Improving the Energy Performance of Multi-Unit Residential Buildings Using Air-Source Heat Pumps and Enclosed Balconies

by

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A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Department of Civil Engineering
University of Toronto

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Abstract

Existing multi-unit residential buildings (MURBs) are important assets for urban regions such as Toronto, Canada. These buildings provide high-density housing and allow for the efficient provision of public services and utilities. However, MURB energy-use imposes a significant environmental burden. A preliminary part of the study presented here found that the median energy intensity of MURBs in Toronto is 300ekWh/m$^2$ and that this energy-use accounts for 17% of residential greenhouse gas (GHG) emissions in the City.

To reduce this environmental burden, this work explores a novel energy retrofit strategy involving a suite-based air-source heat pump (ASHP) operating in an enclosed balcony space which serves as a thermal buffer zone (TBZ) to improve the cold-weather ASHP performance in a heating-dominated climate. More broadly, a methodology for assessing the impact of an energy retrofit measure is developed.

First, energy-use and interior condition data were collected from a 1960s MURB over the course of one year. The subject building was found to have a higher-than-average energy intensity of 374ekWh/m$^2$ and other operational issues including overheating of suites. These data were then used to calibrate an energy model so that the proposed retrofit strategy could be modeled.
Next, the proposed retrofit strategy was tested in a mock apartment unit constructed in a climate-controlled chamber. The testing showed that the coefficient of performance of the ASHP could be improved by operating it in a TBZ with access to heat from solar gains. This finding was used to modify the subject building energy model which showed that applying the proposed retrofit could reduce the annual energy intensity and GHG emissions of the building by 39% and 45%, respectively. An estimate of the impact of applying this retrofit strategy to Toronto MURBs with energy intensities greater than the median results in a median sector energy intensity of 236ekWh/m².
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List of Acronyms

A/C – Air-Conditioning

ASHP – Air-Source Heat Pump

ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers

CDD – Cooling Degree-Day

CMHC – Canada Mortgage and Housing Corporation

COP – Coefficient of Performance

CVRMSE - Coefficient of Variation of the Root Mean Square Error

CWEC – Canadian Weather for Energy Calculations

DAQ – Data Acquisition Unit

DHW – Domestic Hot Water

eQUEST – Quick Energy Simulation Tool

eCO₂ – Equivalent Carbon Dioxide

ekWh – Equivalent Kilowatt-Hour

ERV – Energy Recovery Ventilator

GHG – Greenhouse Gas Emissions

HDD – Heating Degree-Day

HVAC – Heating, Ventilating and Air-Conditioning

MURB – Multi-Unit Residential Building

NMBE - Normalized Mean Bias Error
R<sub>SI</sub> – Thermal Resistance in Système International Units

TBZ – Thermal Buffer Zone
Chapter 1
Introduction

1.1 Background

Our cities are growing. As more of the global population moves into cities, the need for high
density, affordable housing also grows. Multi-unit residential buildings (MURBs) are used to
meet the demands of a growing urban population. In terms of occupied land area and the
 provision of services, high-rise MURBs are considered an efficient housing type. However, due
to the energy intensity and sheer number of these buildings in large urban areas, MURB energy-
use also has a significant negative impact on greenhouse gas emissions (GHG) in cities [1].

Great strides are being made in many jurisdictions around the world to improve the energy
 standards for new buildings thereby reducing the environmental impact. However, the renewal
 rate for the existing building stock is low [2]. Therefore, to significantly reduce the energy-use
 and the related environmental burden of our current building stock, existing buildings such as
MURBs will need to be energy retrofitted.

This thesis is based on the exploration of a novel energy retrofit strategy. This strategy involves
operating an air-source heat pump (ASHP) within a thermal buffer zone (TBZ) created by
enclosing MURB balconies.

The context for this study is MURBs in the City of Toronto. Toronto is a unique place in which
to study MURB energy-use. In North America, it is second only to New York City in terms of
the total number of high-rise residential buildings [3]. Furthermore, MURBs comprise 55% of
the dwelling units in the City of Toronto [4]. It has been estimated that Toronto MURBs emit
over 2.6M tonnes of equivalent carbon dioxide (eCO₂) annually, or more than 17% of the total
annual GHG emissions associated with natural gas and electricity consumption in the City in
2004 [1]. Thus, MURBs contribute significantly to the environmental impact of residential
building energy-use in the City of Toronto. While Toronto will be used as the context for this
study, many urban regions around the world that rely heavily on MURBs for housing stock can
also benefit from the findings of this work.
1.1.1 MURBs in Toronto

Many Toronto MURBs were constructed to provide housing for a rapidly growing population during the 1960s and 1970s. At the time of construction, prior to the 1973 oil embargo, energy was considered plentiful and inexpensive so minimizing building energy consumption was not a priority. These market conditions led to building design decisions which contribute to the high energy intensity of these buildings today. Though every MURB is different, buildings of this post-war vintage, such as the archetype image shown in Figure 1, share many common characteristics and the associated challenges.

Figure 1: Post-war Building Archetype

*Figure Source: [5], reproduced here with permission of the author*

One reason why MURBs have high energy intensities is related to space conditioning. Many of these buildings, particularly those constructed in the 1960s and 1970s, are heated with perimeter hydronic or electric radiators and feature a pressurized-corridor ventilation system. Typically there is no central air-conditioning. Instead window air-conditioning units are installed in some or all of the suites. In-suite radiator controls are often disabled so occupants typically have little control over their suite temperature. During the winter, occupants attempt to regulate the temperature of their suite by using supplementary heaters as needed. In suites above the neutral pressure plane, occupants often open their windows [6] either for temperature control or access to outside air. While excessive energy-use results from air leaky envelopes, this problem is aggravated by the uncontrolled air leakage associated with opening windows. With uncontrolled
air leakage and the effect of stack action, suites tend to be over- or under-ventilated. With poor circulation of fresh air [7], indoor air quality suffers as well. In some MURBs, the mechanical equipment used to supply space heating and ventilation is original to the building, which can result in low energy efficiency due to equipment age. However, as the original mechanical systems reach the end of their design service life, there is an opportunity to change the way the buildings systems function.

Excessive energy-use also results from building envelopes that lose heat due to the provision of little or no thermal insulation. As well, exposed floor slab edges act as efficient thermal bridges, needlessly wasting heat. Other issues include insect, smoke, odour and noise transmission between units [7]. Yet, from a structural standpoint, many of these buildings still have decades of service life remaining [5] making them strong candidates for renewal.

1.1.2 Current Approaches to MURB Energy Retrofits

The capital expenditure required to keep up with building maintenance is significant. A report commissioned by the Canada Mortgage and Housing Corporation [8] estimated that approximately $60M (2013$) must be spend each year on high-rise rental apartment repairs and maintenance in the former cities of Toronto and York. This recommendation, based on approximately one quarter of the number of MURBs in the Greater Toronto Area, is not intended to improve the energy performance but rather to restore these buildings back to a ‘satisfactory level.’

Some building owners view these mandatory expenditures on building maintenance as an opportunity to improve building energy performance. For example, when equipment such as boilers, chillers and air handling units are replaced at the end of their service life, the incremental cost of choosing a higher efficiency model over a standard model can be insignificant relative to the incremental energy cost savings. Projects, such as roof replacements and over-cladding of walls to prevent rainwater penetration, present other opportunities for energy retrofits, such as adding insulation, at a small incremental cost. Though some retrofit projects are relatively comprehensive and can result in significant energy savings [9], most target the ‘lowest hanging fruit’ for the associated shorter payback periods. This short-sighted approach puts the building owner in a reactive position, dealing with building components as they fail rather than investing in a more robust and efficient building system.
Aside from the opportunities in basic building maintenance projects, energy retrofits are also prompted by a need to reduce operating expenses. Particularly in the rental market, utility costs are one of the only expenses that can be influenced by the building owner. Rental rate increases are restricted and most expenses such as building management fees, property taxes and insurance are fixed. As such, building owners can only increase their revenue if they can deliver the required heating, cooling and ventilation in a more efficient and cost-effective manner.

In some jurisdictions, there are also financial incentives to undertake energy retrofit projects [10][11]. Utility companies and energy agencies will sometimes offer rebates for a proven reduction in natural gas or electricity use. Through anecdotal evidence observed by the author, many of these incentives do not appear to be retrofit catalysts for building owners but rather serve to mitigate project risks.

### 1.2 Proposed Retrofit Strategy

The proposed retrofit strategy has been adapted from an idea originally developed for single family homes called Nested Thermal Envelope Design™ (NTED™). This design also uses suite-based mechanical equipment, a current trend in the new MURB construction industry [10]. This section briefly outlines the origin of these two ideas and how they contribute to the proposed retrofit strategy. Following this discussion, the goals of the work and the methods employed are presented.

