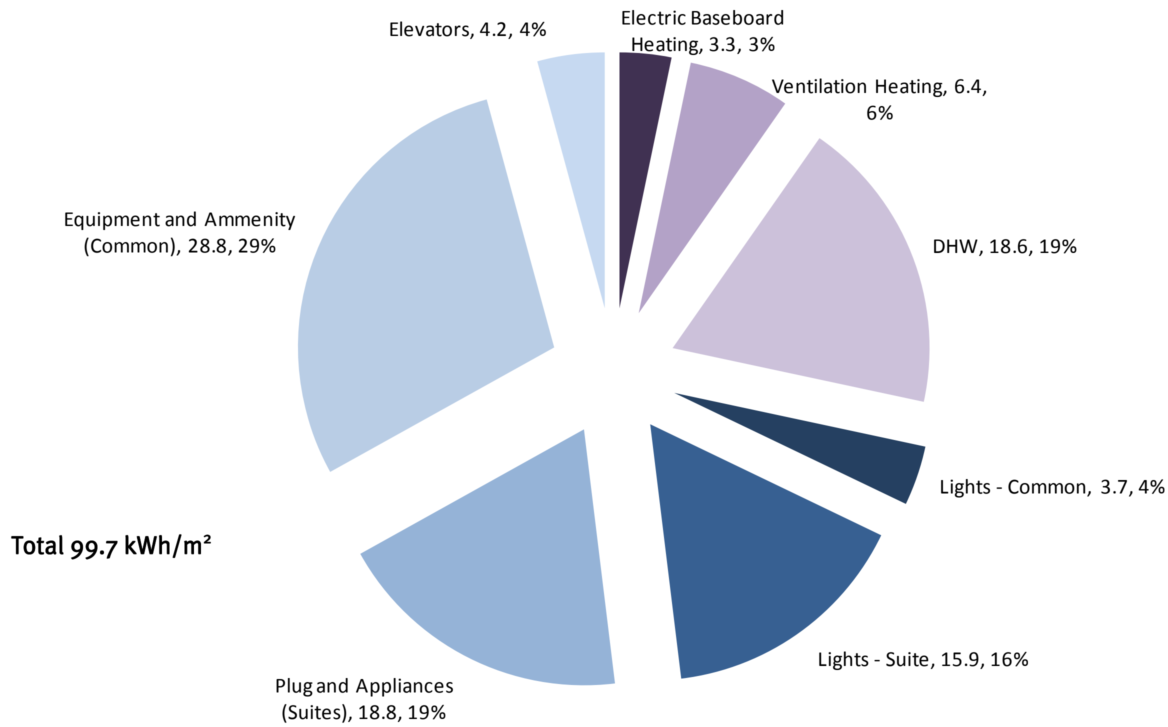


Fig. 7.2.4.41 Distribution of building energy consumption for "best" building with solar DHW and without fireplaces.

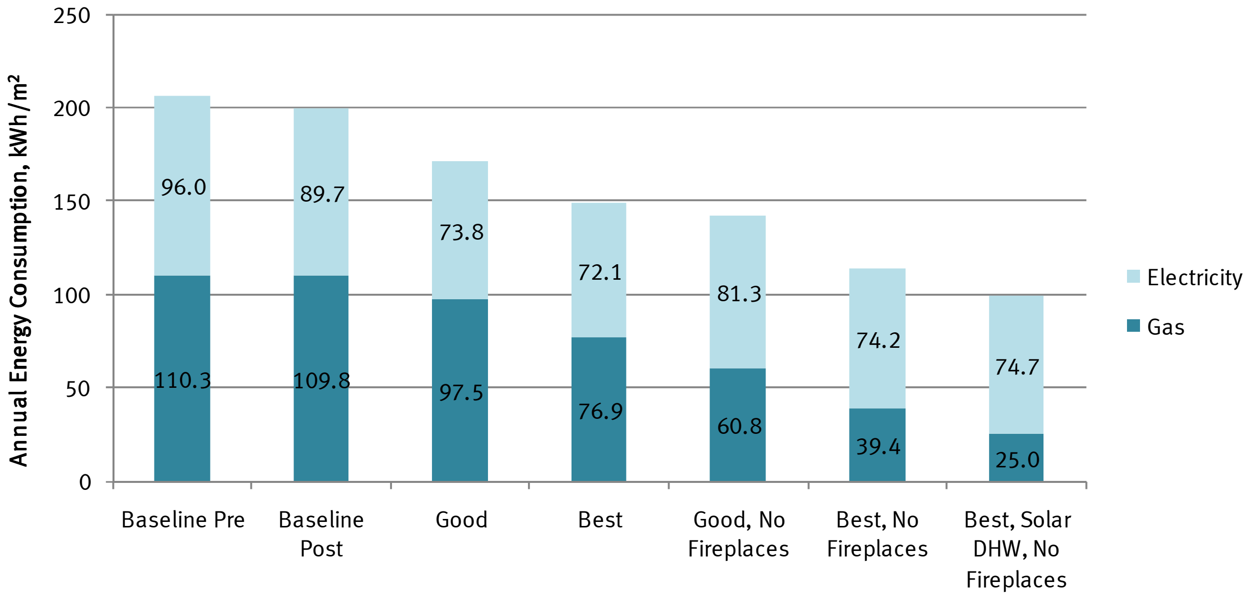


Fig. 7.2.4.42 Annual energy consumption showing "best" scenario with solar DHW.

Energy Consumption vs. Mean Monthly Temperature Plots

Annual gas and electrical energy consumption are plotted versus mean monthly outdoor air temperature to see how energy consumption changes with outdoor air temperature. Fig. 7.2.4.43 shows the plot for the typical building and Fig. 7.2.4.44 shows the plot for the "best" building without fireplaces. In the typical building both gas and electric energy consumption increase with lower outdoor air temperatures. In the "best" building the rate of change is much lower.

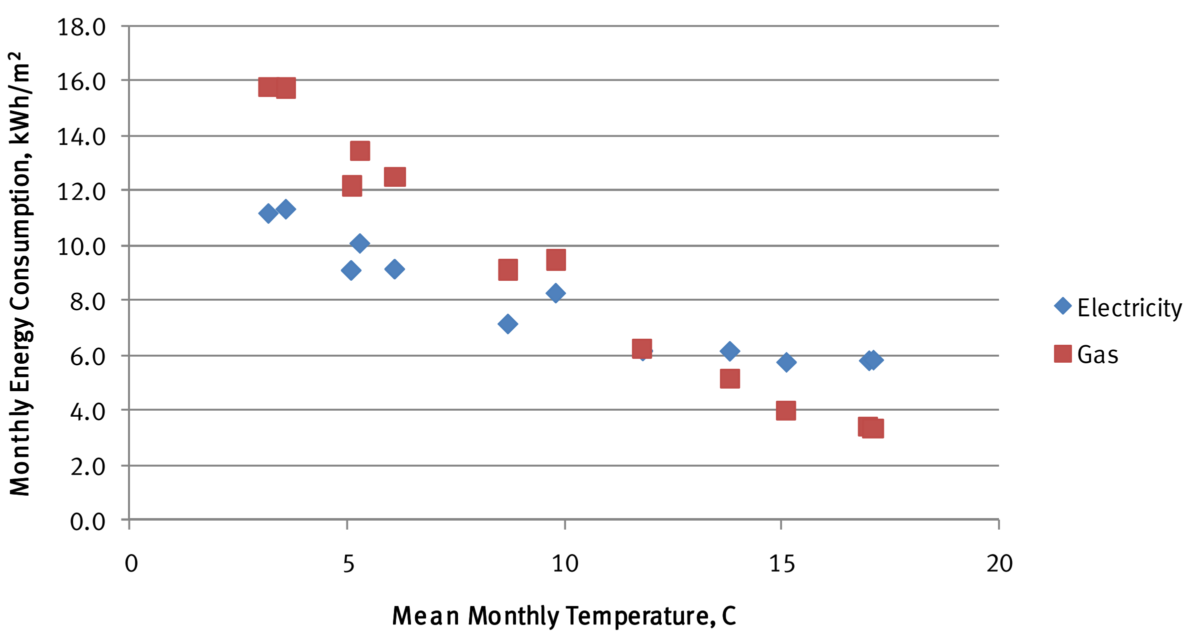


Fig. 7.2.4.43 Annual energy consumption versus mean monthly temperature for typical building.

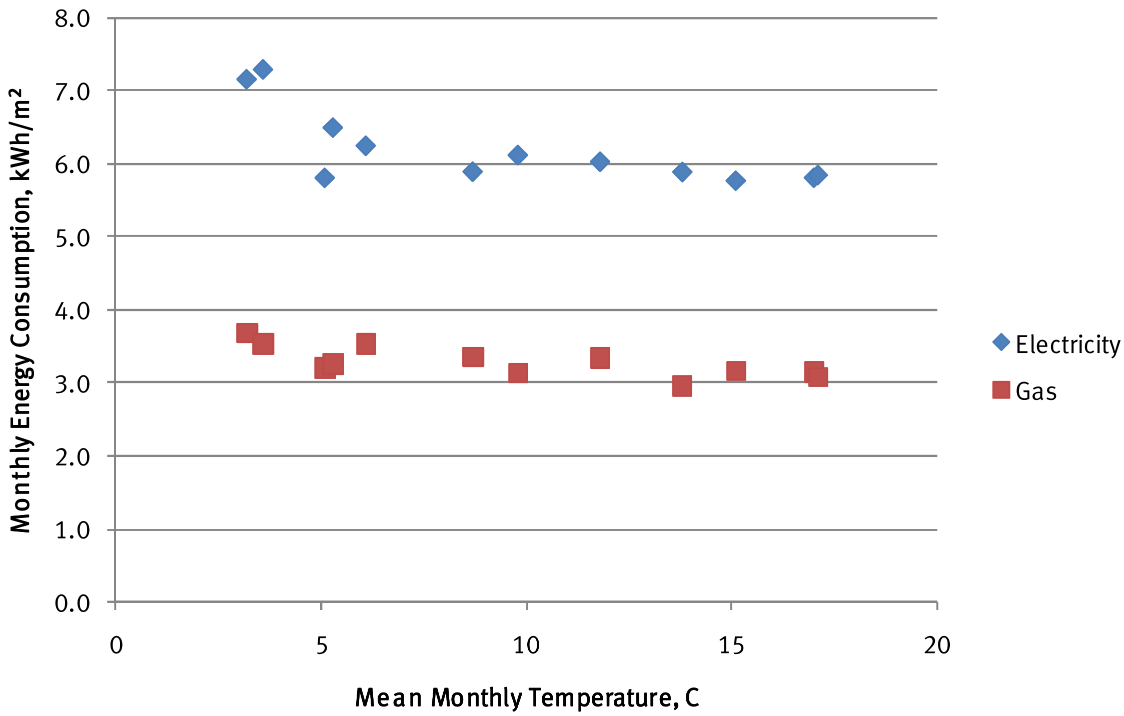


Fig. 7.2.4.44 Annual energy consumption versus mean monthly temperature for "best" building without fireplaces.

7.2.5 Energy Simulations in eQuest

The whole building energy simulations in this study use the DOE2 engine with an interface called FAST, created by EnerSys Analytics, that is customized for multi-unit residential buildings. The computer simulations were also calibrated within FAST so that the simulated output matched actual metered energy consumption data. The DOE2 engine is the most commonly used energy simulation program in industry. Many interfaces have been developed for the DOE2 engine, the most common of which is eQuest, which is available free of charge. The typical building model was simulated using eQuest to determine the differences in the output of the two programs, both of which use the DOE2 engine, and to determine calibrations in eQuest that would be required to match the FAST output.

The typical building was first simulated in eQuest with no ventilation make-up air (electric baseboards only) because this system is easier to simulate in eQuest. Table 7.2.28 and Table 7.2.29 show the electrical and gas consumption simulated in FAST and eQuest. The two simulations have a low percent difference for all end-uses.

A number of calibrations were required in eQuest in order to achieve low percent difference compared to the FAST output. The lighting density, plug load density, miscellaneous loads and domestic hot water flow rate had to be adjusted slightly in eQuest from the input values used in FAST. This is because default schedules were used in both FAST and eQuest, however, the default schedules in these two programs are different. A baseboard capacity had to be applied in eQuest in order to limit space heating, as was done in FAST. The baseboard capacity that gave the same space heat output as FAST was only 7% of the initial, un-calibrated baseboard capacity that eQuest automatically applied.

Table 7.2.28 Simulated Electrical Consumption in FAST and eQuest (MWh).

Month	Heating		Lights		Equipment		Fans		Misc. Loads		Total	
	FAST	EQ	FAST	EQ	FAST	EQ	FAST	EQ	FAST	EQ	FAST	EQ
Jan	62.0	46.9	19.8	19	22.6	21.8	0.03	0.00	26.5	25.6	130.9	113.2
Feb	51.4	41	17.3	16.9	20.4	19.7	0.03	0.00	23.6	23.1	112.7	100.6
Mar	45.9	42.5	18.7	18.5	22.6	21.8	0.03	0.00	25.9	25.6	113.1	108.3
Apr	20.9	33.1	18.1	17.9	21.8	21.1	0.03	0.00	25.0	24.7	85.9	96.8
May	2.5	18.8	18.3	18.8	22.6	21.8	0.03	0.00	25.7	25.6	69.0	85.0
Jun	1.3	5.3	17.7	17.9	21.1	21.1	0.03	0.00	24.9	24.7	64.9	69.0
Jul	1.5	0.6	18.3	18.7	20.2	21.8	0.03	0.00	25.7	25.6	65.6	66.7
Aug	1.3	1.1	18.6	18.6	20.2	21.8	0.03	0.00	25.8	25.6	65.8	67.1
Sep	4.9	15.4	18.1	18	21.8	21.1	0.03	0.00	25.0	24.7	69.9	79.3
Oct	33.8	41	18.8	18.8	22.6	21.8	0.03	0.00	25.9	25.6	101.1	107.2
Nov	55.2	44.8	19.2	18.2	21.8	21.1	0.03	0.00	25.6	24.7	121.9	108.8
Dec	62.3	46.8	19.8	18.7	22.6	21.8	0.03	0.00	26.5	25.6	131.1	112.9
Total	**342.9**	**337.3**	**222.6**	**220.0**	**260.1**	**256.7**	**0.4**	**0.0**	**305.9**	**301.1**	**1,132**	**1,115**
% Difference	1.6%		1.2%		1.3%		100.0%		1.6%		1.5%	

Table 7.2.29 Simulated Gas Consumption in FAST and eQuest (GJ).

Month	Heating		DHW		Total	
	FAST	EQ	FAST	EQ	FAST	EQ
Jan	0	0.0	120	118	144	118
Feb	0	0.0	111	111	133	111
Mar	0	0.0	123	125	146	125
Apr	0	0.0	117	118	137	118
May	0	0.0	117	113	136	113
Jun	0	0.0	110	105	129	105
Jul	0	0.0	109	102	128	102
Aug	0	0.0	106	98	126	98
Sep	0	0.0	102	95	121	95
Oct	0	0.0	108	101	128	101
Nov	0	0.0	108	103	131	103
Dec	0	0.0	114	114	139	114
Total	**0**	**0**	**1,344**	**1,302**	**1,598**	**1,302**
% Diff			3.1%		18.5%	

Make-up air ventilation systems cannot be directly simulated in eQuest as the program does not have the option of simulating a 100% outdoor air system independent of space heating loads (such as conduction and air leakage loads). In order to simulate make-up air, an artificial or “dummy” zone must be created, and outdoor ventilation air is delivered to this zone. The drawback of using this workaround is that the make-up air, which is in reality delivered to the corridors, does not affect the space heating simulated in the suites. That is, lowering the make-up air temperature does not increase suite electric baseboard space heating in the simulation, and raising the make-up air temperature does not decrease suite heating in the simulation.

A simulation of the typical building including make-up air was created in eQuest using this work-around method. The same calibrations applied in the previous simulation (without make-up air) were applied in this simulation. Table 7.2.30 and Table 7.2.31 show the electrical and gas consumption simulated in FAST and eQuest. The two simulations have a low percent difference for all end-uses.

Table 7.2.30 Simulated Electrical Consumption in FAST and eQuest (MWh).