NTED™, developed by Pressnail and Richman at the University of Toronto, involves the construction of a building within a building or, in other words, a core space surrounded by a TBZ [12]. During the heating season, an ASHP is used to recover heat that is lost from the core to the TBZ. By operating an ASHP in the TBZ, which is warmer than the exterior, the coefficient of performance (COP) of the ASHP is improved.

The use of a TBZ can be coupled with suite-based mechanical equipment. Such equipment is becoming more common in new construction and is preferred by both occupants and property managers [13]. These systems can provide better occupant control of the interior environment and present an opportunity to shift direct financial responsibility for energy-use from the building owner to the individual occupants. When paired with compartmentalization, or air sealing between suites and corridors, further benefits of suite-based space conditioning can be
realized. These include improved fire safety and indoor air quality as well as the reduced effects of stack pressure and the associated uncontrolled air leakage [14]. In contrast with a typical central heating, ventilating and air-conditioning (HVAC) system where the building is conditioned to a single minimum set point temperature, suite-based systems can also save energy by delivering energy only when and where it is needed.

The proposed retrofit strategy involves replacing the central space heating equipment in a MURB with suite-based ASHPs to provide demand-based space conditioning. However, ASHPs have not been widely adopted for heating in colder climates because the COP is lower when outdoor temperatures are colder. To maintain efficient operation of the ASHP on the coldest days of the year, more heat must be made available for pumping. One opportunity, unique to MURBs, is to make use of the existing balcony space as a TBZ. By enclosing the unconditioned balcony, a volume of air, heated by passive solar gains and heat losses from the apartment, can be used to increase the COP of the ASHP. The work presented here explores how this alternative use of ASHPs operating in cold climates may be able to take advantage of an often underutilized architectural feature: the MURB balcony.

1.2.1 Study Goals and Methods

The primary goal of this work is to determine the impact of the proposed retrofit on MURB energy-use and, more broadly, establish a methodology for comprehensively assessing the impact of building energy retrofits. However, as the effect of a suite-based retrofit strategy cannot be separated from whole-building performance and, in turn, building stock performance, sub-goals of the work include characterization of MURB energy-use in Toronto and the energy-use of a subject MURB to which the retrofit strategy could be applied. The strategy to achieve these goals involved first gathering and analyzing MURB energy-use and building data to characterize the performance of the existing building stock and to identify the worst energy performers. This was followed by a detailed investigation of the operation of a typical MURB so that testing of this novel energy retrofit strategy could be informed by the operating conditions of an actual building. Then, the proposed retrofit strategy was tested using a mock-up in a laboratory and the performance was modeled. Finally, the impact of the proposed retrofit measure was assessed at the suite, building and building stock level. Figure 2 shows the general
methods used in this work while the chapters that follow provide specific details of the equipment and techniques employed.

Figure 2: Methods Employed

1.3 Thesis Structure

This thesis is formed by a compilation of four journal papers. The first paper describes an investigation of MURB energy-use in Toronto and shows correlations between building characteristics and energy-use. The second paper describes the monitoring of an occupied building and the use of the data collected to improve the calibration a whole-building energy model. The third paper describes the laboratory testing of an ASHP operating in a TBZ as well as the development of a suite-based energy model calibrated to the performance data collected. The fourth and final paper combines the results of the second and third papers supplemented by additional energy modeling and data processing to generate an estimate of the energy savings associated with implementing the proposed retrofit strategy in an existing MURB. The thesis ends with a general discussion of the impact of the proposed energy retrofit strategy and a brief conclusion. The remainder of this section includes a summary of each chapter to follow. Details of the contributions of each author and the publication status are provided in Appendix A.
To efficiently reduce the energy-use and environmental impact of the MURB sector, buildings with the highest energy intensity need to be identified. Accordingly, Chapter 2 presents correlations between building characteristics and energy-use. A wide range of energy intensities were revealed and it was found that typology-specific energy-use trends could not be established. The variability in energy intensities found was generally attributed to differences in building operation and it was suggested that many buildings can realize improved energy performance by changing operating procedures. The building characteristic exhibiting the strongest correlation with energy-use was fenestration ratio.

Energy modeling is a useful tool for evaluating the performance of possible building energy retrofit measures. Traditionally, energy models are developed using data collected from building floor plans and site visits and are then calibrated using utility bills. In Chapter 3, data gathered from one year of monitoring were assembled to characterize the actual building performance and to calibrate a refined energy model. It was found that the interior temperature measurements and the sub-metered suite electricity use were the most useful for improving the accuracy of the energy model compared to a traditional approach that only uses data from utility bills. Other data collected including window operation and differential air pressures were useful for determining how the building was operating.

Chapter 4 details the laboratory testing of the proposed retrofit strategy. The temperature drawdown of the TBZ and the associated impact on the COP were observed and the solar heat gain rates required to improve the COP of the ASHP were identified for a range of exterior temperatures. Using the laboratory results, a suite-based energy model was developed and calibrated to simulate the performance of the ASHP operating in the TBZ. Although the software could not model a variable-speed ASHP, it still provided reasonable predictions of the ASHP performance below 10°C using a single-speed ASHP model.

The goal of work presented in Chapter 5 was to determine the impact of the proposed retrofit strategy on the energy performance of the subject MURB. Here, the calibrated whole-building model from Chapter 3 is combined with the results from the laboratory testing described in Chapter 4 to estimate this impact. First, a suite-based energy model reflecting the subject building was generated. Due to limitations encountered with the energy modeling software, a model output processor was also developed to determine the energy flows from the TBZ to space
heating and hot water storage. The resulting energy reduction factors were applied to the calibrated whole-building model to determine the impact of the proposed retrofit. The proposed retrofit measure was found to significantly reduce the energy-use of the subject building while also reducing the frequency of overheating on the south side of the building.

The focus of this work is on the application of a proposed retrofit measure to a subject MURB. However, Chapter 6 extends the discussion beyond the scope of each of the individual papers forming this thesis and considers the impact of the proposed retrofit on the Toronto MURB stock as whole. This study also shows how the energy performance of the proposed retrofit measure can be improved by using a different TBZ configuration: projected versus inset balconies. Finally, the qualitative benefits of the proposed retrofit measure are presented along with a discussion of how the approach described in this thesis can be applied more broadly to assess other energy retrofit strategies.

Chapter 7 briefly summarizes the key findings from each of the previous chapters and provides several general conclusions about the operation of ASHPs within TBZs as an energy retrofit measure for MURBs.
Chapter 2
Correlating Energy Consumption with Multi-Unit Residential Building Characteristics

This chapter describes the process of determining the energy-use of multi-unit residential buildings (MURBs) in Toronto. The objective was to determine how to easily identify MURBs with the highest energy intensity. In doing this, buildings with the greatest environmental impact could be targeted first to efficiently reduce the impact of the MURB stock as a whole. To accomplish this objective it was necessary to determine the energy intensities of a large sample of MURBs and then to identify the building groups with the highest energy intensities. This way, policy recommendations targeting those groups with the highest energy intensities could be developed.

Beginning with an outline of the approach, this chapter provides details of previous MURB energy studies. The assembly and processing of energy-use and building data are then described. Next, the energy-use data are presented and correlations between energy-use and building characteristics are discussed. The chapter concludes with a summary of the findings and recommendations to improve MURB energy-use data going forward.

2.1 Approach

Many Toronto MURBs were designed and built during the 1960s and 1970s and, therefore, they exhibit similar architectural features and mechanical system characteristics. Accordingly, this part of the study examined correlations between building typologies and energy-use. Correlations between normalized energy-use and building characteristics were sought using two distinct data sets. The preliminary data included 108 buildings from three existing databases. A meta-analysis of this data was carried out, and it was concluded that additional energy data and more complete details about building characteristics were needed. A second, refined data set with 40 buildings was then assembled from the best quality data in the Meta-Analysis Data Set and supplemented with buildings that were new to the study. Since this Refined Data Set contained more detailed and comprehensive building information, it became possible to examine how various building characteristics, previously unexplored in the meta-analysis, affected energy-use. The results of the search for correlations between similar basic building
characteristics and energy-use are reported here and the significance of the findings is discussed. Recommendations for researchers and policy makers on building energy-use data collection strategies and benchmarking practices were made so that better quality data can be used to develop policy interventions to efficiently reduce energy-use and greenhouse gas (GHG) emissions in existing MURBs.

2.2 Previous Work

A number of studies, based on consumer-supplied energy data of MURBs in the Greater Toronto Area, sought correlations between energy intensity and various characteristics such as building vintage, height and floor area. All of the studies included less than 100 buildings. The results of one study showed no significant correlations [15] while the other studies found correlations (some without a specified strength) between energy intensity and building height, gross floor area, vintage ownership type, aspect ratio and common area size [16][17][18][19][20][21]. The correlations indicated that privately-owned buildings had higher average energy intensities than public housing, buildings heated with natural gas exhibited higher average energy intensities than those heated electrically [18], buildings constructed after the 1990s used more energy than older buildings [19], and more compact buildings used less energy [20].

In the current work, a sample size larger than the previous investigations described was sought with the aim of developing stronger correlations. To the author’s knowledge, this work is the only Toronto-specific published study that examines correlations between energy-use and specific envelope and mechanical system characteristics. These types of correlations are important for identifying the largest contributing factors to energy intensity. By identifying these factors, retrofit measures can be prioritized and new building code measures, such as decreased fenestration ratios, can be supported. Finally, all results have been normalized to the Canadian Weather for Energy Calculations (CWEC) Toronto standard weather year so that other researchers can easily use these data.

2.3 Building Characteristics and Energy-Use Data

As described, data were assembled from existing data sets to form the Meta-Analysis Data Set and were later supplemented with more detailed data to form the Refined Data Set. The
characteristics of each data set are presented here along with details on how the data sets were used and the limitations that must be considered when reviewing the analysis.

2.3.1 Meta-Analysis and Refined Data Sets

To build on the work of others, existing MURB energy-use data sets were sought. The Meta-Analysis Data Set combined energy-use data and basic building characteristics from three sources namely: the Canada Mortgage and Housing Corporation’s “High-rise Building Statistically Representative” (HiSTAR) Database and the Green Condo Champions Program and Tower Renewal Benchmarking Initiative, both provided by the Toronto Atmospheric Fund.

This Meta-Analysis data set included 108 buildings, as shown in Table 1, which represented an estimated 4.8% of the entire mid- and high-rise MURB population and 1.8% of the total MURB population in Toronto [22]. Building construction dates ranged from 1941 to 2009. Building heights ranged from four to 46 stories and gross floor areas ranged from 2,000m² to 101,700m². A summary of the complete Meta-Analysis Data Set is provided in Appendix B.

The Refined Data Set included 31 buildings from the Meta-Analysis Data Set and 9 new buildings including: two that were the focus of a study by Tzekova et al. [23]; three that were the subject of a community energy plan for the City of Toronto [24]; and the remainder were obtained from energy audit reports conducted by engineering consulting firms for projects being carried out by the City of Toronto’s Tower Renewal Office.

This smaller Refined Data Set represented 1.9% of the mid- and high-rise MURB population and 0.7% of the entire MURB population in Toronto. The buildings had construction dates that ranged from 1960 to 2003 and building heights that ranged from 5 to 28 stories. The sample buildings varied in size from 24 to 250 suites. A summary of the complete Refined Data Set is provided in Appendix C.
Table 1: Data Sources for Energy-Use Analysis

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of Buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Meta-Analysis Data Set</td>
</tr>
<tr>
<td>High-rise Building Statistically Representative Database (Canada Mortgage and Housing Corporation)</td>
<td>55</td>
</tr>
<tr>
<td>Green Condo Champions Program (Toronto Atmospheric Fund)</td>
<td>42</td>
</tr>
<tr>
<td>Tower Renewal Benchmarking Initiative (Toronto Atmospheric Fund)</td>
<td>11</td>
</tr>
<tr>
<td>Other (various sources)</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>108</td>
</tr>
</tbody>
</table>

Considering the building heights and vintages sampled, the inventory from both the Meta-Analysis Data Set and the Refined Data Set was compared to an estimate of the entire MURB population in Toronto, as shown in Figure 3. The “percentage of sample” refers to the proportion of the total number of buildings in the particular data set that fall within a given category. Similarly, the “percentage of population” refers to the proportion of the total number of buildings in Toronto that fall within a given category. If the “percentage of sample” is larger than the “percentage of population”, then that category is over-represented in the sample and vice versa.
Figure 3: Comparison of the Height and Vintage of the Buildings Sampled with the Toronto MURB Population

The data for the number of Toronto buildings in each height and vintage category has been calculated by adjusting data derived from the TObuilt database [25]. The TObuilt database is an online resource that contains information on building characteristics for 1,530 high-rise MURBs (greater than eight stories), and 125 mid-rise MURBs (five to eight stories).

Limitations of the Meta-Analysis Data Set include a slight over-representation in the mid-rise category and a corresponding slight under-representation in the high-rise category. In terms of building vintage, the Meta-Analysis Data Set significantly over-represents the population of buildings constructed between 1981 and 2000.

With respect to the quality of the data, portions of the Meta-Analysis Data Set were incomplete or missing and the building characteristics data were not sufficiently detailed. In some cases, monthly electricity data were not available or only annual natural gas or electricity data were provided. Additionally, the Meta-Analysis data generally lacked information about mechanical system efficiencies and building envelope details.
A Refined Data Set of 40 buildings was assembled to address the data limitations of the Meta-Analysis Data Set. More complete energy consumption data and information about building parameters such as fenestration-to-wall ratio, envelope thermal resistance and mechanical equipment efficiency were available for these buildings.

Overall, the Refined Data Set sample distribution of building height, also shown in Figure 3, was similar to the Meta-Analysis distribution. As with the Meta-Analysis Data Set, there was also an over-representation of buildings from the 1990s.

2.3.2 Data Set Usage and Sources of Error

Both data sets were analyzed to determine correlations between building characteristics and energy-use. As maximizing the number of buildings included in each correlation was a priority, the larger Meta-Analysis Data Set was first examined for correlations with readily available building characteristics such as vintage, size and occupancy type. The Refined Data Set was then used to seek correlations with certain building envelope and mechanical system properties. The Meta-Analysis correlations were repeated for the Refined Data Set to ensure there were no significant differences between the data sets.

2.3.2.1 Energy Intensity Determination

Most of the correlations were sought with respect to energy intensity. The energy intensity of each building was determined by dividing the total weather-normalized energy consumption by the gross floor area. The gross floor area represents the total area containing residential suites, lobby, common areas, and any conditioned recreational areas. It typically did not include underground parking areas even though these spaces are at least partly conditioned in many buildings.

It is important to note that the calculation method for the gross floor area data collected from the sources listed in Table 1 is not known. One publication reported that, depending on the calculation method, the floor area of a building can vary by up to 20% [20]. Often, the gross floor area is estimated from floor plans of the building, from physical measurements, or from values obtained from real estate information. These methods may not yield accurate measurements of the total floor area. The most accurate gross floor area information is likely to
exist for condominiums since this information is important for subdividing ownership of the building.

To determine the energy-use per suite, the average suite size was needed. Detailed data on various suite and common space areas was not available so an “attributed” suite size was used rather than the actual suite size. The average attributed suite area was estimated by dividing the gross floor area by the number of suites. This average attributed suite area is larger than the actual average suite size because it also includes a portion of the common areas.

2.3.2.2 Sources of Error

The accuracy of the energy intensity values may be affected by errors in the gross floor area as well as by the use of the average attributed suite floor area. Additionally, if the underground parking area is conditioned but not included in the gross floor area calculation, the energy intensity based on the occupied space of the building will be overestimated. Conversely, building energy intensity will be underestimated if the underground parking garage area is included in the gross floor area, but is only partly conditioned. The effect of an inaccurate estimation of the floor area of conditioned space will be diminished with a larger data set as errors offset one another; however, more detailed data are generally required with respect to whether parking garages are included in the gross floor area and whether these spaces are conditioned.

Information about the building characteristics used in the correlation analysis of the Refined Data Set was gathered from the energy audit report for each building. Building information was collected by more than 12 individuals from at least seven engineering consulting firms. The practices and the assumptions made by each firm vary, and the judgment of each individual may contribute to inconsistencies and variability in the data. Since the energy data and building information were not collected specifically for this study and since information was not necessarily recorded with the aim of being directly comparable with other data sources, the data were scrutinized for inconsistencies. Since data sources were not generally identified in audit reports, it is not known whether some of the data, such as fenestration ratio and boiler efficiencies, were estimated as opposed to actually measured.

To minimize the effect of these errors, further research was conducted. For example, supplementary data sources such as photographs of the buildings obtained through internet
searches were used to verify information such as the fenestration ratio, the presence of balconies and exposed slab edges, the typical type of wall construction, the number of floors, as well as the window air-conditioning units and roof-top equipment such as make-up air units. Building address searches were used to obtain more information about the ownership type and the presence of amenities such as pools or fitness facilities. Finally, census information combined with the number of suites was used to estimate the average number of occupants per suite. However, it is important to note that, even with an accurate estimate of the number of occupants, occupant behaviour will always vary. For example, energy-use profiles vary between buildings that house young families compared to buildings that house senior citizens. Obviously, census information by tract cannot provide the necessary building-level detail about occupant profiles.