Month	Heating		Lights		Equipment		Fans		Misc. Loads		Total	
	FAST	EQ	FAST	EQ	FAST	EQ	FAST	EQ	FAST	EQ	FAST	EQ
Jan	61.0	46.9	19.8	19	22.6	21.8	1.4	1.20	26.5	25.6	131.2	114.4
Feb	49.0	41	17.3	16.9	20.4	19.7	1.2	1.10	23.6	23.1	111.4	101.7
Mar	43.5	42.5	18.7	18.5	22.6	21.8	1.3	1.20	25.9	25.6	111.9	109.5
Apr	20.2	33.1	18.1	17.9	21.8	21.1	1.2	1.20	25.0	24.7	86.4	98.0
May	2.8	18.8	18.3	18.8	22.6	21.8	1.3	1.20	25.7	25.6	70.6	86.2
Jun	0.3	5.3	17.7	17.9	21.1	21.1	1.3	1.20	24.9	24.7	65.2	70.2
Jul	0.5	0.6	18.3	18.7	20.2	21.8	1.3	1.20	25.7	25.6	65.9	67.9
Aug	0.4	1.1	18.6	18.6	20.2	21.8	1.3	1.20	25.8	25.6	66.2	68.3
Sep	4.8	15.4	18.1	18	21.8	21.1	1.2	1.20	25.0	24.7	71.0	80.5
Oct	32.6	41	18.8	18.8	22.6	21.8	1.3	1.20	25.9	25.6	101.1	108.4
Nov	53.4	44.8	19.2	18.2	21.8	21.1	1.3	1.20	25.6	24.7	121.3	110.0
Dec	61.7	46.8	19.8	18.7	22.6	21.8	1.4	1.20	26.5	25.6	132.0	114.1
Total	**330.2**	**337.3**	**222.6**	**220.0**	**260.1**	**256.7**	**15.4**	**14.3**	**305.9**	**301.1**	**1,134**	**1,129**
% Difference	-2.1%		1.2%		1.3%		7.4%		1.6%		0.4%	

Table 7.2.31 Simulated Gas Consumption in FAST and eQuest (GJ).

Month	Heating		DHW		Total	
	FAST	EQ	FAST	EQ	FAST	EQ
Jan	234	212	120	118	354	330
Feb	187	171	111	111	298	282
Mar	192	176	123	125	315	301
Apr	149	139	117	118	267	258
May	102	105	117	113	219	218
Jun	49	63	110	105	159	168
Jul	30	45	109	102	139	146
Aug	29	41	106	98	135	139
Sep	77	79	102	95	179	173
Oct	145	129	108	101	253	230
Nov	200	180	108	103	308	283
Dec	232	207	114	114	346	321
Total	**1,627**	**1,547**	**1,344**	**1,302**	**2,971**	**2,850**
% Difference	4.9%		3.1%		4.1%	

7.3. Towards More Thermally Efficient and Net Zero Building Enclosures

A series of final energy model simulations are presented which demonstrate the opportunities and potential for the thermal performance of the building enclosure to reduce MURB space heating loads in Vancouver, BC to very low and eventually to levels where onsite power generation can make-up this load (ie a net zero MURB).

The simulations are based on the typical MURB model and analyze the specific performance of Wall R-value, Window U/R-value, Window Solar Heat Gain and Enclosure Airtightness.

The plots provide insight into potential enclosure targets for net-zero type MURBs and provide relative comparisons to current energy use. Further research is required to better understand how variables such as occupant behaviour, comfort, mechanical systems etc., would affect these predicted energy performance levels in a net zero MURB.

7.3.1 Diminishing Returns of Wall and Window R-value

Simulations were completed using the typical building model to determine the effect of increasing the wall R-value on space heat consumption for various window to wall ratios (WWR) and window U-values. Fig. 7.3.1 shows the annual suite electrical space heat energy consumption for various wall R-values with different WWRs and window U-values. The plotted energy consumption does not include gas make-up air heating energy, which would be addressed in a net zero building with heat recovery ventilation. The plot shows the diminishing returns of increasing the effective wall R-value. Increasing the wall R-value has a greater effect on reducing energy consumption for lower window to wall ratios and higher window U-values.

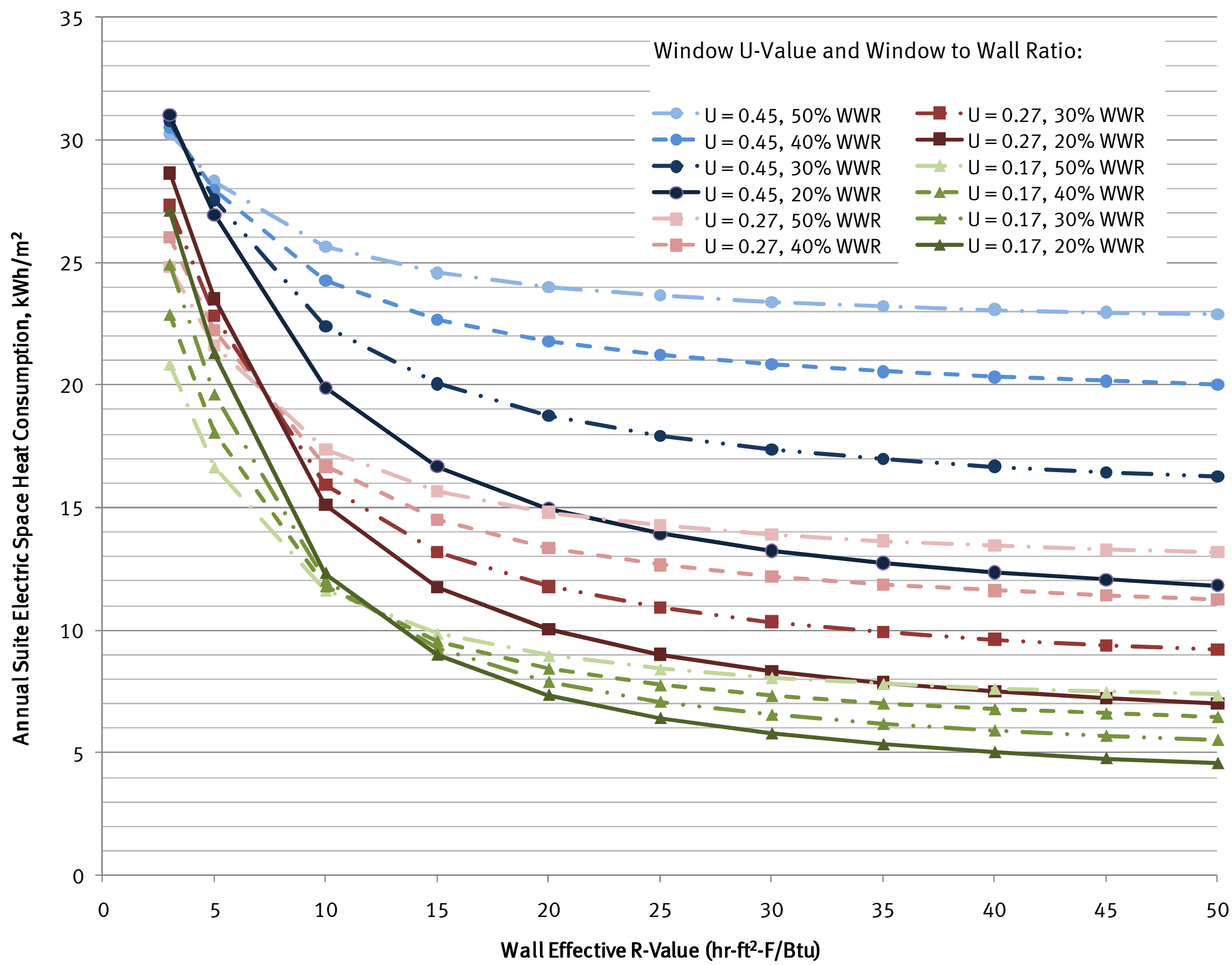


Fig. 7.3.1 Diminishing returns of effective wall R-value for various window to wall ratios and window U-values.

The plots start with current space heating intensity levels of 30 kWh/m^2/yr (Window U-0.45 or greater and 50% WWR, and walls of R-5 or less). Space heating reductions down to a level of between 5 and 10 kWh/m^2/yr (i.e. 500 to 1000 kWh for a 100 m^2 apartment, \$35 to \$70/yr) of electric space heat is shown to be possible with reasonable window U-values (U-0.24 to U-0.17) in low ratios, and what are currently minimum standard effective wall R-values (greater than R-15 to R-20). Diminishing returns are quite obvious, particularly for wall R-values when poor performing windows in high ratios are used. Fig. 7.3.2, Fig. 7.3.3, Fig. 7.3.4 and Fig. 7.3.5 show separate plots for window to wall ratios of 20%, 30%, 40% and 50% respectively.

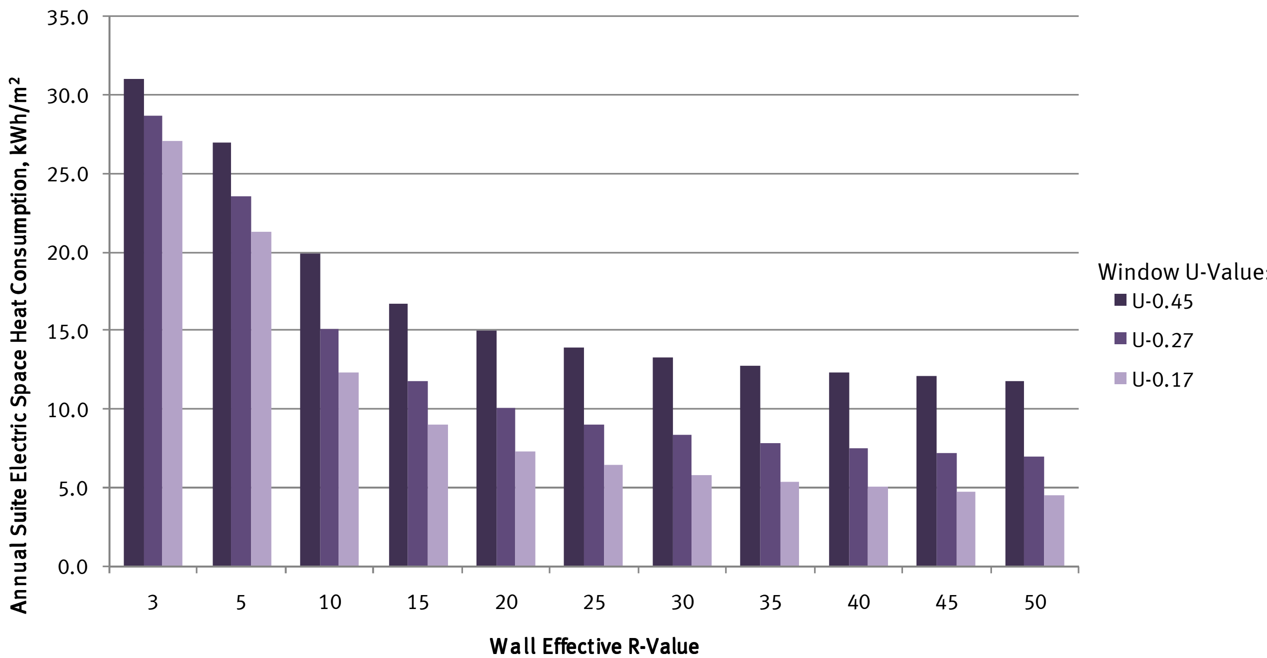


Fig. 7.3.2 Annual suite electrical consumption for 20% WWR.

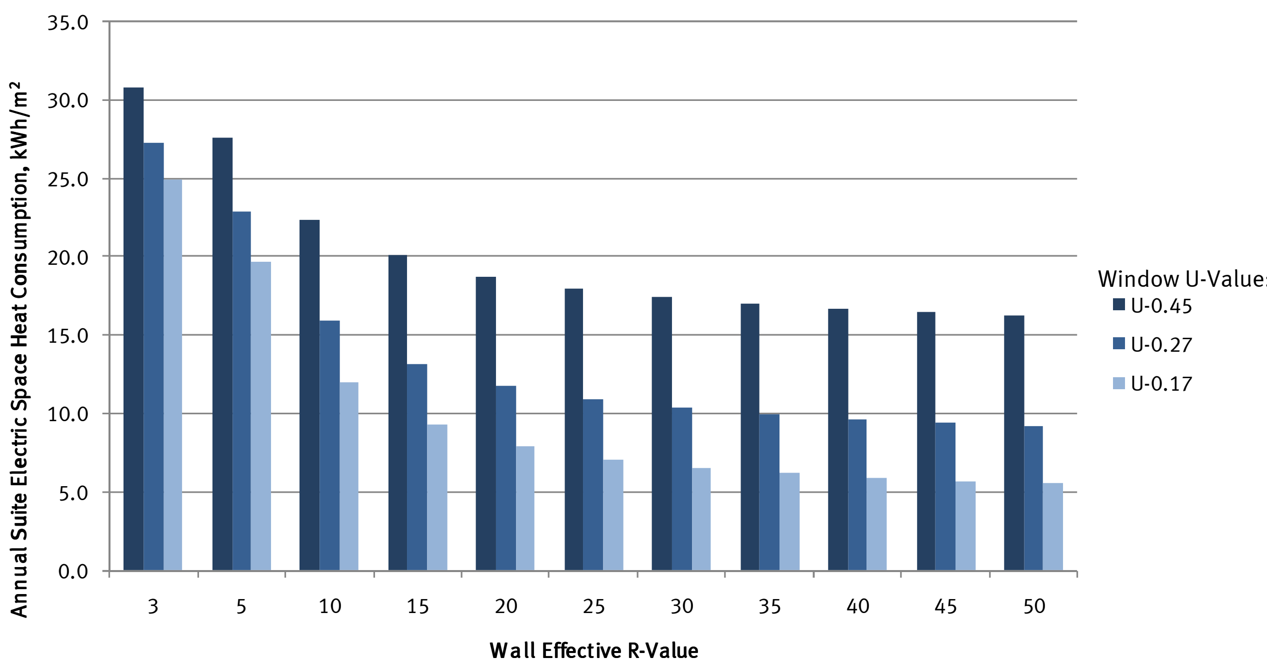


Fig. 7.3.3 Annual suite electrical consumption for 30% WWR.

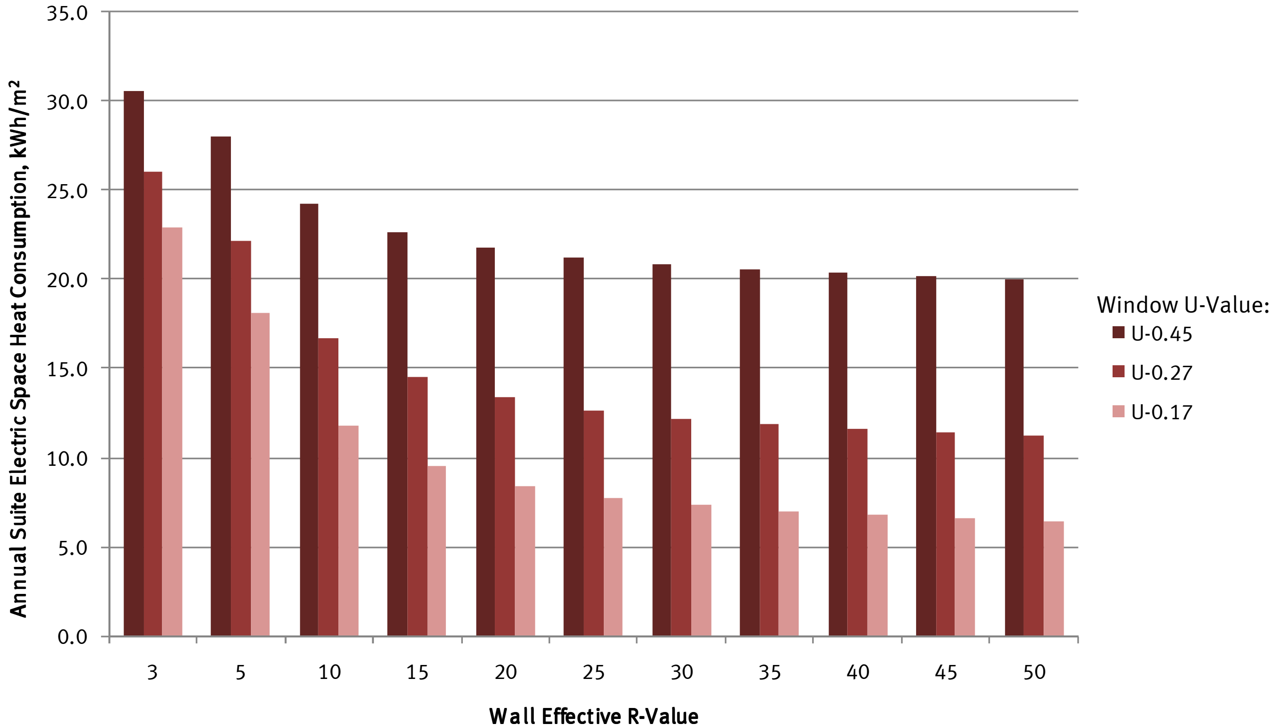


Fig. 7.3.4 Annual suite electrical consumption for 40% WWR.