2.4 Data Processing Procedure

From building to building, the energy data varied according to location, billing periods and billing years. Therefore, normalization was required to account for these variations. The normalization processes applied depended on the data characteristics and was different for each data set. A spreadsheet program was used for all of the normalization processing and an example of the procedure used is provided in Section 2.4.1. Following the normalization process, buildings were categorized according to the heating system type and the presence of air conditioning to ensure comparisons were made between similar buildings.

2.4.1 Data Normalization

Three different normalization processes were undertaken: calendarization, normalization of the total energy consumption and finally, weather normalization.

Calendarization was carried out to allow buildings with different billing cycles to be directly compared. Meter reading dates were used to apportion energy-use to a particular calendar month.

For one data source, total consumption normalization was required when the sum of the monthly energy consumption did not equal the total annual consumption provided. This “difference” can occur because utility companies will sometimes estimate consumption and make a subsequent adjustment based on an actual meter reading. This discrepancy was minimized by distributing the “difference” equally among the months of the affected year before the weather normalization
process was started. Where total consumption normalization was required, the adjustment did not change the total annual consumption by more than 2%.

The energy consumption data were collected from a range of years for buildings in the Greater Toronto Area. Weather conditions vary from year to year and location to location thereby influencing energy-use. Thus, energy consumption data must be weather normalized to a common year and location to allow for comparison between buildings. The weather normalization process involved the following steps:

1. The monthly energy consumption data for all of the available months were plotted versus the monthly degree-days, as shown in Figure 4 for a sample building.

2. Linear regression was then used to determine a line of best fit for the data.

3. The coefficient of determination or the “$R^2$ value” of the linear regression was used to indicate how well the degree-days explained the building energy-use.

4. The base load was generally determined from the y-intercept of the line-of-best-fit equation. An alternative method for calculation of the base load is described in Section 2.4.2.1.

5. The equation of the line of best fit was then used to determine the energy consumption over a “standard weather year.” This was done by entering the monthly degree-day data from the standard weather year into the line-of-best-fit equation to determine the resulting standard monthly energy consumption.

6. The sum of the monthly energy consumption represented the weather-normalized annual energy consumption value.
Figure 4: Determination of the Base Load Component of Building Natural Gas Consumption Through the y-Intercept Method for a Sample Building

The historical monthly Heating Degree-Day (HDD) and Cooling Degree-Day (CDD) data were obtained from Environment Canada for the applicable locations and years. All degree-days for both historical weather and the standard reference year were calculated with an 18°C base, using the assumption that heating is not required until the exterior temperature falls below this base temperature [26]. The standard weather year was based on data from the CWEC database. The CWEC data used in this paper were based on Toronto mean temperatures from 1960-1989.

HDDs were used for the natural gas weather normalization while three separate correlations were performed with electricity data to capture the possible use of electricity for both heating and cooling. The three correlations included monthly electricity consumption data plotted against 12 months of HDD data, 12 months of CDD data, and a composite of 6-month HDD (November through April) and 6-month CDD data (May through October). The resulting trend with the highest coefficient of determination was used for the normalization. If either the 6-month HDD or 6-month CDD regression resulted in the best correlation, the electricity consumption data were normalized by a composite of six months of HDD and six months of CDD.
2.4.2 Data Classification

Following weather normalization, further data processing of the Refined Data Set was necessary before determining the influence of building characteristics on energy-use. This additional processing of the Refined Data Set was completed because the more detailed data available in this part of the study warranted investigation beyond the total natural gas and electricity intensities. First, the base (weather-independent) component and the variable (weather-dependent) component of the natural gas and electricity consumption were identified. Additionally, the buildings were classified according to the primary heating system type.

2.4.2.1 Base Load Determination

Two methods were used to determine the base load component. The first method used the y-intercept from the weather normalization, as shown in Figure 4, to determine the base load estimate.

The second method used the average of the two months of lowest energy consumption to estimate the base load. For natural gas loads, the two months of lowest consumption were typically July and August. For electrical loads in buildings with air-conditioning, April and October were typically the lowest. Generally, the “y-Intercept Method” was preferred but the “Low Average Method” was used for buildings exhibiting a relatively low $R^2$ value in the weather normalization because the y-intercept was deemed less certain.

Base and variable electricity consumption were determined using the y-Intercept Method on the best of the three correlations between electricity use and HDD and CDD as described in Section 2.4.1.

2.4.2.2 Heating System Type Determination

Buildings were classified according to primary heating system type to ensure that like-to-like comparisons were made between the buildings within the Refined Data Set.

Toronto is a heating-dominated climate therefore the most significant contributor to variable or weather-dependent load is space heating. So, to verify the heating system information provided in the audit reports, the weather-dependent, variable heating and electricity use was plotted against one another, as shown in Figure 5.
Figure 5: Determination of Primary Heating Fuel Source Based on the Variable Natural Gas and Electricity Intensity of Each Building

Buildings with high variable natural gas intensity (greater than 100ekWh/m²) and low variable electricity intensity (less than 30kWh/m²) were assumed to have natural gas space heating. Natural gas is the primary fuel source used in Toronto because it is readily available and more economical than using electricity for space and domestic hot water heating. As expected, the majority of buildings in the study were classified as natural gas space heating. Some building data included details of the type of natural gas space heating system – hydronic radiators or fan coil units. Some buildings, with high variable electricity loads and low variable natural gas loads were assumed to use electricity for the primary space heating system, also shown in Figure 5. Buildings with relatively low variable energy intensities in both energy source categories were classified as combination systems. Therefore, buildings were allocated to one of three groups: natural gas space heating, electric space heating, or a combination of both.

Some buildings also had air-conditioning, which was either suite-based or centrally supplied. The presence of air-conditioning in a building was determined using the results of a correlation between total electricity use and CDD. If the coefficient of determination was greater than 0.5, it was assumed that the building had air-conditioning.
Using the findings from Figure 5 and the correlations between electricity use and CDD for each building, the heating system type and the presence of air-conditioning were determined. Table 2 summarizes the number of buildings assigned to each category.

Table 2: Summary of Building Space Conditioning Classes

<table>
<thead>
<tr>
<th>Building Space Conditioning Class</th>
<th>Number of Buildings Assigned to each Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primarily Natural Gas Space Heating</td>
<td>29</td>
</tr>
<tr>
<td>Primarily Electrical Space Heating</td>
<td>3</td>
</tr>
<tr>
<td>Combined Natural Gas and Electrical Space Heating</td>
<td>4</td>
</tr>
<tr>
<td>Air-conditioned Buildings</td>
<td>11</td>
</tr>
<tr>
<td>Buildings with anomalously low energy-use (Possibly missing some energy-use data)</td>
<td>4</td>
</tr>
</tbody>
</table>

2.5 Results and Discussion

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

2.5.1 Energy-Use

Figure 6 shows the weather-normalized energy intensity for each building in the data sets, with a median of 300ekWh/m². The worst performing buildings (grouped as the highest 10% of energy users) used more than three times the amount of energy consumed by the best performers (lowest 10% of energy users). This indicates a high level of variability in the data sets. However, there is some uncertainty as to whether the energy data of the two best performers, in particular, are complete given the extremely low energy intensity of these buildings.
The range in energy intensity may reflect a variety of factors. These factors include differences in the way the buildings are operated, in the efficiency of the major mechanical and electrical systems, and in the materials and methods used to construct the building envelope.

A study of building energy-use in New York City assessed annual energy intensity in a similar way [27]. The authors of the New York study suggested that the buildings with the highest energy intensities could achieve significant reductions in energy-use through low-cost means such as adjusting controls, sensors and schedules of the mechanical equipment. They estimated the impact of this change by considering a few different energy reduction scenarios.

Based on their findings, it is believed that the highest energy intensity buildings from the Refined Data Set could achieve the median energy intensity of the sample through relatively inexpensive adjustments to building operations and maintenance. This assumes that the Refined Data Set sample is representative of the actual Toronto MURB population, which is discussed in Section 2.3.1, and that these low-cost energy-savings opportunities in New York City are similar to the opportunities available in the Toronto MURB stock. If these assumptions are true, simple energy conservation measures could reduce the energy consumption of the entire Toronto MURB building stock by more than 10%, as shown in Figure 7. Going further, if the buildings were

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**Figure 6: Total Annual Energy Intensity of the Sampled Buildings**

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able to achieve an energy intensity equivalent to that of the 75th percentile, the total reduction in energy-use would be more than 35%.

![Graph showing energy intensity across buildings.](image)

**Figure 7: Projected Impact of Energy Consumption Reductions on the Refined Data Set**

Further research on the worst energy performers in the Toronto MURB stock is needed to determine what proportion of building energy-use can be influenced by these operational changes. Table 3 summarizes the weather-normalized minimum, maximum and average total annual energy intensity as well as the associated GHG emission intensity based on Toronto emissions factors and the average energy source mix of each data set.
Table 3: Summary of Building Energy-Use Statistics

<table>
<thead>
<tr>
<th>Data set</th>
<th>Energy Intensity (ekWh/m²)</th>
<th>GHG Emission Intensity (kg eCO₂/m²)</th>
<th>Energy Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Avg</td>
</tr>
<tr>
<td>Meta-Analysis</td>
<td>88</td>
<td>520</td>
<td>295</td>
</tr>
<tr>
<td>Refined</td>
<td>91</td>
<td>514</td>
<td>292</td>
</tr>
</tbody>
</table>

GHG emission intensity calculations are based on the following factors for Toronto: 1.879kg/m³ of natural gas and 0.11kg/kWh of electricity [28]

The average energy mix of the Refined Data Set (33% electricity and 67% natural gas) is only slightly different from the published energy mix of apartment buildings in Ontario: 34% electricity and 66% natural gas [29]. The GHG emission intensity figures together with average building size and number of MURBs are consistent with another published estimate which reported that Toronto MURBs erected between 1945 and 1984 were responsible for between 2.0M and 2.2M tonnes of equivalent carbon dioxide (eCO₂) [30].

Generally, the results of this analysis are in line with existing studies [15][16][17][18] when weather-normalization procedures are considered. Figure 8 shows the average, maximum and minimum energy intensity for the other Toronto and Ontario studies discussed in Section 2.2 along with the average HDD for the years from which the energy data were taken.
Disparities between this study and others are due, in part, to different weather normalization practices. The data in this study were normalized to the CWEC standard weather year to directly compare buildings with data from different years. As discussed in Section 2.4.1, this standard year is based on the average weather data in Toronto for a 30-year time period from 1960-1989. This standard weather year may be colder or warmer than the base years used in other studies resulting in differences in the weather dependent component of building energy use. For example, the CWEC has over 20% more HDDs than the average of HDDs from 1990 to 2011.

### 2.5.2 Correlation between Building Characteristics and Energy-Use

With the normalized energy intensity data compiled, correlations with various building characteristics were sought. The Meta-Analysis Data Set included only basic properties such as building height and vintage while the Refined Data Set included more detailed data such as envelope characteristics and mechanical system details. A selection of the most significant correlations from each data set is presented here.
2.5.2.1 Meta-Analysis Data Set

The aim of this study was to associate energy intensity with building typologies. As architectural typologies are typically associated with a particular time period, the first correlation investigated was between building energy-use and the date of construction. Figure 9 shows the results of this correlation along with two trend lines indicating the moving average based on five years and ten years. An explanation of how these moving averages were determined is provided in Appendix D. Average energy intensities decreased from older to younger buildings until the 1980s, as indicated by the moving average trend lines. From the 1980s to the 1990s, average energy intensities then started to increase slightly.

![Figure 9: Influence of Building Vintage on Energy Intensity](image)

The higher energy intensities of the oldest buildings in the data set could be due to the combination of the age of the mechanical systems and the condition of the building envelope. However, the increased energy intensities in the newer buildings were thought to be due to the energy-saving effects of better thermal insulation and air-tightness measures being offset by higher fenestration ratios. This trend of increasing fenestration ratios was confirmed with data obtained for the Refined Data Set, as shown in Figure 10.
Increasing fenestration ratios may explain the apparent paradox of the declining energy-efficiency of the modern MURBs in the data set. This issue is being addressed by new codes and standards such as the Toronto Green Standard and 2012 Ontario Building Code requirements.

No correlation could be found between energy intensity and gross floor area, number of suites or building height. Naturally, the total building energy-use increases with size, however the correlation between energy intensity and building size is not strong enough to suggest a trend even when buildings are classified by vintage or ownership type. The lack of correlation is likely due to the significant variation of the energy intensity data as previously shown. This finding suggests that policy makers can set the same energy performance benchmarks for high-, mid-, and low-rise MURBs. However, this finding differs from another study based on a Canada-wide sample from the HiSTAR database [18] which showed that buildings between seven and 20 stories were the most energy intensive group.

Investigation of the Meta-Analysis Data Set also included an exploration of the relationship between energy intensity and ownership type and attributed suite size. Buildings were divided into four groups: Co-operatives (owned, subsidized), Condominiums (owned, not subsidized),
Subsidized rental apartments (rented, subsidized) and Market rental apartments (rented, not subsidized). Note that many condominium units are rented out which means that, even if suite owners pay for their individual suite energy use, the actual occupant or energy consumer, may not pay the energy-use separate from rent. Instead, it is likely that renters in condominium buildings pay a fixed monthly rental rate regardless of how much energy they use. Thus, conclusions about occupant behavior with respect to being directly responsible for energy use costs cannot be made.

Figure 11 shows the variation in attributed suite size for each ownership type where the average attributed suite size of the condominium buildings appears larger than the other building types. However an analysis of the variance between the building types indicated that the difference is not statistically significant.

![Figure 11: Influence of Ownership Type on Attributed Suite Size](image)

Then energy intensity of each ownership type was determined on an area basis and on a suite basis, as shown in Figure 12. On a gross floor area basis, condominiums appear to have the lowest average energy intensity, but on a per suite basis, they appear to have the highest energy intensity, as shown in Figure 12. While an analysis of variance between the building types did
not show a statistically significant difference for the energy intensity by area, the difference between building types for energy intensity on a suite basis was statistically significant.

Figure 12: Influence of Ownership Type on Energy Intensity

When viewed on a suite basis, the higher energy intensity of the condominium building can be attributed to generally higher incomes and therefore more household appliances and electronics. This higher per-suite energy intensity can also be attributed to the greater common area loads often seen in condominiums such as pools and gyms. The energy intensities of the subsidized rental buildings on a per suite basis were lower compared to the other ownership types. This can perhaps be explained by restricted operating budgets and limited common areas, typical for this ownership type.

In addition to examining how energy intensity is influenced by building characteristics, a correlation between attributed suite size and building construction date was sought to see if generalizations could be made about how suite size has changed over time, as shown in Figure 13.
Figure 13: Changing Attributed Suite Size with Building Vintage

From the oldest buildings in the data set to the newest buildings, the average attributed suite size increased but this trend this could be influenced by the size of the common areas, the actual suite sizes or both.

2.5.2.2 Refined Data Set

Within the Refined Data Set, buildings were first grouped according to heating system type to ensure a like-to-like comparison. Variables relating to the mechanical and electrical systems, the building envelope, and the occupancy characteristics were then examined to determine their influence on energy intensity. First, these individual variables were tested against various measures of energy-use (normalized by number of suites or suite area) to determine where correlations existed. The correlations revealed the expected relationships. Two of the strongest correlations are presented here and four additional correlations are included in Appendix E.

Since the majority of heat loss and solar heat gain through the building envelope is through the glazing, it was thought that the larger the fenestration ratio, the greater the resulting heating and cooling loads. This expected correlation is revealed Figure 14. The relationship, with respect to natural gas consumption, is stronger in buildings with double-glazed windows than in buildings
with single-glazed windows. This stronger correlation with double-glazed windows is shown by the higher coefficient of determination in Figure 14.

![Figure 14: Influence of Fenestration Ratio on Variable Natural Gas Intensity](image)

**Figure 14: Influence of Fenestration Ratio on Variable Natural Gas Intensity**

It is possible that the coefficient of determination for buildings with single-glazed windows is lower than buildings with double-glazed windows because single-glazed windows are generally older and the glazing units are in worse condition. Thus, the air-tightness of the glazing assemblies may be the significant factor that governs heat loss for these buildings, as opposed to just the fenestration ratio. Generally, if buildings with single-glazed windows are assumed to be older than those with double-glazed windows, other envelope components may also contribute to air leakage which would, in turn, affect space heating energy use. However, this does not account for older buildings that have been retrofit with double-glazed windows. To explore the impact of glazing air tightness versus overall building envelope air tightness, more data are required.

Similar to the correlation with space heating energy, a higher fenestration ratio also leads to greater air-conditioning loads \( R^2 = 0.58 \) for electricity intensity versus fenestration ratio for
double-glazed windows in Figure 90 in Appendix E). This is to be expected because of the higher transmission of solar gains and conductive heat gains through glazing during the summer.