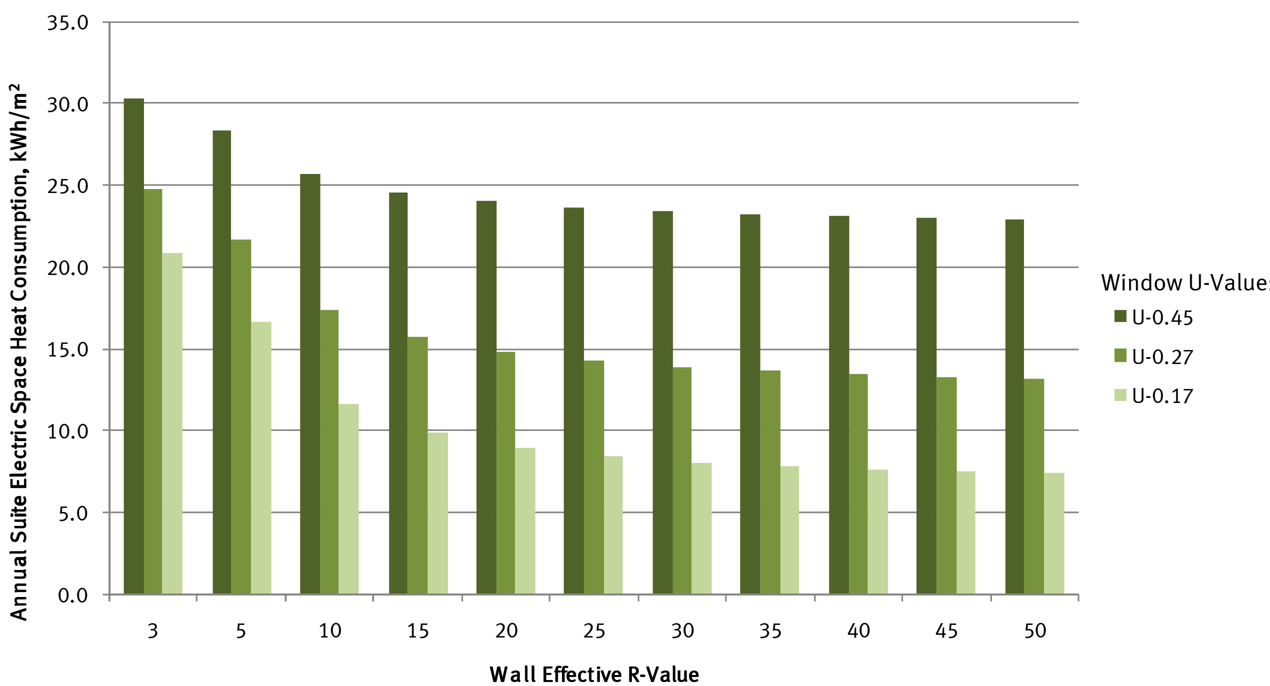


Fig. 7.3.5 Annual suite electrical consumption for 50% WWR.

7.3.2 Window Solar Heat Gain

Simulations were completed using the typical building model to determine the effect of increasing the window solar heat gain coefficient (SHGC). The simulations used an effective wall R-value of 18.2 and a window U-value of 0.17 (R-5.9), using window to wall ratios of 20%, 30%, 40% and 50%. The resulting annual suite electrical heating consumption is shown in Fig. 7.3.6. The plot shows a decrease in heating energy as the SHGC increases. This occurs because a higher SHGC means more solar heat is transmitted to the space to offset the heating load.

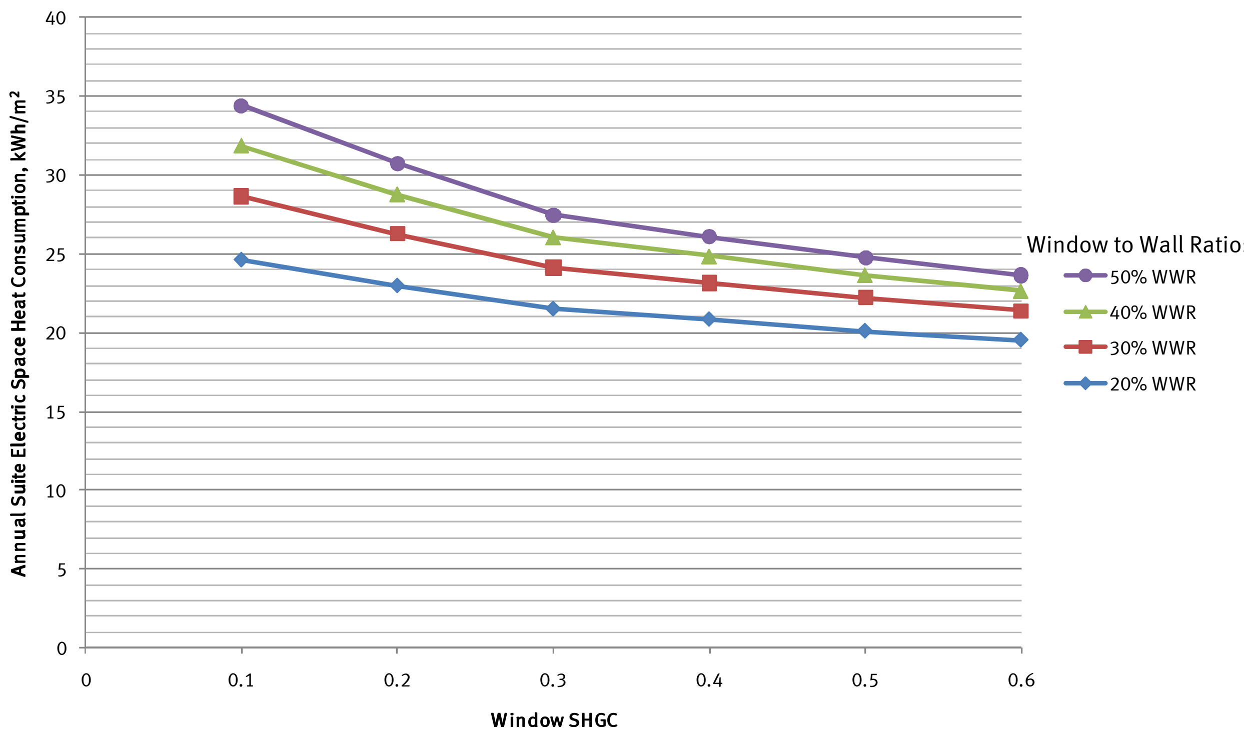


Fig. 7.3.6 Annual suite electric space heat consumption vs. window SHGC.

While solar heat gain offsets the heating load to reduce space heat consumption, it can also cause increased cooling energy consumption or overheating. If a building has a cooling system, increasing the SHGC will also increase cooling energy. This effect does not show up in this study since none of the study buildings nor did the "typical building" have a dedicated cooling system. If the building does not have a cooling system, increasing the SHGC can cause overheating and may drive occupants to install individual air conditioning units or result in other comfort related problems. Increasing the window SHGC does not necessarily reduce energy consumption and must be evaluated for each scenario, taking into account the climate, window orientation and shading. In most cases, increasing the SHGC will adversely affect occupant comfort and other performance characteristics for this building type, particularly when improved insulating characteristics for the building enclosure assemblies are adopted.

7.3.3 Enclosure Airtightness

Fig. 7.3.7 shows a plot of space heat electrical consumption versus air leakage rate for two different enclosures. The plotted energy consumption does not include gas make-up air heating energy. The air leakage rate has a greater effect on space heat consumption for the better building enclosure. As the air leakage rate becomes large, the energy consumption of the two enclosures gets closer together indicating that air leakage dominates the heating load for very high air leakage rates.

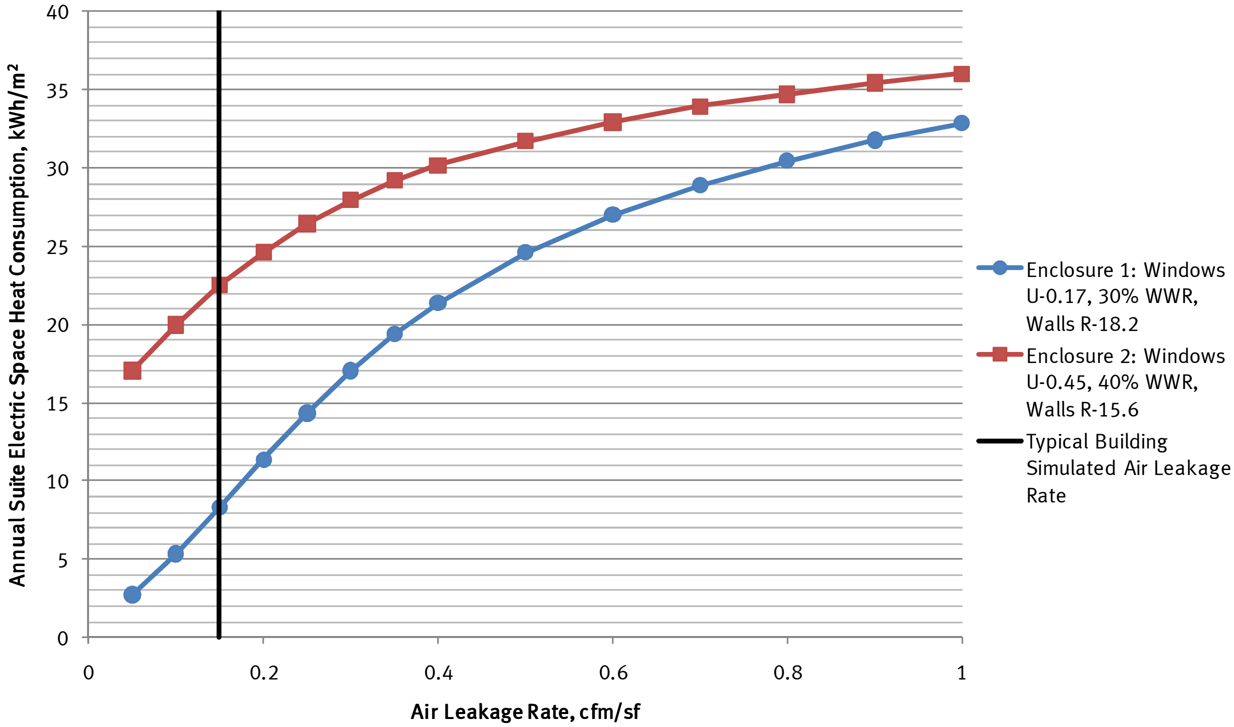


Fig. 7.3.7 Annual suite electric space heat consumption vs. air leakage rate.

Each of the plots in the previous sections pointed towards much more energy efficient building enclosures than are currently being constructed or allowed by minimum energy standards (i.e. ASHRAE 90.1-2004 or 2007). However, the industry is currently constructing MURBs that perform poorly in terms of overall enclosure thermal efficiency levels. There is significant and room for improvement which may be achieved with even small changes to current practice and energy code requirements.

8. CONCLUSIONS AND IMPLICATIONS FOR CURRENT AND FUTURE PRACTICE

High-rise multi-unit residential buildings (MURBs) of strata or condominium ownership are becoming one of the most common building types in urban centres of North America. This building type accounts for a significant proportion of residential energy use and greenhouse gas emissions. The energy performance of MURBs has not been studied in detail and little information is available regarding actual energy consumption and greenhouse gas emissions (both the total and distribution of), moreover and there is no consistent guidance regarding how to design MURBs to ensure adequate energy performance when in service. The primary objective of this study is to provide data, analysis, and practical findings for the industry to move forward and improve the energy efficiency of MURBs. These findings may be used to determine better building enclosure design strategies to reduce energy consumption and associated greenhouse gas emissions, while considering the other building functions (such as comfort, ventilation, and moisture control) for both new and existing buildings.

To perform this study, energy consumption data for more than 60 mid- to high-rise (5 to 33 storeys) MURBs was collected and studied. Half of these MURBs had undergone complete building enclosure rehabilitations within the past decade. The data combined with detailed information on each building including as-built drawings, mechanical system assessments, and operation histories was used to assess the energy consumption for each MURB. This allowed for the opportunity to assess the energy performance impacts of building enclosure rehabilitations performed to address moisture damage on this building type.

While this study looked specifically at the energy consumption of condominium MURBs within the climatic region of south coastal British Columbia, the findings are also relevant to other climate zones and other building types including rental apartments, social housing, and even commercial buildings. Findings with respect to the thermal performance of building enclosure assemblies are particularly relevant to all building types.

The total energy use intensity for the 39 study MURBs buildings was found to be in the range of 144 to 299 kWh/m²/yr with an average of 213 kWh/m²/yr for all years of data reviewed (Fig. 8.1). On average 51% of the energy consumption within a MURB is natural gas (make-up air, domestic hot water and gas fireplaces), with the remaining 28% being electricity used within the suites (electric heat, lighting, plug loads etc.) and 21% electricity being used in common areas (lighting, elevators, fans, pumps, some electric heat etc.). In general, those buildings with higher energy consumption tended to have more energy consuming equipment and amenities, being higher ventilation rates, gas fireplaces, pools, hot tubs and other common amenities, whereas those building with lower energy consumption tended to be simpler older buildings with lower ventilation rates and with fewer amenities. The total energy consumption is equal to 21,926 kWh/yr per suite on average, with a range from 11,566 to 34,812 kWh/yr with one high end building at 50,611 kWh/yr.

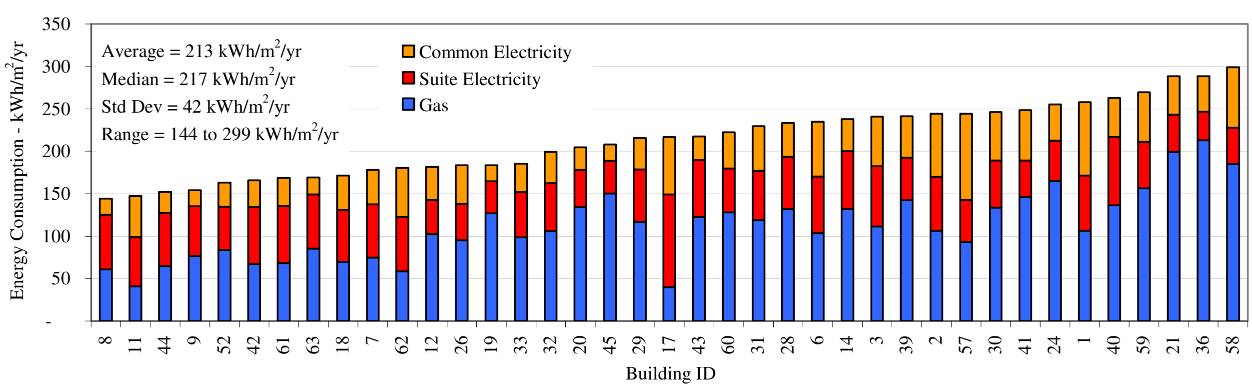


Fig. 8.1 Total Energy Usage per Gross Floor Area – Sorted Low to High, Split by Electricity (Common & Suite) and Gas.