Glazing thermal conductance (U-value) is another factor contributing to heating and cooling loads. Higher U-values mean that more heat transfer occurs and thus heating and cooling loads will presumably be higher. This was confirmed for both heating and cooling as shown by the positive correlation between U-value and energy use in Figure 91 for heating energy ($R^2 = 0.46$) and in Figure 92 for buildings with air conditioning (A/C) ($R^2=0.46$) in Appendix E. The stronger correlation between heating energy and fenestration ratio for buildings with double-glazed windows, compared with the U-value correlation, suggests that glazing area may have a greater effect on heating energy intensity than window thermal conductance.

Another factor affecting building heating loads is the efficiency of the heating system. It was expected that the more efficient the heating system, the lower the resulting variable natural gas intensity. However, the correlation between variable natural gas intensity and boiler efficiency, as shown in Figure 15, was relatively weak with a coefficient of determination of 0.08. This may be due to the fact that the boiler efficiencies provided in the audit reports may not reflect the actual efficiency of the heating system. Therefore, while the approximate relationship is correct, the correlation could be stronger with data that better reflects the actual performance of the heating system.

![Figure 15: Influence of Boiler Efficiency on Variable Natural Gas Intensity](image)

$R^2 = 0.08$
The provided boiler efficiencies are either rated or estimated. The rated efficiency is intended to be an indication of the efficiency of the boiler when it was new and properly commissioned; however, it is possible that this efficiency was never achieved. Also, as the boiler ages, efficiency declines. The rate of decline depends on maintenance practices, the boiler use patterns, the type of boiler, and the boiler and pipe configuration. The influence of boiler age on variable natural gas intensity was also investigated but resulted in a similarly weak correlation ($R^2 = 0.06$ as shown in Figure 93 in Appendix E), likely due to the wide range of factors affecting boiler efficiency.

Therefore, for some of the variables such as boiler efficiency and fenestration ratio, the coefficient of determination was lower than expected because the data may not always reflect the actual conditions of the building. For other variables such as the thermal conductance of the glazing, it was speculated that a different building characteristic such as glazing air-tightness may govern the energy-use relationship instead. However, this hypothesis could not be tested since no data relating to glazing air-tightness were available.

Given the systems-based interaction between building components, instead of one variable at a time, considering a group of variables may better explain the range of energy intensities across the building stock. Therefore, multi-variable regression analyses were conducted to determine the influence of a combination of variables. A step-wise forward selection method was used for each energy use component to determine the highest adjusted $R^2$ value. The adjusted coefficients of determination in the multi-variable linear regression models conducted for the various components of energy intensity were not significantly better than the single linear regression analysis (adjusted $R^2 = 0.57$ for total energy intensity and adjusted $R^2 = 0.18$ for variable natural gas intensity). Furthermore, the variables logically thought to influence the particular energy use components examined did not appear in the list of variables that increased the coefficient of determination. For example, boiler capacity improved the correlation with variable natural gas intensity but boiler efficiency and boiler age did not. While this is, in part, due to the type and quality of data available, it may also point to the fact that different buildings will have different governing variables. For example, the parameter most influencing variable natural gas in one building might be air leakage while in another building it might be the fenestration ratio. A summary of all correlations investigated is provided in Table 23 in Appendix E.
Finally, buildings that were significantly different from the identified trends were examined in greater detail to determine the reasons for the anomalies. The analysis of anomalies revealed that there was not one particular factor that could explain a large group of the anomalies. Rather, information on any special facilities, such as a pool or on-site daycare included in the buildings, aided in the explanation of a number of the anomalies.

2.6 Conclusions and Recommendations

This part of the study revealed a wide range in the energy intensities of Toronto MURBs and that typology-specific energy-use trends could not be established. Nevertheless, a series of interesting observations and conclusions are presented here including recommendations that could be adopted by both future researchers and policy makers.

2.6.1 Data Set Characteristics

The data sets represented the population reasonably well in terms of the division between mid- and high-rise, however, some vintage categories were over-represented due to one of the data sources being from the newer condominium market. Based on the analysis conducted, there did not appear to be any correlation between energy intensity and building height or size. Therefore, specific policies for different building size groups may not be needed.

2.6.2 Energy Intensity Data

The observed energy intensities were highly variable. With this wide range attributed to differences in the way buildings are operated, it was suggested that many buildings can realize significant improvements in energy performance by changing operating procedures. Further research that refines the estimated impact of these operational improvements in the Toronto MURB population is needed. However, more data are required to do this.

To gather these data, the City of Toronto should require reporting of energy-use data and the associated building characteristics. This can either be triggered by the sale or rental of a property [31] or through participation in a retrofit funding scheme. Alternatively this information can be required of all buildings annually [27]. Data can be collected by the property owners or this process can be automated by seeking permission to access smart meter data directly from utility providers. Any required reporting must establish guidelines so that data are collected in a
uniform manner to be easily integrated into a common building energy-use database. Additionally, all energy audits undertaken on a voluntary basis should include explicit information on how data, such as the conditioned floor area, were calculated or a reference to the standard audit guideline followed. Any estimates or assumptions should also be clearly stated and justified.

2.6.3 Energy Mix

Toronto MURBs have significantly higher natural gas intensities compared with electricity intensities. This is consistent with the provincial average building energy consumption breakdown [29]. To significantly reduce the GHG emissions associated with the Toronto MURB sector, natural gas savings measures should be promoted.

2.6.4 Correlation Analysis

Generally, the relationships observed between energy intensity and various building characteristics were as expected. However, for some variables, such as the boiler characteristics in particular, the influence on energy intensity was not as strong as anticipated, as discussed in Section 2.5.2.2.

The energy intensity of buildings decreased with date of construction up until the 1980s when energy intensities began to increase again. This declining energy efficiency may be explained by increased fenestration ratios offsetting the gains of better air-tightness and envelope thermal resistance. To support this explanation, relatively strong correlations between fenestration ratio and variable natural gas intensity were found as well as the presence of increasing fenestration ratios in newer buildings. However, the fenestration ratio cannot be easily altered in an existing building. This challenge has recently been addressed by the prescriptive measures in the new 2012 Ontario Building Code regulations.

Heating system efficiency, second only to glazing characteristics such as the fenestration ratio, is the variable most closely linked to energy intensity. However, the lower-than-expected coefficient of determination between variable natural gas and boiler efficiency could indicate that efficiency estimates of existing boilers are either not accurate or that boiler efficiency does not adequately describe the performance of the heating system as a whole. A cost-effective method for determining more accurate mechanical system efficiencies should be developed.
2.6.5 Weather Normalization

Using a ‘standard weather year’ is a rational way of making energy comparisons between various building studies. Many researchers and consultants have already relied heavily on the use of the CWEC standard weather year; therefore, there are compelling reasons for continuing this approach of weather normalization. However, using the standard weather year to predict energy savings from retrofit measures may lead to erroneous results in periods of changing climate or microclimate conditions. Of particular concern is the risk of over-stating estimated savings due to retrofits.

To avoid this risk, an approach to normalization such as the use of a Climate Index that is referenced to the standard weather year could be developed. Similar to the Consumer Price Index, a Heating Climate Index Value 1.0 could be assigned to the heating degree-days in the CWEC standard weather year, and the heating degree-days in other weather periods could be assigned a corresponding Index Value. A similar approach could be taken with CDDs. With a system like this in place, data from different sources could be readily compared using different reference time frames depending upon the desired outcome of the investigation.

By adopting the recommendations outlined, the body of data on MURB energy-use and building characteristics could be improved so that researchers can develop a more accurate and complete representation of the energy performance of these buildings. By furthering the work presented here, policy makers will have the information they need to efficiently target the highest energy intensity MURBs, thus maximizing the impact of energy conservation spending to reduce the impact of this sector.
Chapter 3
Using Suite Energy-Use and Interior Condition Data to Improve Energy Modeling of a 1960’s Multi-Unit Residential Building

To significantly reduce the energy-use and the related environmental burden of our building stock, existing buildings will need to be energy retrofitted. Planning an energy retrofit usually begins with an assessment of the building condition and the gathering of energy-use data. This assessment phase provides a benchmark so that potential retrofit strategies can be evaluated based on retrofit costs and the corresponding expected return due to energy savings.