On average, 37% of the total energy consumed within MURBs is used for space conditioning (space heating and ventilation) with a range from 24% to 52% as determined from bill analysis (Fig. 8.2). Although the majority of the buildings incorporated electric baseboards to provide the space heat to the suites and common areas, 69% of the space heat energy was provided by gas burning equipment (make-up air tempering and fireplaces, where present) shown in Fig. 8.3. Gas for heating or tempering of ventilation air makes up the majority of this total in all of the study buildings, and gas fireplaces use a proportionally high amount of energy for the limited heating benefit they provide. The findings highlight a significant disconnect between building energy consumption and direct billing to occupants for their share of total energy usage. Specifically, natural gas is commonly metered at one location in a MURB and apportioned to owners by their strata lot entitlement and not by actual use. Individual suite metering to encourage energy conservation may help to address this disconnect for gas fireplaces and hot water usage.

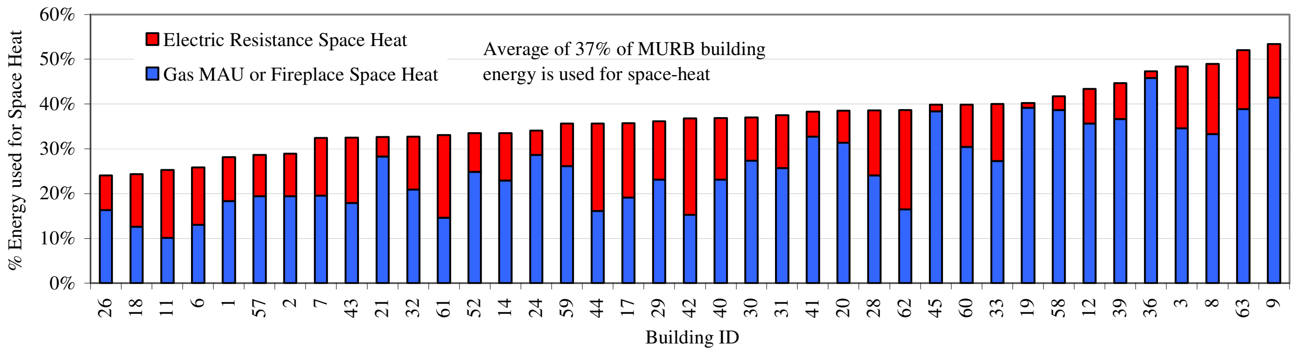


Fig. 8.2 Approximate Percentage of Total Energy which is used for Space Heat, Split by Portion of Gas and Electricity.

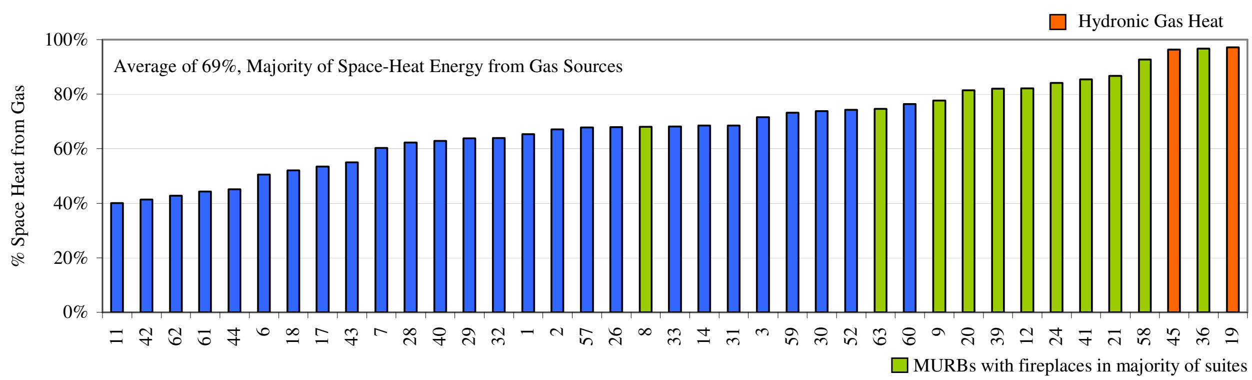


Fig. 8.3 Approximate Percentage of Total Building Space Heat which is from Gas Energy.

Our review of the MURBs by year of construction found that space heating and overall energy consumption has not decreased in newer, more modern MURBs and actually appears to have increased slightly (Fig. 8.4). Newer MURBs constructed use more energy on average than the older MURBs (constructed in the 1970s and 1980s) based on the analysis of the 39 study buildings. In addition, the overall effective thermal performance of MURBs has not improved, and the amount of space heating associated with ventilation has increased (i.e. ventilation rates provided to pressurized corridors – but not necessarily to the suites). The use of gas fireplaces in newer buildings has also displaced more efficient electrical space heat.

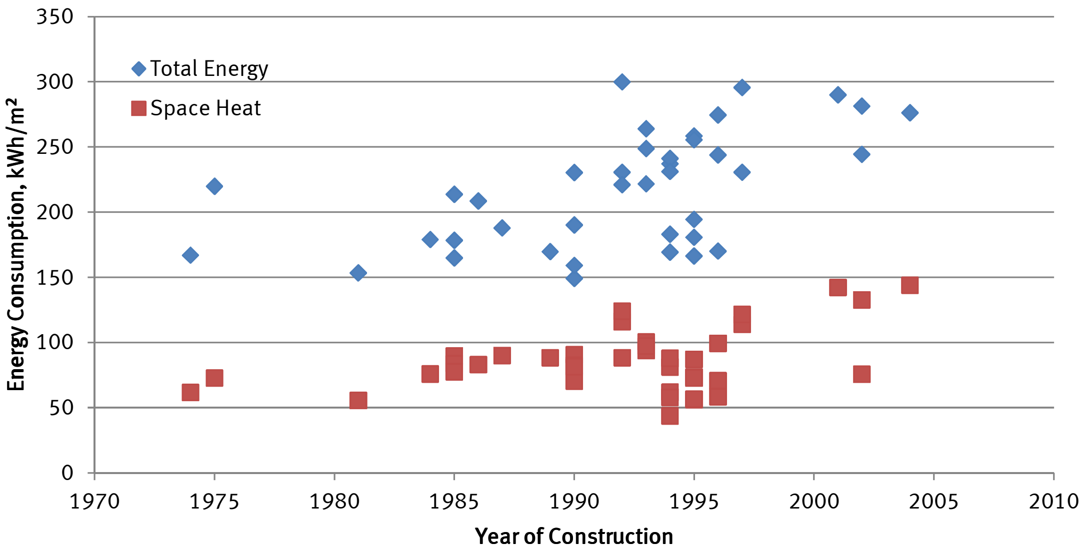


Fig. 8.4 Total and Space Heat Energy Consumption within Study MURBs by Year of Construction.

Since multi-unit residential buildings typically remain in service for a very long time and are difficult to retrofit, upgrade, convert, or demolish due to the multiple and differing ownership agendas, it is imperative that any opportunities to reduce the energy consumption loads be realized at initial construction and over the service life of the building (i.e. during retrofits, rehabilitations, or renewals work).

Renewals of mechanical systems (i.e. boilers, ventilation equipment, and domestic hot water) can be, and often are, readily implemented over the lifetime of a MURB, with components being replaced or upgraded at the end of their useful service life. However, retrofits or renewals of the building enclosure assemblies to reduce the space heating requirements of a building are much more costly and difficult to implement and, therefore, enclosure upgrades are rarely undertaken over the service life of a building unless other performance issues act as a catalyst. Moreover, improvements to enclosure systems can have a significant influence on service system upgrades (for example, a better insulated enclosure will require a smaller boiler or heating plant). From the initial design, through the service life of a MURB, better coordination and collaboration between HVAC mechanical engineers and building enclosure engineers and architects may better support the design, commissioning, operation and maintenance and any renewals work for a building.

There is need for improved occupant engagement as part of the operation of these buildings. Energy conservation measures in the form of better education of occupants with the use of sub-metering of all energy uses (in particular fireplaces and domestic hot water) and in-suite energy displays, as well as better controls such as programmable thermostats for space heat are needed to bridge the disconnect between occupant energy use and energy consumption in strata condominiums.

Within the Lower Mainland of BC and also in other regions of North America, a large population of buildings has and will continue to be rehabilitated to address premature failure of the building enclosure due to moisture related problems. Unfortunately, for reasons primarily related to short-term cost, little or no attention is typically directed at energy conservation strategies and/or greenhouse gas emissions when rehabilitating these buildings. However, the energy consumption and greenhouse gas emissions savings that occur as a result of building enclosure rehabilitations (not energy retrofits) was assessed as part of this study. The study found that significant savings can be realized by improved enclosure assemblies (e.g. improved windows, reduced thermal bridging and airtightness characteristics) at no little to no additional cost above necessary repairs.

The impact of building enclosure upgrades was assessed in detail for 13 sample buildings representative of the larger building set. Eleven of these buildings underwent full building enclosure rehabilitations (pre-post buildings) and two of these buildings are representative of typical high-rise MURB construction over the past decade.

Detailed whole building energy models were assembled to determine the building enclosure characteristics, including area quantities and overall effective R-values later used for energy simulation calibration. Heat transfer simulation of the building enclosure components found that the overall effective building R-values are less than R-3.0 $ft^2 \cdot h \cdot °F/Btu$ for typical MURBs representative of architectural styles from the 1970s to the present. For the 11 pre-post buildings, the overall R-values were improved from an average of R-2.4 pre-rehabilitation to R-3.4 post-rehabilitation (an improvement of 44%) shown for each of the 13 buildings in Fig. 8.5. The newer buildings had overall R-values slightly over R-2.0 effective, significantly less than ASHRAE 90.1-2004 and 2007 prescriptive requirements. The calculated enclosure R-values are used as inputs in comparing energy modeled results to actual performance characteristics. This information, along with air leakage testing data, is used to better determine actual air leakage rates of these buildings in-service during the time periods assessed.

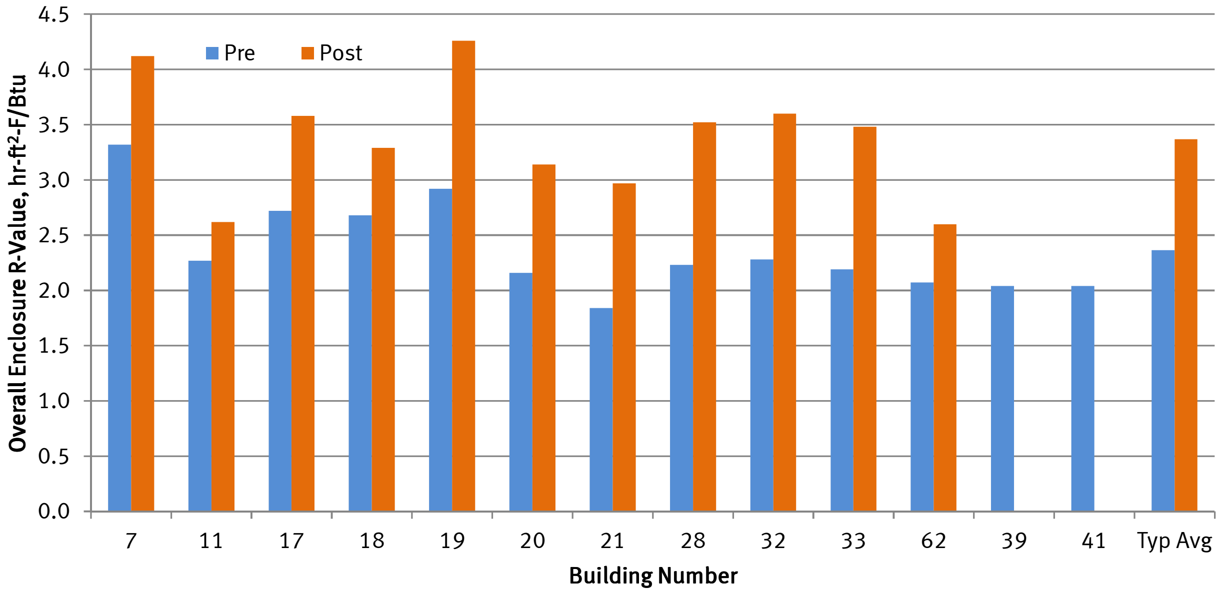


Fig. 8.5 Summary of calculated Pre- and Post-Rehabilitation Overall Effective Enclosure R-values.

Average pre-rehabilitation normalized energy use intensity for the eleven detailed pre-post buildings was 203 $kWh/m^2/yr$ and post-rehabilitation was 188 $kWh/m^2/yr$, for a total energy savings of 8% and space heat savings of 14%. For these eleven pre-post buildings, typical whole building energy savings ranged from 1% to 19% and space heat savings ranged from 9% to 22% depending on the total electric and gas heat and overall energy mix within the building. Overall greenhouse gas emissions were reduced on average by 9%, or 22.6 tCO_2 equivalent. Based on these study findings, the potential to significantly improve the energy consumption characteristics exists as part of future building rehabilitation or renewal programs. Fig. 8.6 presents the total energy and space heat energy savings observed in the eleven pre-post study buildings.

In each of the rehabilitated MURBs, further energy savings could have been realized by investing in upgrades to the building enclosure and by improving space heating and ventilation systems at the time of the rehabilitation.

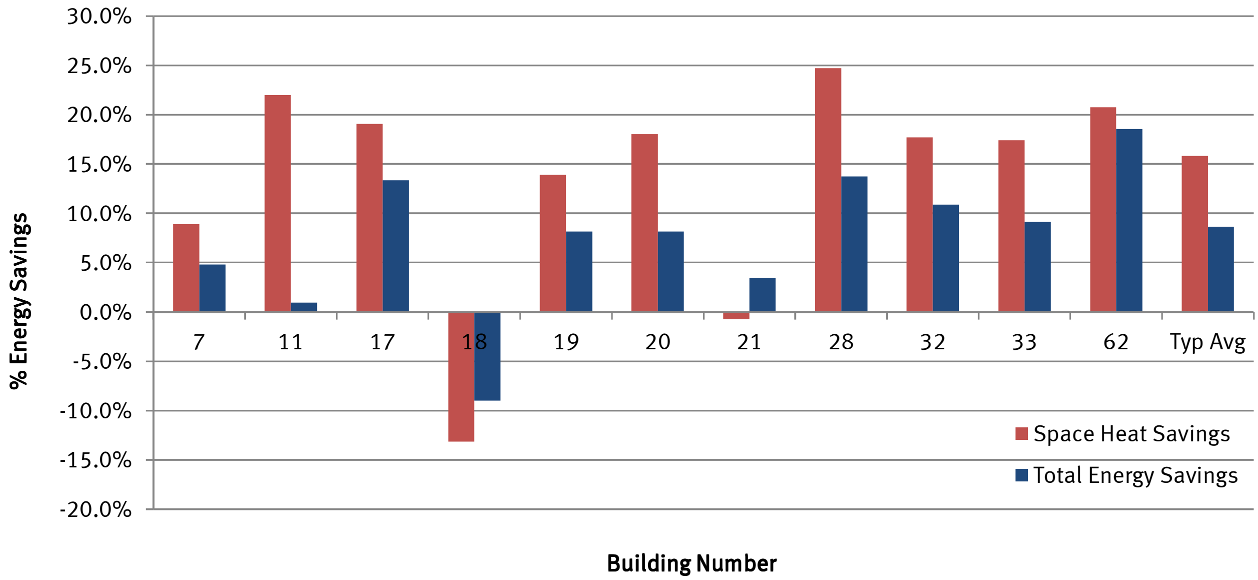


Fig. 8.6 Summary of Total and Space Heat Energy Consumption Savings (%) Pre- to Post-Rehabilitation.

The 13 study buildings were used to develop an average or typical building energy model that is representative of energy consumption within high-rise MURBs in the Lower Mainland. The typical building was then simulated to determine the impact of various enclosure and ventilation parameters on energy consumption. Fig. 8.7 presents the energy distribution for a typical MURB, summarizing these 13 buildings and Fig. 8.8 presents the greenhouse gas emission distribution. As shown, space heating (ventilation or make-up air, electric baseboards and fireplaces) account for 49% of energy consumption in the typical building. The remaining energy consumption is attributed to 16% DHW and 35% electricity for lights, appliances and other equipment. Of the space heating energy, 12% is for electric baseboards, 18% fireplaces and 19% ventilation make-up air heating.