In addition to benchmarking, the assessment process involves generating an estimate of the expected retrofit energy savings. To do this, a building energy-use model is usually developed for the subject building and then calibrated with utility bill data. Once calibrated, the model can be used to assess potential energy and greenhouse gas emission savings associated with various retrofit measures. However, there is no precise method to ensure calibrated energy models accurately predict actual building energy use [32]. It is well recognized that just because a model has been calibrated using gross building energy data, it does not necessarily follow that accurate predictions of retrofit energy savings will result. While there is always uncertainty in any computer simulation, an indication that the calibrated model may not be an accurate predictor of retrofit energy savings occurs when the predicted breakdown of energy end-uses or the modeled interior conditions are different from observations of the existing building. Whether or not this difference is acceptable can be compared to generally accepted limits such as those specified in American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14 [33]. Thus, confidence in the accuracy of the modeling output increases when the calibrated model output not only matches the utility data, but it also accurately predicts the observed energy end-use breakdown and the interior conditions such as zone temperatures.

Unfortunately, energy-use patterns and interior conditions in multi-unit residential buildings (MURBs) are not as well documented as commercial buildings. Given the sparse data for MURBs and the complexity and interrelated nature of residential energy consumption [34], an energy modeler seeking to improve the calibration of an energy model must make many assumptions about parameters affecting interior conditions and the behavior of occupants. Such assumptions may lead to inaccurate energy savings predictions.
The goal of this part of the work is to determine whether the traditional approach of calibrating an energy model using gross utility data can be improved by using energy and interior condition data collected through a building monitoring program.

3.1 Approach

The work began with the development of an energy model based on information from building floor plans and audit reports. Utility bill data was calendarized and weather normalized for use with a standard weather file. Then, the model was calibrated using the processed utility data. Herein, calibrating the model in this way is known as the “Traditional Approach.” Given the parameters that are unknown when the Traditional Approach is used, a monitoring program was developed for an occupied MURB. One year of data was collected and used to recalibrate the energy model. Use of these data, which included suite conditions, energy-use and local weather data, to recalibrate the model is referred to as the “Refined Approach.” After development and calibration of the two energy models, the modeled suite temperatures and energy end uses were compared with the monitored data to determine how well each model represented the actual building energy-use and interior conditions. Finally, recommendations about which parameters were most critical to improving the accuracy of the energy model were made.

3.2 Subject Building

MURBs constructed in the 1960’s and 1970’s exhibit many similar features including exposed slab edges, air-leaky exterior envelopes, pressurized-corridor make-up air supply, hydronic baseboard heating and no central air-conditioning. In an attempt to maximize the relevance of the findings, a subject building exhibiting these characteristics was selected. The selected building, shown in Figure 16, is 20-stories and was constructed in 1968. It is one of two student family housing buildings at University of Toronto. This building was selected because, in addition to exhibiting similar features of 1960’s and 1970’s MURBs, drawings, utility bills and audit reports were readily available. Furthermore, the building manager provided frequent site access, allowed installation of the monitoring equipment and facilitated communication with the occupants to enable in-suite monitoring. Basic details of the subject building are provided in Table 4.
Table 4: Details of the Subject Building

<table>
<thead>
<tr>
<th>General Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gross Floor Area</strong></td>
</tr>
<tr>
<td><strong>Number of Suites</strong></td>
</tr>
<tr>
<td><strong>Number of Occupants</strong></td>
</tr>
<tr>
<td><strong>Other details</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Building Envelope</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Walls</strong></td>
</tr>
<tr>
<td><strong>Glazing</strong></td>
</tr>
<tr>
<td><strong>Roof</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity</strong></td>
</tr>
</tbody>
</table>

### Heating System

<table>
<thead>
<tr>
<th></th>
<th>2,934,000 BTU/hr</th>
<th>3 boilers</th>
<th>2006</th>
<th>Hot water radiators without in-suite control</th>
</tr>
</thead>
</table>

### Cooling System

<table>
<thead>
<tr>
<th></th>
<th>Unknown</th>
<th>101 window air conditioning (A/C) units observed</th>
<th>varies</th>
<th>Capacity estimated at 7,000-10,000 BTU/h per unit</th>
</tr>
</thead>
</table>

### Domestic Hot Water (DHW) System

<table>
<thead>
<tr>
<th></th>
<th>2,400,000 BTU/hr</th>
<th>2 boilers</th>
<th>original to building</th>
</tr>
</thead>
</table>

### Ventilation and exhaust

Air handling unit on roof supplies fresh air to corridors. Two central exhaust fans (one for kitchen fans and one for bathroom fans).

Unlike other student residences on campus, this building is occupied by couples and young families. While it is not vacated during the summer months, the number of summertime occupants drops by about 15% compared to the rest of the year. This drop in the number of occupants affects domestic hot water (DHW) use and suite-based electrical loads. These changes have been captured in the models by modifying the number of occupants between summer and winter.

### 3.3 Energy Model Development

The Quick Energy Simulation Tool (eQUEST), developed by the U.S. Department of Energy (DOE), was used to model the subject MURB. This whole-building energy simulation program was chosen because, in addition to modeling new construction, it is commonly used in industry for retrofit measure assessments.

Development of the basic model began with entering of all of the known data. This was followed by estimating values for the uncertain parameters. The estimated parameters were then adjusted to calibrate the model using whole-building energy consumption data. Most of the building details were determined from floor plans, an audit report, interviews with the building manager and site visits. It was not possible to model the particular combination of heating and cooling systems in the building using the Design Development Wizard in eQUEST. The heating, ventilating and air conditioning (HVAC) systems that could not be modeled together included hot water radiators for heating, suite-based packaged terminal air-conditioning units for cooling.
in a selection of suites and conditioned ventilation air supplied to the corridors. However, since the space heating system was switched off completely for the summer season, coincidental heating and cooling was unlikely. Thus, summer and winter models were generated separately with the appropriate seasonal space conditioning systems and then the model outputs were manually combined to generate a complete year.

All available data including occupant density, fenestration ratio per elevation, building envelope details, boiler and tank capacities and quantities as well as fan and pump power were used as inputs for the model. For some unknown parameters such as fan air flow rates and air leakage, estimates were made using values found in the literature [35][36]. These parameters were kept the same for both the Traditional and Refined Approaches. Other unknown parameters such as lighting and plug loads, DHW consumption, zone temperatures and heating loop capacities were used for the model calibration but were also bounded by values from the literature. All model inputs and the sources of these inputs are provided in Appendices F, G and H.

### 3.4 Traditional Approach

Once the model was constructed unknown or uncertain parameters were used to calibrate the model performance to the utility bill data. Many researchers have shown the value of calibration by comparing preliminary models based only on building inputs with those that have been calibrated using monthly utility data. Hanam et al. [36] showed that their un-calibrated models consistently over-estimated natural gas and suite-based electricity consumption and underestimated common area electricity use. Another researcher, Danielski [20], found that the modeled energy-use of 22 apartment buildings was on average 19% lower than the actual energy consumption. To improve the accuracy of the model in this study, the basic model developed as described in Section 3.3 was calibrated using the energy consumption data from utility bills.

#### 3.4.1 Energy Consumption

To run the building energy model, a weather file is needed. Without access to a complete weather file that matches the period of utility bill data, the energy modeler must first weather normalize the billing data to the local area standard weather year used by the energy modeling program. In this case, the Toronto weather file in eQUEST is based on the Canadian Weather for Energy Calculations (CWEC) standard weather year from the City’s main airport.
Utility bill data from 2009 to 2013 was used for the normalization process. Although billing data from 2002 to 2008 was available, it was not included in the analysis because the building had undergone significant energy retrofit measures prior to 2009 including window and boiler replacements as well as a lighting retrofit. If the pre-retrofit data had been included, the resulting normalized values would likely overstate the estimated energy consumption of the subject building in the standard weather year.

The billing data was first calendarized to generate consumption based on each calendar month rather than between arbitrary meter reading dates, as described in Touchie et al. [1]. Then, using the procedure outlined in Section 2.4.1, the natural gas data were plotted against heating degree days (HDDs), assuming a base temperature of 18°C. Next, the line of best fit was determined, as shown in Figure 17. Eighteen degrees is generally accepted in as the base temperature for HDD calculations in Canada because this is the exterior temperature below which space heating would be required [26]. The predicted CWEC standard year natural gas consumption was then determined using the equation of the line of best fit and the standard year monthly HDD totals.

Figure 17: Influence of HDD on Natural Gas Consumption

\[ y = 1250x + 208000 \]

\[ R^2 = 0.97 \]
Typically, the base natural gas consumption associated with DHW is determined from the y-intercept of the plot shown in Figure 17, as described in Section 2.4.1. However, the y-intercept of the best-fit line yielded a summertime natural gas consumption that overestimated the actual by 34%. Therefore, the normalized values were replaced with the actual consumption for the period when the building space heating system was switched off.