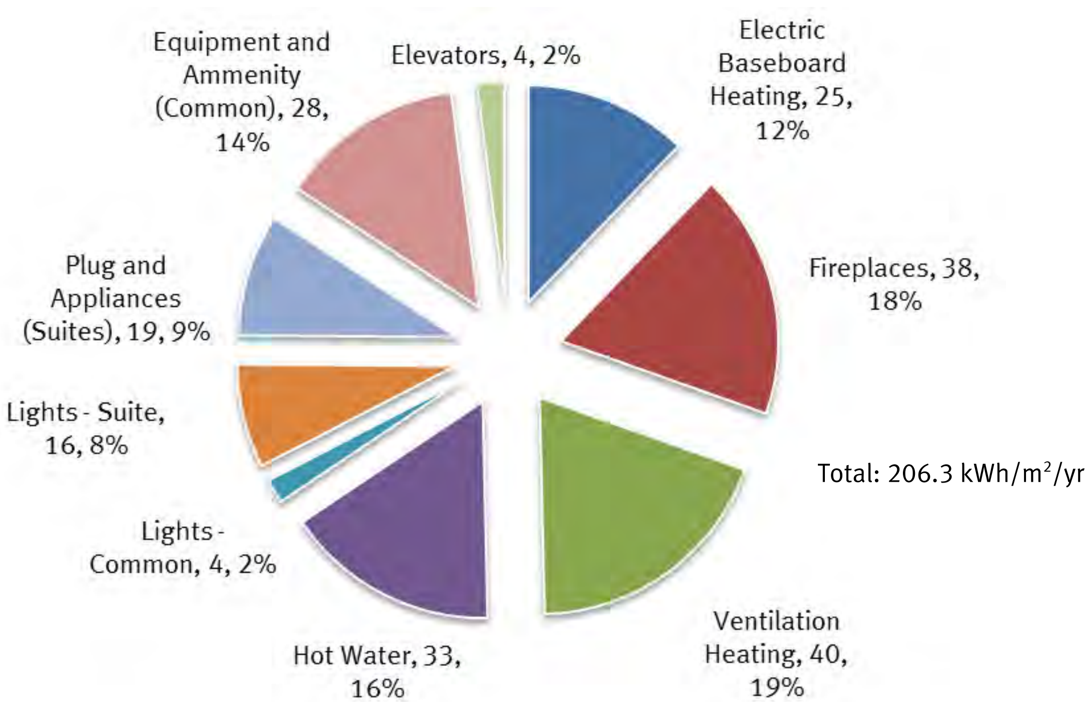


Fig. 8.7 Distribution of annual energy consumption in the simulated typical MURB developed from the 13 detailed study buildings. Units shown in kWh/m^2/yr and percentage of total (206.3 kWh/m^2/yr).

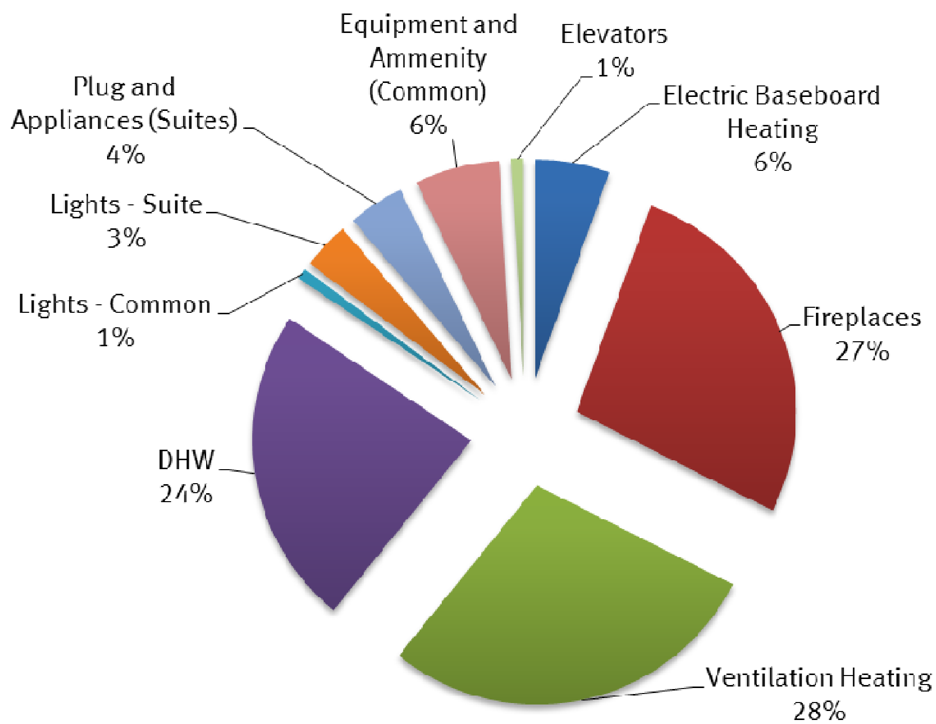


Fig. 8.8 Distribution of annual energy consumption in the simulated typical MURB developed from the 13 detailed study buildings. Units shown in kWh/m^2/yr and percentage of total (206.3 kWh/m^2/yr).

Trends observed pre- to post-rehabilitation show a trade-off relationship between gas-heated make-up air and electric baseboard space heat. In several buildings, the electric space heat stayed the same or increased slightly post-rehabilitation, whereas the gas-make-up air heat dropped. The influence of airflow and ventilation on energy consumption is an important consideration that requires further research to fully understand. The study confirmed that a large range of ventilation rates within the buildings exists, and that this air flow, and in particular ventilation rate has a significant impact on the energy consumption of the buildings. Unfortunately, higher ventilation rates provided to the common areas through pressurized corridors do not necessarily mean more or better ventilation within the suites.

While many buildings are in need of energy efficiency upgrades or improvements, those buildings that require necessary repair or rehabilitation to address moisture ingress or other widespread building enclosure performance problems represent perhaps the largest and most unique opportunity for implementing energy efficiency improvements and reduce space heating loads. Significant energy savings in MURBs can be realized by investing in upgraded energy efficiency measures for buildings already undergoing rehabilitation or renewals work for other purposes and have the enclosure exposed. These opportunities include improving glazing and wall assemblies, in conjunction with better control of air flow (both improved ventilation strategies, and reduced air leakage). The incremental cost for upgraded energy efficiency measures above baseline rehabilitation designs can often be justified by the potential energy savings. Examples include adding insulation into walls, use of more thermally efficient cladding supports to reduce thermal bridging, or the use of higher performance window frames and glazing than the minimum.

In terms of new construction, much higher thermally performing windows and reasonable glazing ratios (i.e. less than 40%) can effectively reduce space heating loads and associated energy consumption. In terms of targets, glazing assemblies with R-values in the range of R-4 to R-6 (i.e. Energy Star Zone C & D windows) should be considered for use in mid- and high-rise buildings. Overall effective wall assembly R-values (accounting for all thermal bridging) in the order of current ASHRAE 90.1 and 189.1 standards are suggested minimums (i.e. R-15.6 to R-18.2). Compared to current practice, which is on average less than R-5 for exterior walls, this requires the more effective use of the same level of currently provided insulation (i.e. by the reduction of thermal bridging at cladding supports, and thermal breaks within balcony and projecting slabs etc.). Roofs and decks should also be insulated effectively to minimum ASHRAE 90.1/189.1 levels; however, the impact of roof R-values on the overall thermal performance of a MURB is small due the relatively small area of a roof on a tall building compared to the exterior walls.

Better control of air flow within, and through buildings is a key factor in reducing energy consumption in this building type. Compartmentalization of suites and floors, already necessary for fire, smoke, odour and noise control also helps to control stack and mechanical pressures, reducing the loads on the ventilation systems.. Optimal airtightness levels for both for the building enclosure and the whole building under in-service conditions should be determined. While enclosure airtightness is important, normal window operation and occupant behaviour can result in effective building airtightness characteristics that are orders of magnitude worse (higher) compared to the performance characteristics of the enclosure assemblies. Open windows also affect pressure distributions and air flow within tall buildings. This highlights the need for in-suite ventilation and heating systems where individual occupants are directly responsible for their own energy consumption, and where occupant behaviour has less of an impact on the energy consumption of the rest of the building.

The study findings clearly identify the need to move away from the traditional pressurized corridor approach of MURB ventilation and de-couple ventilation from space heating. Separate in-suite ventilation and space heat systems should be considered, that incorporate heat recovery. The calibrated energy simulations for a typical building showed significant benefits with the use of heat-recovery ventilators (either in-suite or ducted central systems) on energy consumption. Direct ventilation systems with heat recovery will also improve occupant comfort, even in temperate climates such as Vancouver. As part of these the improvements to ventilation strategies, compartmentalization is necessary to control stack and mechanical pressures across the building enclosure and across the ducts of in-suite systems so that these systems can operate.

The energy simulations performed as part of the study identified remarkable opportunities to reduce energy consumption when integrated building solutions are adopted that include improvements to the thermal performance of the building enclosure (walls, roofs and windows), airtightness, space heating system, and ventilation strategies. Reductions in space-conditioning (in-suite space heating and ventilation) loads from greater than 100 kWh/m^2/yr to less than 10 kWh/m^2/yr were achieved using the calibrated typical building model by implementing these combined energy efficiency measures. Within Fig. 8.9, this is demonstrated for a typical MURB by implementing “good” and “best” new design or retrofit strategies which improve window and wall thermal performance and ventilation systems within the typical MURB.

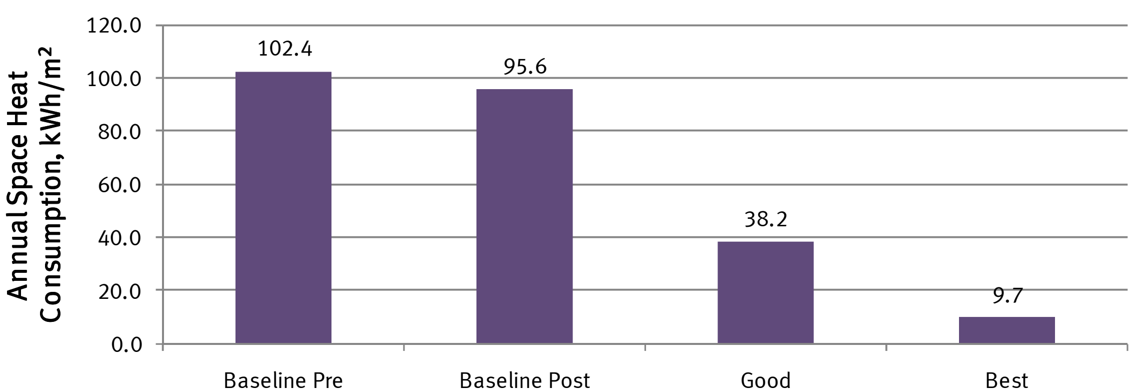


Fig. 8.9 Annual simulated energy consumption of improved MURBs, kWh/m^2/year.

Looking forward in the design of more efficient MURBs, a holistic approach that better considers occupant behaviour and all building systems is required. This approach needs to be based on actual building performance data using a feed-back loop in order to make real improvements. Whole building energy labelling for MURBs, real-time in-suite energy meters, and the reporting of actual energy use data as well as other building operation and performance characteristics should be made available to all parties in order to effectively build on past improvements. An increased demand for more efficient, durable buildings will result from this better understanding of actual building performance.

The following sections reiterate the findings from the study in the context of strategies to build, rehabilitate, and retrofit MURBs (and other buildings) to be more energy efficient, comfortable, healthy and liveable spaces.

- Reduce the energy consumption loads by improving the thermal performance of the building enclosure. Improved industry awareness of current thermal performance is necessary to understand not only the impact, but how to determine and enforce concepts such as effective R-values, and the how the influence of weak thermally performing elements such as thermal bridges and window area affects overall performance.
- Control airflow within MURBs, by airtightness (interior and exterior), compartmentalization, and effective ventilation systems. The concept and benefits of enclosure airtightness is well understood, but the importance of airflow within buildings moving heat, moisture, and contaminants is lacking and needs to be addressed. The study findings confirm that more energy efficient and effective ventilation strategies are necessary for MURBs.
- Engage and educate building developers and occupants, particularly with respect to where and how energy and is used within MURBs. As part of this strategy, there is a need to correct the disconnect between energy use and payment for consumption.
- Improve industry guidelines with respect to energy conservation.
- Implement tune-ups or retro-commissioning of existing buildings similar to commissioning performed (or that should be performed) at the initial construction of a building. Buildings, similar to automobiles, require regular maintenance to remain in optimal energy performance.

8.1. Reduce Space heating Loads – Improve the Building Enclosure

The average energy consumption intensity (both natural gas and common electricity) within mid- to high-rise condominium MURBs appears to have increased over the past 20 to 40 years based on the data from the current study. The largest influence in the increase in total energy consumption appears to be an increase in energy for space heat. Both the actual energy consumption data and detailed assessment of effective insulating values for the building enclosures of the study buildings also indicate that there have not been appreciable improvements to the overall insulating characteristics of these buildings. A fundamental starting point for the reduction in energy consumption for this type of building is higher performance building enclosure assemblies to reduce the loads.

Current practices do not generally assess the overall effective insulating values. Insulating characteristics are typically assessed for individual components such as windows, or the main field of opaque wall areas, however, the impact of all of the interface conditions and thermal bridging elements are typically not considered. For example, U-values for typical windows may be assessed, but flashings, deflection headers, corner posts, frame reinforcing (where needed), etc. are typically not included in the assessment. The largest differences between typical practice values and detailed assessment of effective values for glazed assemblies were found when comparing the standard NFRC sized windows to coupled window-wall type assemblies using actual sizes and all components.

There was a somewhat serendipitous improvement in overall enclosure R-values for all of the study buildings as a result of improvements made to the building enclosure to address water-penetration performance issues. This improvement is related primarily to the reduced thermal bridging, either with improved window assemblies, and/or from the change from insulating within the stud cavity to placing insulation to the exterior of the sheathing (exterior insulated). The improvement in the opaque portion of wall R-values can be attributed to less framing members penetrating the insulation, and the insulation covering over the large thermal bridges such as slab edges, and framing at wall corners and window perimeters. However, the remaining thermal bridging at balconies, cladding girts and clips, brick-shelf angles, and other penetrations still results in relatively low overall wall R-values. The overall wall R-value is primarily influenced by the lowest thermally performing element, which tends to be the windows so that improvements in window performance conversely results in the greatest overall impact on this aspect of performance.

The overall effective building enclosure R-value of the 13 study buildings ranged from R-2 to R-5 hr·ft^2·F/Btu (U-0.5 to U-0.2 Btu/ hr·ft^2·F). This is slightly better than the center of glass value of a typical IGU, but is not surprising in view of the low effective wall and window R-values when accounting for thermal bridging through framing, slabs, and actual window sizes. These low overall R-values result in excessive heat-loss (and gain) through the building enclosure and are therefore a prime focal point in order to create and operate more energy efficient MURBs.

Effective window R-values ranged from R-1.3 hr·ft^2·F/Btu for non-thermally broken aluminum frames with clear IGUs to R-2.2 for thermally broken aluminum frames with low-e IGUs up to a maximum of R-2.5 for higher performance frames with good low-e coating(s) and argon filled IGUs. This R-value represents a typical mix of fixed, operable and sliding door assemblies. Significantly higher overall window R-values of up to R-3 can be achieved with triple glazing in aluminum frames and higher of up to R-4 to R-6 when low-conductivity frames with double and triple IGUs are utilized.

The figure below demonstrates an area weighted U-value calculation to determine the overall enclosure R-value; by only assessing the wall R-value, window/door R-value and percent window/door area. Typical R-values for MURB wall assemblies are around R-5 effective; however, up to R-10 can be achieved by minimizing thermal bridging elements such as balconies. In comparison, an effective R-value of approximately R-16 is the ASHRAE 90.1-2007 minimum prescriptive requirement for steel framed wall assemblies in Climate Zone 5.

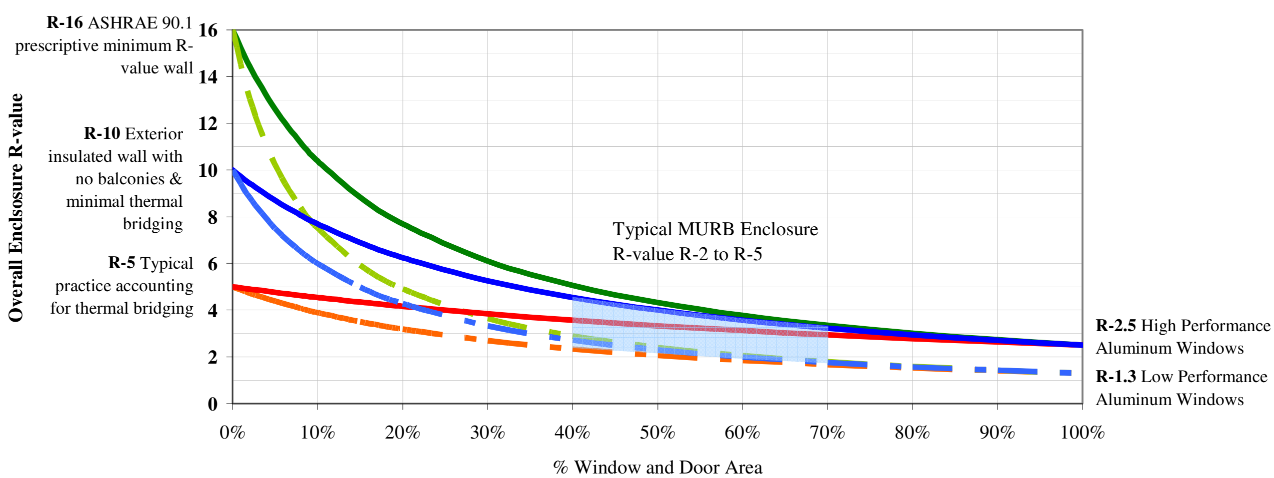


Fig. 8.1.1 Overall Enclosure R-value (hr·ft^2·F/Btu) for Typical MURB Wall and Window Assemblies.

While current construction practice for wall and window assemblies results in overall R-values of R-2 to R-5, the impacts of higher performing windows can be significant, with the ability to achieve overall effective R-values of up to R-10 readily using currently available technology.

The impact of improving both the effective wall and window R-values for a typical MURB with 40% window to wall area is demonstrated in Fig. 8.1.2, developed from the results of the energy modeling.

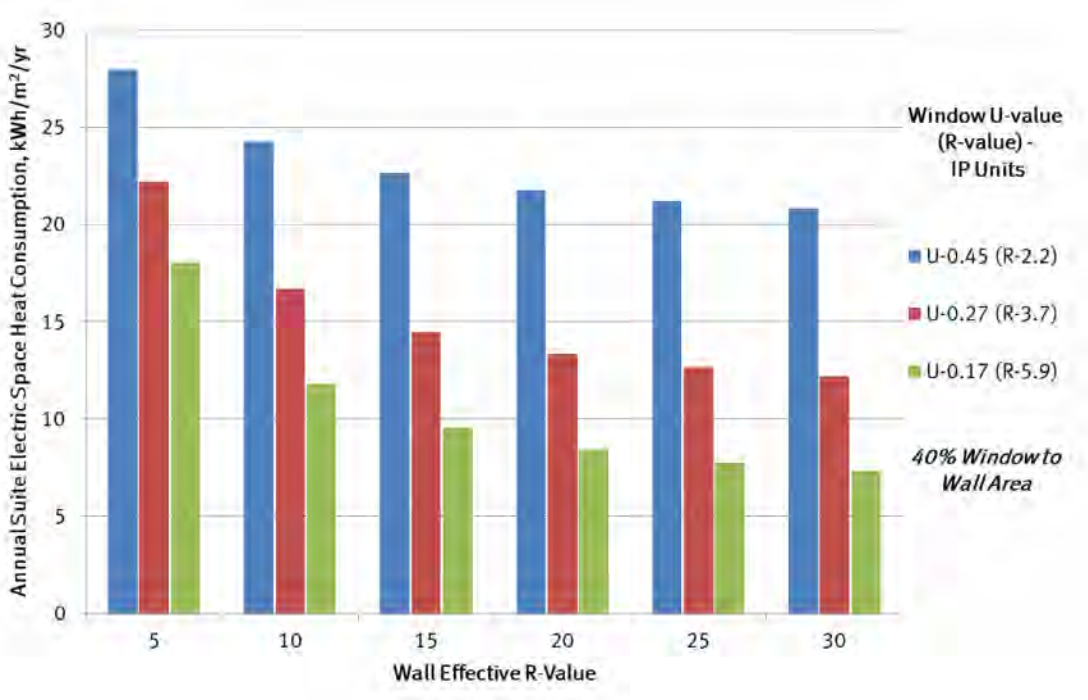


Fig. 8.1.2 Impact of Wall and Window Thermal Performance on Annual Suite Electric Space Heat within a typical MURB in Vancouver, BC.

Higher effective wall R-values are possible through changes to current common practices. Strategies for reducing thermal bridges through and around the wall insulation in non-combustible construction may include thermally isolated balconies and projections, clip cladding supports, low-conductivity framing, and offset brick shelf angles amongst other strategies. Spandrel panels common in window-wall assemblies also need to be addressed as the thermal performance of the opaque spandrel assemblies is typically only slightly better than the windows.

In addition to reducing the space heat loads, other building system loads need to be considered. The study identified significant energy consumption associated with fireplaces, pools, and other building equipment. Although not the focus of this study, improvements of this equipment is suggested to further improve MURB energy efficiency further.

8.2. Control Airflow – Airtightness, Compartmentalization and Ventilation

The reduction of enclosure air leakage and internal air flow within a MURB is a key factor in energy conservation. Air that moves through the building enclosure results in a direct loss of heat energy. The heating energy required to offset air leakage losses may not always be required at the suite in which it was lost due to uncontrolled movement of air within the internal spaces of the building. For example, under winter-time stack-effect, air will typically infiltrate lower floor suites, rise through the inside of the building and exfiltrate at the upper floor suites. This may result in extra heating required at lower floor suites, whereas upper floor suites will be too hot. Similarly wind and mechanical pressurization will also affect infiltration and exfiltration through suites in the building. Accounting for the influence of operable windows and occupant behaviour (such as opening windows to reduce heat at the upper floor suites), the air flow within and through a building is very difficult to effectively control, and is difficult to assess when predicting energy consumption.

As an industry we have a conceptual or qualitative understanding of air flow and air leakage issues with high-rise buildings under the influence of stack effect, wind and mechanical pressures and occupant behaviour (Lstiburek 2000). However, greater quantitative understanding is required to determine the space heat impact and to refine air flow and air leakage control strategies.

Currently, computer energy models calculate air infiltration using a user-input air leakage rate and an average building operating pressure, corrected for wind speed at each hour. Since the simulated infiltration load is largely based on a user-input estimation of air leakage, energy modeling of air leakage and its impact on space heat loss in a MURB is inaccurate. A better understanding of the actual pressures in MURBs is needed to improve energy modeling estimates and actual energy consumption. Information on the in-situ pressures within different suites of various MURB archetypes in different climates over the hours of an entire year is needed to improve energy modeling beyond assumptions of ideal case stack-effect scenarios.

Enclosure airtightness can be measured, but it is expensive and a complicated task in a high-rise MURB. In addition, windows are closed when airtightness is measured, so the usefulness of this measurement is questionable for an in-service MURB due to the other factors not typically evaluated as part of this testing (stack effect, wind speed, mechanical system operation, use of operable windows, etc.). It is difficult to determine an average net difference in pressure over the course of a year for use in energy simulations.

The relative impact of the in-service air leakage rate can be demonstrated using computer modeling. Fig. 8.2.1. shows the annual suite electric space heat consumption in a MURB in Vancouver subjected to varying average air leakage rates for two enclosure scenarios, the first a baseline enclosure representative of standard construction, the second a high performance enclosure. While the baseline enclosure obviously uses more energy than the high performance enclosure, the impact of air leakage is more profound when a high performance enclosure is used.

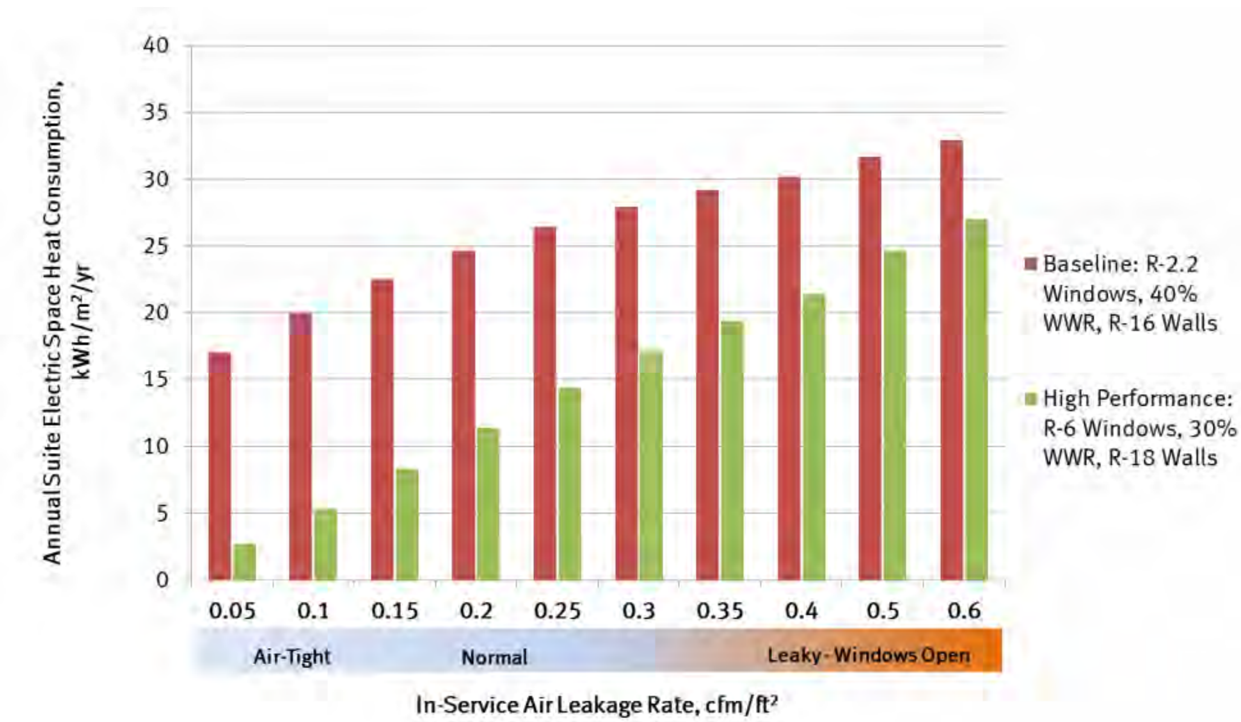


Fig. 8.2.1 Impact of In-service Air leakage Rate on Annual Suite Electric Space Heat Consumption in a Typical MURB in Vancouver, BC.

While the airtightness of the enclosure is an important variable, open windows significantly alter the effective airtightness of the building enclosure. Open windows decrease the effective airtightness by one to two orders of magnitude in service. Correspondingly, this reduced airtightness drops the building pressure and possibly the effective air leakage rate. Simply closing the windows (or reducing the number of operable windows) is not an option. In fact, operable windows are effectively the primary source for make-up air in many of the suites since suite door undercuts are ineffective in providing air from the pressurized corridors. Further, short circuiting of air flow from door undercuts directly to exhaust ducts results in inadequate air exchanges in portions of the building suites. In addition, much of the corridor make-up air flows directly up the building and to the exterior through the stairwell corridors and elevator shafts (Refer Fig. 8.2.2). Condensation and other related problems are common in many of the study building suites due to inadequate supply of make-up air to the suites.

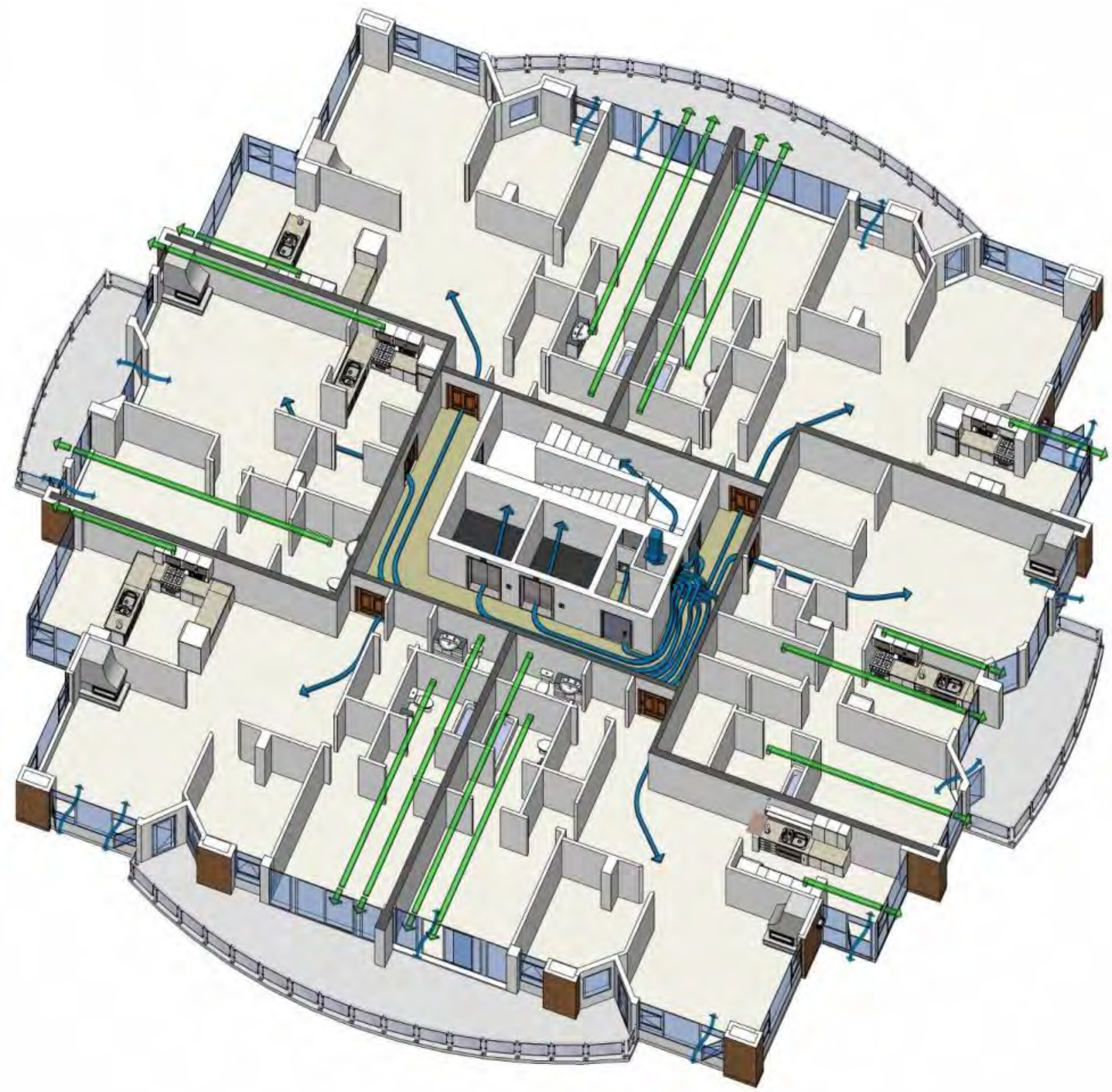


Fig. 8.2.2 Floor plan of Building 20. Note that only a portion of the make-up air migrates below the suite entry doors. Significant amounts of make-up air flows up the stairwell corridors, elevator shafts and other paths.

To address ventilation and heating system energy consumption, ventilation and heating can be de-coupled, and suites within MURBs compartmentalized, heated/cooled and ideally ventilated independently from the remainder of the building, and controlled by the occupant. While mechanical systems can be shared between compartmentalized suites, it may be preferable for suites to have individual ventilation and heating/cooling systems (i.e. the hotel approach). Compartmentalization helps to address many of the larger issues in MURBs including make-up air unit gas consumption, air leakage, building stack effect, air flow between suites, billing allocation, sound/odour control, fire separation, occupant behaviour and comfort. Heat recovery should be incorporated as part of the make-up air supply. Refer to Fig. 8.2.3 below for an example of a possible ventilation strategy.

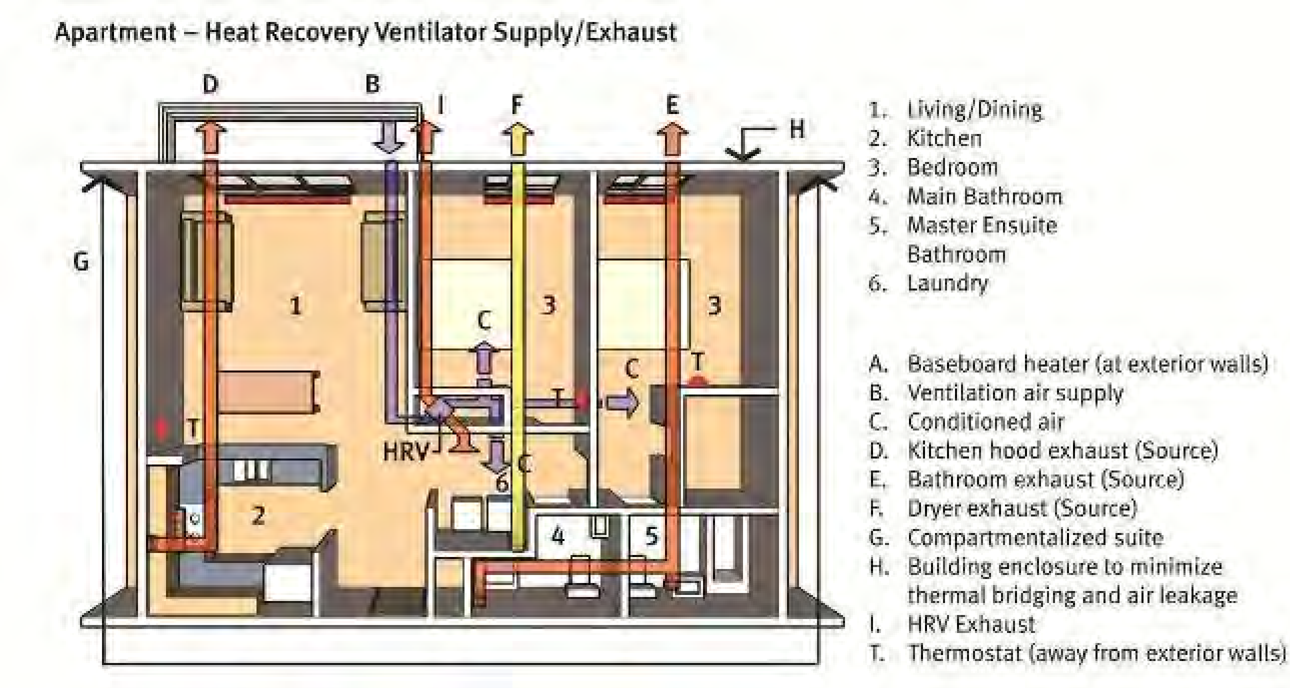


Fig. 8.2.3 Conceptual example of a compartmentalized suite with a direct supply of make-up air and heat recovery.

The energy savings from improvements to ventilation systems is demonstrated using the typical MURB energy model, comparing the energy consumption for a pressurized corridor approach (MAU) to a central ducted HRV system and in-suite HRV system in Fig. 8.2.4. The model assumes design flow rates for the pressurized corridor typical of current practice (in order of 100 cfm/suite and hence over-ventilated), whereas the ducted in-suite system benefits from a lower ventilation rate of on average 40 cfm/suite as this volume actually reaches the suite.

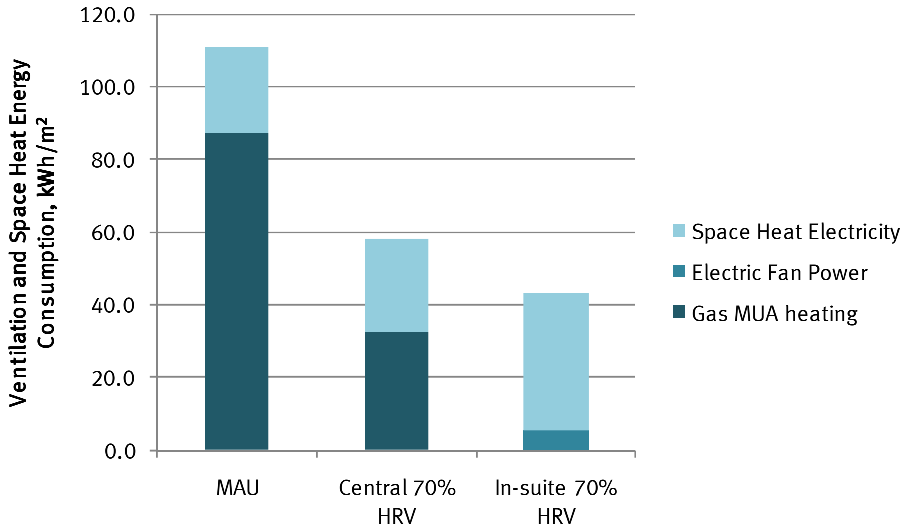


Fig. 8.2.4 Ventilation and Space Heat Energy Consumption for Different Ventilation Approaches.

8.3. Engage and Educate Building Developers, Designers and Users

The increasing energy consumption trend relates to disconnects between the building designers, building users, and actual building performance. The lack of available energy consumption data is an obstacle in designing new buildings, and inhibits building users from taking measures to reduce their energy consumption. Once the consumption data was assembled for the study buildings, it was found that only 35% of the total energy consumed by a suite is paid directly by the occupant or owner, with the remaining 65% of the energy paid by the strata corporation and passed on to the individual owners along with other costs in the form of strata or condominium fees.

The average energy distribution and associated costs per suite in a typical MURB are as follows:

- 28% of the energy consumed is for suite electricity, which is equal to $408/suite/year or 35% of the total energy cost, paid by the suite owner or occupant.
- 21% of the energy consumed is for common area electricity, which is equal to $323/suite/year or 27% of the total energy cost, paid by Strata Corporation or Owner Group.
- 51% of the energy consumption is for gas (make-up air heat, fireplaces and domestic hot water), which is equal to $455/suite/year or 38% of the total energy cost, paid by Strata Corporation or Owner Group.
- In buildings where fireplaces are present, approximately $200/suite/year may be used, paid by the Strata Corporation.

Although there is a general desire to conserve energy by building occupants, the actual amount paid by them misrepresents their energy consumption and therefore they typically do not appreciate the total energy bill. There is a lack of awareness of how the activities of building users impact energy consumption as well as other building performance characteristics. For example, building occupants do not typically see their gas consumption associated with the operation of fireplaces, or heating of ventilation air as a result of open windows.

It would be desirable to have energy consumption and other data readily available to the occupants in order for them to reduce their consumption. Ideally, this information would be integrated with other building asset management data in order to optimize available resources over the service life of the facility. Strategies for consideration in the design and construction of new residential buildings can include individual consumption metering, building operation data collection, maintenance and renewals planning tools, etc. By implementing these systems and collecting the actual performance data, this information can be compared with the initial design assumptions, better enabling the building users to determine how to best operate their building.

8.4. Improve Guidelines and Energy Performance Requirements for MURBs

The new National Energy Code for Buildings (NECB) together with industry standards such as ASHRAE 90.1, provide enhanced benchmark energy performance targets and guidance by which energy efficient buildings can be designed and constructed. In the current ASHRAE 90.1 standard, for example, both effective and nominal thermal resistance values are prescribed for insulated wall areas. However, as this study has demonstrated, to reduce space heating loads, effective enclosure R-values would have to improve to meet current ASHRAE 90.1 prescriptive minimum values and more stringent targets in other green building standards (such as ASHRAE 189.1). While some thermal bridging is accounted for in the ASHRAE 90.1 effective thermal resistance requirements, the overall thermal resistance of building enclosure assemblies such as at balconies, overhangs and building projections, brick shelf-angles, or alternate cladding support systems, may not reflect actual thermal performance conditions.

Guidance documents highlighting simple calculation methodologies in combination with energy performance values for common building enclosure arrangements based on guarded hot-box testing and detailed thermal modeling would be of significant benefit to designers and builders as they conduct energy modeling to comply with prescriptive requirements in codes and standards, for building rating systems and for sizing mechanical systems. Based on the results of the study and industry feedback, design professionals often do not undertake this exercise due to the complicated nature of the task and its iterative process. Such guidance documents would encourage designers and builders to innovate and improve upon the thermal performance of existing assemblies in order to keep pace with evolving energy codes and standards.

The collection of actual building energy (gas and electricity) data, as was done in this research study, provides an opportunity to benchmark and compare this building type on the energy consumption spectrum, as well as to compare against energy targets in codes and standards and/or the initial design assumptions and targets established by design professionals. However, the metrics to be used for this purpose are not clear, particularly for MURBs. There is a wide variety of building forms, types, densities, etc., which influence energy intensities, depending on the metric used whether it be on a per floor area basis (such as kWh/m2/yr typically referenced in this report), wall area basis, occupant basis, or other form of measure. In addition, occupant behaviour has a major impact on energy consumption. Therefore, building operation assumptions as part of the design documents should be stated as part of meeting more stringent energy efficiency requirements.

8.5. Implement Building Tune-ups and Retro-Commissioning

Based on the findings, the mechanical systems within many MURBs are often not performing as designed, resulting in wasted energy. In the mechanical assessments of the study buildings, and other reviewed by the authors in the past decade, it is apparent that building mechanical equipment and systems are often in need of simple tune-ups or retro-commissioning to improve energy efficiency.

Retro-commissioning is the act of re-tuning or re-commissioning the existing equipment and systems including building enclosure components within a building. It is the systematic process by which owners ensure that their buildings and mechanical systems are optimize to meet current operational needs. The retro-commissioning process within existing buildings is similar to the commissioning performed (or that should have been performed) at initial construction of a building to make systems operate as designed. Retro-commissioning can also mean installing controls, or upgrading components with new parts that may not have been available at time of construction (i.e. electronic thermostats).

This study did not assess the energy savings impacts of retro-commissioning, however, the assessments and analysis identified several key building components within MURBs typically in need of tune-ups. These tune-ups will, in most cases, result in immediate energy savings to the building owners with minimal or even no capital expenditure. These recommendations are by no means a comprehensive list, and may not be relevant for all buildings.

⇢ Make-up Air Units

- The gas used to temper ventilation air by make-up air units can be the largest single component of energy use within MURBs, particularly those MURBs constructed in the past decade. Maintaining make-up air units in optimal condition is essential, and is usually performed by maintenance contractors at regular servicing intervals. Of note, filters need to be changed regularly (i.e. every season or more frequently) so that design airflow rates reach the corridors. Significant reductions to design flow rates can be realized by filters plugged with dust after only a few months of use, which affects both occupant health and energy consumption.
- When considering energy conservation with respect to make-up air units, it is important to consider the purpose of ventilation air within MURBs – for occupant health. For this reason, the make-up air unit flow rate should never been turned down, turned-off, set-back or put on a timer, unless a professional can demonstrate that sufficient ventilation rates are reaching the occupants (i.e. minimum ASHRAE 62 levels, 15 cfm/person). It is important that the industry is aware of the potential health risks and moisture issues that can arise as a result of turning off or reducing make-up air flow rates, even while a potentially appealing energy conservation measure.
- The strata or owner group may consider turning down the set-point temperature of the make-up air unit. A set-point of around 15°C is typically assumed in design and is sufficient for tempering of the make-up air. However, in practice, a set-point of 21°C or higher is often set by the Strata Corporation or maintenance personnel to address complaints of low corridor temperatures or comfort. The building users should be made aware of the significant energy costs that results from turning the set-point temperature up. The thermostat for the air tempering heat should be adjusted to the design set point temperature (approximately 15°C) in the winter time, and heating (not flow) shut-off during the warmer summer months when this added heat is not required. The addition of electronic controls to the make-up air unit will improve this process. The set point temperature and other performance settings on the make-up air appliances should be regularly monitored with the building's mechanical service contractor.
- Door-threshold sweeps are often installed by tenants to address noise, odours, or drafts from the corridors. This blockage of the door undercuts obstructs the mechanically supplied ventilation air from reaching the suites. Suite owners should maintain this open threshold as initially designed for the building.

To demonstrate the potential of adjusting the make-up air set-point temperature within a MURB, two graphs summarizing several energy simulations are shown which present the gas (make-up air heat) and electricity (suite electric baseboard heat) for a typical 1980s-1990s MURB and a Modern 2000s MURB. The differences in the two energy models are primarily related to the base building enclosure inputs and the different MAU flow rate. As shown, as the MAU temperature is decreased, the amount of gas energy is reduced. Correspondingly the amount of suite electric space heat increases by a small amount. The net impact is an energy savings for the building.

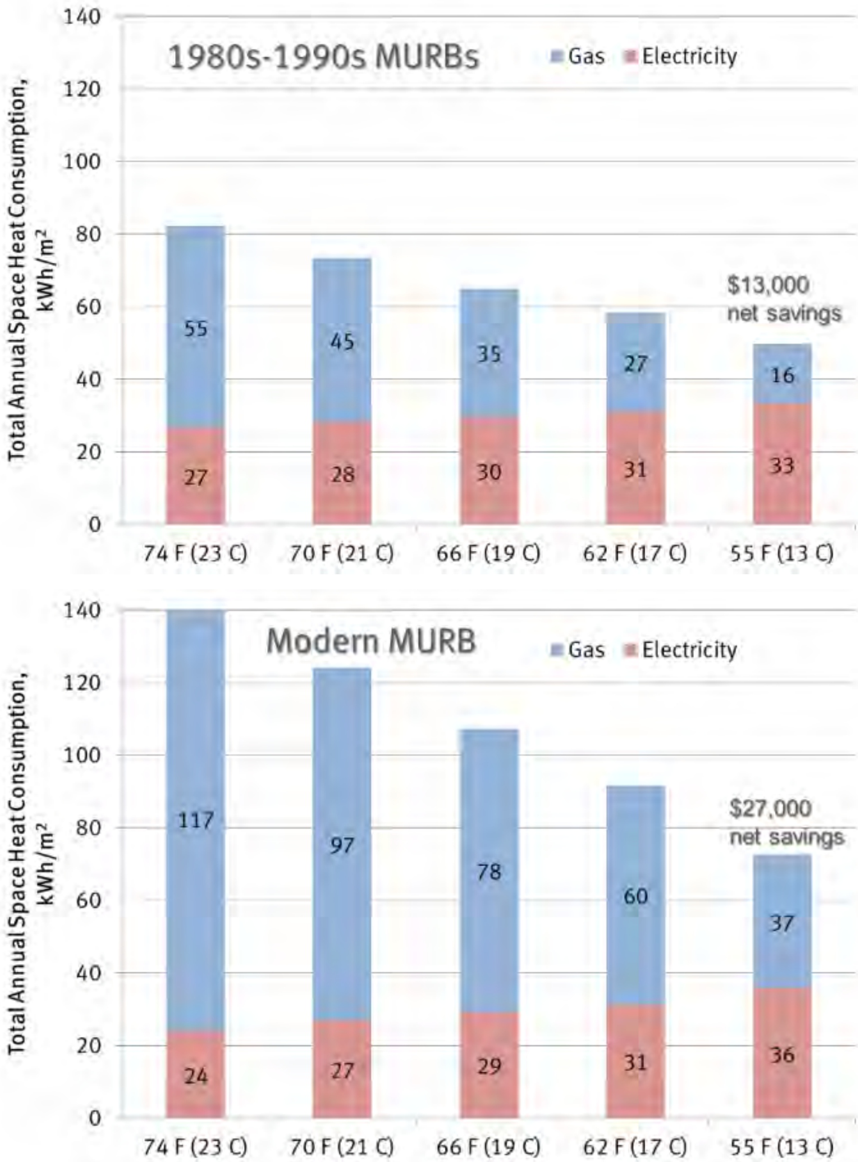


Fig. 8.5.1 Impact of MAU set-point temperature on gas (MAU) and electric space heat (suite baseboards) within either a typical 1980s-1990s or a Modern 2000s MURB. Note as the gas space heat is reduced, it affects the required amount of in-suite space heating, however, the net result is an energy savings.

⇢ Natural Gas Fireplaces

- On average, the natural gas fireplaces within the study MURBs consumed 18 GJ/yr, with a range of 13.3 to 24.1 GJ/year (3694 to 6694 ekWh/yr). Owners may wish to reconsider fireplace use and controls to reduce this energy use.
- Sub-metering of fireplace gas consumption is recommended using thermal meters in new construction and existing buildings. Sub-metering will apportion gas use to the fireplaces users and will in turn encourage conservation, particularly considering the large proportion of energy consumption for these appliances. Within most MURBs, the gas for individual fireplaces is part of common area gas use, which also includes make-up air tempering, domestic hot water, and possibly other equipment (such as pools or hot tubs). A pilot project was implemented by the owners of building 41 to reduce energy consumption that included sub-metering of the gas fireplaces. It is estimated that after the first year of sub-metering and pilot lights shut off during the summer months that fireplace gas consumption was reduced by approximately on half.

- Gas pilot lights should be shut off during summer months to conserve energy. Within building 41 of the study, it was found by sub-metering that 60% of the 138 units leave their pilot lights on year round, and 12 units use their fireplaces regularly over the summer. Since the gas consumption is a common expense, strata corporations should consider building-wide pilot light shut-off programs.
- On-off switches should be replaced with thermostat and/or timer controls.
- Regular servicing and maintenance by a licensed contractor should be adopted to optimize their use.

⇢ Electric Baseboard and Hydronic Radiator Thermostats

- The installation of electronic thermostats with programmable set-points should be considered as an upgrade to bimetallic or mercury controlled thermostats to control electric baseboards.

⇢ Domestic Hot Water

- Regular maintenance of the domestic hot water systems is required. Temperature adjustments and controls can improve energy efficiency. Significant energy savings were seen in a few MURBs in the study which converted from continuous recirculating loop to on-demand hot water systems as part of a renewals / upgrades program.

⇢ Elevators

- Elevators rely on controls to be energy efficient. Older elevators may not have controls that are effective at conserving energy, or have controls that are broken or malfunctioning. Since elevators are specialized equipment, and overview mechanical audits may not adequately consider elevators as part of the review. A review of elevator energy consumption and controls by specialized elevator consultants and service contractors is recommended. For example, in several of the 1980's-1990's MURBs within the study, the AC-DC motor convertors were running continuously (timers broken on not installed) even though the cabs were stationary, resulting in thousands of dollars of wasted energy.

⇢ Lighting

- Lighting upgrades to compact fluorescents/LEDs or more energy efficient fluorescent light bulbs and ballasts are relatively low cost, and payback is typically short for these upgrades. Within suites, owners should consider replacement of light bulbs with more efficient types.
- Common areas such as corridors and stairwells typically have lighting on 24 hours a day, seven days a week. Occupancy sensors can be installed if existing lights and ballasts can accommodate them. Installing occupancy sensors in these areas can result in a significant energy savings, often with a short payback period.

⇢ Air-Sealing, Weatherization and Compartmentalization

- Exterior window and door gaskets and weather-stripping is a maintenance item which affects enclosure airtightness and hence energy savings. A periodic review and replacement of the gaskets and weather-stripping is recommended. Broken window hardware should also be repaired or replaced as necessary.
- Within the building, the air-sealing of mechanical, plumbing and electric shafts and penetrations through floors and suite walls, and weather-stripping of stairwell and elevator doors should be confirmed to reduce airflow between floors and suites, and improve compartmentalization. This air-sealing also improves the efficiency of the make-up air systems to deliver air to the suites and not be lost through the stairwell, garbage chute, and elevator shafts and exhaust out of the building. Typically, the more air that reaches the suites from the corridor, the less heat energy that is required within the suites.

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GLOSSARY AND DEFINITIONS

Air leakage	The uncontrolled flow of air through the building enclosure (i.e. Infiltration or exfiltration) as the result of building pressurization and the enclosure airtightness.
Airtightness	A measure of the air-porosity of the assemblies that make-up the building enclosure at a certain pressure difference. Airtightness can be visualized in terms of an equivalent sized hole in the building enclosure. Typically airtightness is measured at a standard test pressure of 50 or 75 pa to overcome the effects of wind and stack effect and obtain a repeatable measurement.
Air barrier	The materials and components that together control the airflow through an **assembly** and limit the potential for heat loss and **condensation**.
Apartment	A multi-unit residential building in which each unit and the common areas are owned by one owner. The individual units are rented out to tenants who pay rent to the owner.
Assembly	The arrangement of more than one material or component to perform specific overall functions.
Awning window	A window with a top-hinged **sash** that swings out at the bottom. *See also* **hopper window**.
Balcony	An outdoor horizontal surface intended for pedestrian use, which projects from the building that it is not located over a living space or acting as a roof. *See also* **deck**.
Below-grade	The portion of a building that is below ground surface level.
Building enclosure	The environmental separator for the building as a whole. The parts of the building that separate inside conditioned space from unconditioned or outside space while facilitating climate control. Referred to as one type of **environmental separator** in Building Codes.
Casement window	A window with a vertically-hinged **sash** that opens in or out.
Casing	An interior trim molding installed around windows and doors to conceal the area between the wall and the edge of the **jamb**.
Cladding	A material or component of the wall **assembly** that forms the outer surface of the wall and is exposed to the full force of the environment.
Combustible construction	Construction that does not meet the requirements for **noncombustible construction**.
Compartmentalization	Separating a single volume (floor/room/suite/office) within a larger building volume with the primary intention of controlling airflows into, within and out of the enclosed space caused by wind, stack or mechanical pressures. Compartmentalization is typically performed for fire, smoke, odors and acoustic separation; however, it also has important benefits for HVAC control. An example is the air-sealing of floors and vertical shafts within a multi-storey building to control air movement and pressures.
Composite window	A window with two or more **lites** within one or more **frame(s)**.
Condensation	The appearance of moisture (water vapour) on a surface caused by air coming into contact with a surface that is at or below the **dewpoint** temperature of the air.

Condominium	A multi-unit residential building in which each unit is individually owned and the common areas are jointly owned.
Corner post	A **mullion** that joins two windows at an angle to form a corner.
Coupling adapters or coupling bars	A special extrusion, tube, or specific shape that joins two individual window frames together, either vertically or horizontally, to form a **composite window**.
Cross cavity flashing	**Flashing** that intercepts and directs any water flowing down the cavity of a wall **assembly** to the exterior. Sometimes located at the window head level functioning as a **head flashing**.
Deck	An outdoor horizontal surface intended for pedestrian use, which projects from the building that is located over a living space and also functions as a roof. *See also* **balcony**.
Detail	A location within a building enclosure assembly where the typical **assembly** construction is interrupted by a **penetration** of the **assembly** or interfaces with an adjacent **assembly**.
Dewpoint	The temperature at which air is saturated with water vapour (100% RH). Adjacent surfaces at temperatures lower than the dewpoint will lead to the formation of **condensation** on the surface.
DHW	Domestic hot water.
Double-hung window	A window with two vertical sliding **sashes**, one above the other, that are mounted on separate guides allowing either or both to be opened at one time. *See also* **single-hung window**.
Drained cavity	The space behind a watershed surface, such as the wall **cladding**, that provides a **capillary break** facilitating drainage of liquid water present within the **assembly**.
Durability	The ability of a building or any of its components to perform the required functions in its service environment over a period of time without unforeseen cost for **maintenance**, **repair** or **renewal**.
Effective thermal resistance value	An improved approximation for the thermal resistance of a building **assembly** section accounting for the effects of **thermal bridging**. *See also* **nominal thermal resistance value**.
Emissivity	The measure of a surface's ability to emit long-wave infrared radiation.
Environmental separator	The separation of environmentally dissimilar places, most commonly inside conditioned spaces and outside unconditioned spaces. *See also* **building enclosure**.
Exterior insulation finish system (EIFS)	An exterior wall **cladding** system that incorporates insulation and a reinforced stucco-like covering.
Face seal	A **perfect barrier** rain penetration control strategy that relies on the elimination of holes through a single layer, usually the **cladding**. *See also* **concealed barrier** and **perfect barrier**.
Failure	The inability of a material, component, **assembly**, **interface**, or detail to perform its intended function(s).
fenestration	The arrangement and proportion of window and door openings in a building.
Fixed window	A window that does not open.
Flange-mounted window	A window installed in a rough opening that utilizes fin-shaped projections from the **frames**, which are attached to the exterior face of the **sheathing**.

Flashing	The material used to prevent water penetration or direct the flow of water at **interfaces** and joints between construction **assemblies**.
Frame (glazing)	The associated **head**, **jamb**, **sill**, and where applicable, **mullion** and **muntin** members that house the **sash** or fixed **glazing** when assembled.
Frame (structural)	The primary and secondary structural members of a building that supports other structural and nonstructural components of the building.
GigaJoule (GJ)	A unit of energy commonly used to measure gas consumption.
Greenhouse Gases (GHG)	Gases or compounds that lead to heat being trapped in the atmosphere, primarily via blocking infrared radiation that would otherwise be reradiated out to space. Greenhouse gases are emitted during the production of electrical energy and burning of natural gas. The predominant greenhouse gas is carbon dioxide (CO2), however, methane, nitrous oxide, sulphur hexafluoride, perfluorocarbons, hydrofluorocarbons are concerns. Scientific evidence suggests that maintaining current GHG emission rates will likely lead to serious adverse climate impacts.
Glazing	The act of furnishing or installing glass in an opening.
Head	The horizontal member that forms the top of the window **frame**. *See also* **sill**.
Head flashing	**Flashing** that is installed in a wall over a window opening or projection.
High-rise	A building greater than 10 storeys in height. Within this report, it may also refer to a **mid-rise** for simplification.
Hopper window	A window with a bottom-hinged **sash** that swings in or out at the top. *See also* **awning window**.
Horizontal movement joint	A horizontal joint on a wall that provides capability for differential movement of portions of the building structure (**expansion joint**), or prevents or localizes cracking of brittle materials such as stucco (**control joint**).
Horizontal slider window	A window with **sashes** that slide horizontally on guides to open and close.
Heating, ventilating, and air conditioning (HVAC)	The system used to condition the interior air of a building.
Hygrothermal	The combined effects of moisture and heat transfer through building materials.
Insulating glazing unit (IGU)	**Glazing** that consists of two or more **lites** separated by a hermetically sealed air space joined around the edges.
Interface	A location within the **building enclosure** where two different components or **assemblies** meet.
Kilowatt hour (kwh)	A unit of energy commonly used to measure electrical consumption.
Jamb	The vertical members that form the sides of a window or door **frame**.
Life cycle cost	The cumulative amount of money required to develop, install, own, operate, maintain, and dispose of an asset over its projected life.
Low-e coating	Low-emissivity coating applied to a glass surface to reduce radiation heat transfer and improve the **U-value**.
Low-rise	A building less than or equal to 4 storeys in height.

Maintenance	A regular process of inspection, minor repairs, and replacement of components of the **building enclosure** to maintain a desired level of performance without unforeseen **renewals**.
Make-up air (MUA)	Outdoor air supplied to the building to replace exhaust air and exfiltration. In multi-unit residential buildings make-up air is often supplied to corridors and intended to enter suites through the entry door undercuts. **Make-up air** is typically tempered at the source (i.e. Before it is supplied to the space), and therefore contributes to space heating (whether intentional or not). Make-up air may also be cooled. *See also* **space heating**. Make-up air is typically provided by a **make-up air unit.**
Make-up air unit (MUA)	A large air handler that conditions 100% outside air for ventilation, and no re-circulated air, is known as a make-up air unit (MAU). Air is heated, typically by natural gas within make-up air units. Make-up air units are typically located on the roof.
Mid-rise	A building greater than 4 storeys and less than 10 storeys in height. Throughout the report a mid-rise building may also be called a high-rise for simplification.
Mulled window assembly	An **assembly** of two or more individual windows that are installed in a single, rough opening joined by **coupling adapters**.
Mullion	The vertical or horizontal frame member that separates two or more window units.
Muntin	The vertical or horizontal sash member that separate **lites** within a window into smaller sections.
Murb	Multi-Unit Residential Building. In this report this refers to **condominiums.**
Nominal thermal resistance value	The R-value of a material only (i.e. Insulation). The nominal value does not account for the use of the material within an assembly of materials with differing thermal properties and thermal bridges.
Noncombustible construction	Construction in which a degree of fire safety is attained by the use of noncombustible materials as defined in the building codes. *See also* **combustible construction**.
Operable vent	Also referred to as an **operable window**, a window that may be opened or closed to accommodate ventilation.
Operable window	*See* **operable vent**.
Parapet	The part of a wall that extends above the roof level.
Penetration	An intentional opening through an **assembly** for ducts, electrical wires, pipes, and fasteners to pass through.
Premature failure	The inability of an **assembly**, **interface**, or **detail** to perform its intended function(s) during its expected service life.
Pressure moderated rainscreen	A rainscreen assembly with reduced pressure differentials across the **cladding** to further limit water penetration. Features could include compartmentalization of the exterior **drained cavity** and optimization of venting arrangement, cavity size, and stiffness of the cladding and **air barrier**. Pressure moderation does not typically occur in practice.
Primary structure	A structural system that carries the gravity loads and lateral loads imposed to the foundation. *See also* **secondary structure**.
Punched window	A single window frame installed in a wall opening.

Rainscreen	A rain penetration control strategy that relies on **deflection** of the majority of water at the cladding but also incorporates a cavity that provides a drainage path for water that penetrates past the cladding.
Rehabilitate	A program of comprehensive overall improvements to the building enclosure assemblies and **details** so that it can fulfill its originally intended functions.
Repair	The localized or minor reconstruction of **assemblies**, components, or materials of a **building enclosure** so that it can fulfill its originally intended functions.
RSI value or R-value	A material's thermal resistance to conductive heat flow. Higher values indicate greater insulating capabilities. The inverse of U-value.
Sash	The framework of a window that holds the glass.
Secondary structure	A structural support system (framing, clips, and fasteners) required to transfer the imposed gravity loads and lateral loads acting on or through the **building enclosure** to the **primary structure**.
Service life	The actual period of time during which building enclosure materials, components, and **assemblies** perform without unforeseen **maintenance** and **renewals** costs.
Sill	The horizontal member that forms the bottom of the **frame**. *See also* **head**.
Single-hung window	A window with an operable bottom **sash** and a fixed top sash. *See also* **double-hung window**.
Soffit	The underside of the elements of a building, such as roof overhangs or beams.
Solar heat gain coefficient (SHGC)	The fraction of solar radiation admitted through a window, both directly transmitted, and absorbed and subsequently released inward. The lower a window's shgc, the less solar heat it transmits, and the greater its shading ability.
Space conditioning	The general term for heating (to heat the building to some desirable indoor temperature), cooling (to extract heat to cool the building down to a desired temperature) and ventilation (the provision of outdoor air to an interior space). Regardless of the means of generating the desired quality (temperature, humidity, flow rate, and quantity of outdoor air) the air is said to be conditioned. In parts of bc and other cooler temperate climates where cooling is not required in murbs, the space is only heated and ventilated.
Space heating	Providing heat to a space within a building, either a suite or a common area. This may be in the form of convection (forced air such as make-up air) or radiation (such as electric baseboards and hydronic radiators).
Stud	A series of vertical framing members used in walls and partitions.
Sub-sill flashing	A membrane material placed under the window frame within the rough opening to drain water that penetrates through or around the window frame to the exterior of the water resistive barrier.
System	An **assembly** of materials and components that work together to perform a specific function, such as an air barrier system.
Thermal break	A material with low conductivity that is placed between two conductive materials, such as a metal **frame**, to reduce heat flow and decrease **condensation** potential.

Thermal bridging	The transfer of heat through building enclosure elements that have relatively low thermal resistance in comparison to adjacent elements. Studs within an insulated wall **assembly** are one example.
Threshold	The lowest horizontal member of a door that rests on the floor between the jambs of a door frame.
Tilt-and-turn windows	A window that functions as a **casement window** and **hopper window**.
U-value	The measure of the conductive heat transmission property of a material or **assembly** of materials, expressed as a rate of heat flux through a material. The inverse of **r-value or rsi**.
Ventilation	The process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature with the space.
Ventilation (natural)	The flow of air through open windows, doors, grilles, and other planned penetrations driven by natural pressure differentials.
Ventilation (mechanical)	The intentional movement of air into and out of a building using fans and intake and exhaust vents.