Similar to the natural gas normalization process, electricity consumption was normalized in three different ways: by 12 months of HDD; by 12 months of Cooling Degree-Days (CDD); and by a hybrid of six months HDD and six months CDD. Originally, the standard-year monthly electricity consumption was going to be determined by using the above regression analysis to find the model with the highest coefficient of determination. Unfortunately, none of the analyses resulted in coefficients of determination ($R^2$) greater than 0.25 ($R^2_{\text{CDD6mo}}=0.24$, $R^2_{\text{HDD6mo}}=0.17$, $R^2_{\text{CDD12mo}}=0.00$, $R^2_{\text{HDD12mo}}=0.23$). Instead, the average electricity consumption for each month of the years of historical data was taken as the “standard” consumption (e.g. standard April consumption equaled the average consumption for April 2009-2013.) The resulting weather normalized monthly energy consumption profile is shown in Figure 18. The annual energy intensity of the subject building based on the CWEC standard weather year was 374kWh/m².

![Figure 18: Standard Weather Year Annual Energy Consumption](image-url)
The subject building had an annual building energy intensity significantly greater than 300kWh/m², the median energy intensity of the city-wide survey of Toronto MURB energy-use presented in Chapter 2. However, the subject building energy intensity is still well within the sample range as shown in Figure 19. The operation of such buildings with high energy intensities needs to be better understood since these buildings provide the greatest opportunity for energy performance improvement.

**Figure 19: Annual Energy Intensity of the Subject Building Compared to the Sample of Toronto MURBs**

The components of energy-use were analyzed further. The base natural gas load of the subject building (25% of total energy-use) is similar to that in a typical MURB (24%) [37]. The proportion of total natural gas consumption (76%) versus electricity consumption (24%) in the subject building varies significantly from the published typical energy mix of apartment buildings in Ontario: 66% natural gas and 34% electricity [29]. While, the majority of buildings are heated with natural gas, the provincial average is influenced by the number of electrically heated buildings. As the subject building is heated with natural gas, this may explain some of the variation from the provincial average. The higher proportion of natural gas consumption can also perhaps be attributed to the lack of insulation in the envelope or inefficiencies in the space heating system which would increase space heating loads. The absence of a central air-
conditioning system also contributes to lower annual electricity use. However, the relatively constant monthly electricity consumption profile that was determined by averaging the same month from each year and is shown in Figure 18 was unexpected, given that 34% of suites have window air-conditioners. This is discussed further in Section 3.5.4.4.

### 3.4.2 Calibration Using Utility Bills

Many energy model calibration techniques have been developed such as those reviewed and proposed by Reddy [32][38] and Hubler et al. [39]. For this work, a calibration procedure similar to that outlined by Hubler et al. [39] was followed. Calibration using the Traditional Approach began with adjustment of the DHW consumption per occupant to 265L (70 gallons) per day to match the average natural gas consumption for the three months in which there was no space heating (June, July and August). A New York study, which was specific to apartment buildings, found that the average DHW consumption was 204L (54 gallons) per occupant with the minimum and maximum at 114L and 284L (31 and 75 gallons), respectively [40]. A Canada Mortgage and Housing Corporation (CMHC) study [41] found that apartment buildings with young families use 44% more water than seniors so it is reasonable that the subject building, occupied primarily by young families, would use more DHW than an average building.

The remaining natural gas and electricity consumption calibration was carried out iteratively as waste heat from electricity loads affects the heating and cooling requirements of the building. To begin, lighting and plug loads by zone were scaled up from the default values to match the electricity consumption in the shoulder seasons. Next, the set point temperatures and heating loop capacities were adjusted slightly to ensure that the zones were modeled at the default set point temperatures and that the modeled natural gas consumption closely matched the normalized actual consumption. Finally, the cooling capacity was adjusted to match the increase in summer electricity consumption.

The resulting modeled natural gas consumption and electricity consumption are shown in Figure 20 and Figure 21 along with the actual consumption weather normalized to CWEC data.
The ASHRAE Guideline 14, Measurement of Energy and Demand Savings [33], recommends and describes the use of two statistical techniques to compare the modeled and measured data. The normalized mean bias error (NMBE) is used to determine the difference between the measured and modeled values on an annual basis and is shown in Equation 1. However, since the positive and negative errors in the NMBE cancel out thereby reducing the NMBE, a second technique is also employed. The coefficient of variation of the root mean square error
(CVRMSE) represents how well the modeled values fit the measured data and is shown in Equation 2.

**Equation 1**

\[
NMBE = \left( \frac{\sum(y_i - \hat{y}_i)}{(n-p)\bar{y}} \right) \times 100% 
\]

**Equation 2**

\[
CVRMSE = \left\{ \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{(n-p)}} \right\} \times 100% 
\]

*where:*

\( y_i = \text{actual monthly energy use} \)

\( \hat{y}_i = \text{predicted monthly energy use} \)

\( \bar{y} = \text{mean monthly energy use} \)

\( n = \text{number of months of energy use} \)

\( p = 1 \) in *ASHRAE Guideline 14 for calibrated simulations*

Improved model calibration is indicated by a lower CVRMSE and NMBE. The CVRMSE and the NMBE for the model calibrated using the Traditional Approach compared with the utility data normalized to the CWEC standard weather year are shown in Table 5. Guideline 14 states that the maximum allowable values of CVRMSE and NMBE, when using monthly data, are 15% and ±5%, respectively [33]. As the CVRMSE and NMBE were within the acceptable ranges, the model was considered appropriately calibrated.
Table 5: Modeled versus Measured Values for the Traditional Approach

<table>
<thead>
<tr>
<th>Comparison between modeled and measured data</th>
<th>Natural Gas</th>
<th>Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CVRMSE</td>
<td>NMBE</td>
</tr>
<tr>
<td>Traditional Approach Model compared to processed utility data</td>
<td>12%</td>
<td>2.4%</td>
</tr>
</tbody>
</table>

### 3.5 Refined Approach

A building monitoring program was designed to improve upon the results from the Traditional Approach, to reduce model uncertainty and to better represent the actual building performance. The program involved observation of three key areas: local weather, building- and suite-level energy consumption and suite conditions. An overview of the parameters measured and the type and location of the equipment used is provided in Table 6. Specifications of the monitoring equipment are described in Section 3.5.3.3.

Table 6: Summary of Monitoring Program Scope

<table>
<thead>
<tr>
<th>Parameter(s)</th>
<th>Equipment</th>
<th>Location in building</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weather Conditions</strong></td>
<td>[Temperature, Relative Humidity, Solar Radiation, Wind Speed and Direction, Rainfall]</td>
<td>Weather Station</td>
</tr>
<tr>
<td><strong>Energy Consumption</strong></td>
<td>Whole-building Natural Gas</td>
<td>Energy meter to monitor pulse and current readings</td>
</tr>
<tr>
<td></td>
<td>Whole-building Electricity</td>
<td>Building Electricity Meter</td>
</tr>
<tr>
<td></td>
<td>Suite-based Electricity</td>
<td>Suites 11, 12, 14A, 14B, 14C</td>
</tr>
<tr>
<td><strong>Interior Conditions</strong></td>
<td>Temperature</td>
<td>Wireless data loggers and sensors</td>
</tr>
<tr>
<td></td>
<td>Relative Humidity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Differential Pressure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Window Displacement</td>
<td></td>
</tr>
</tbody>
</table>
3.5.1 Weather File

There are two issues with using a standard weather file for estimating the performance of retrofit measures in an existing building. First, the calendarization process assumes that consumption on each day of a given billing is equal to all other days in the billing cycle, which is not actually the case. Second, the standard weather year which is used to adjust the annual utility data is typically based on 30-year historical averages which may no longer be representative of the current and future HDD and CDD profiles as the local climate changes. This could result in retrofit savings estimates that are not representative of the actual potential savings. To mitigate the effect of these issues, a weather station was set up on the roof of the subject building to capture the characteristics of the urban microclimate to which the building was exposed. A photo of the weather station is shown in Appendix I. The weather station control panel, located in the mechanical penthouse, received data wirelessly from the weather station in 15-minute intervals and uploaded it to an online database daily. The data were then used to generate a custom weather file for use in the eQUEST simulation. In this way, actual weather conditions could be paired with actual energy consumption rather than relying on normalized values.

3.5.2 Energy Consumption

Many researchers have investigated building, and specifically MURB, energy-use by monitoring energy consumption with a much greater resolution than the data available from utility bills. In a study of energy and water consumption data collected in 15-minute intervals for 34 MURBs [15], buildings which exhibited highly variable natural gas or electricity consumption had generally higher energy intensities. It was indicated that poor controls might be to blame. The authors of a Swedish study [43] used electricity and DHW data in six-second increments over a five-day period from 72 apartments to demonstrate the benefit of reduced interval times when identifying maximum consumption rates. Saldanha and Beausoleil-Morrison [44] monitored electricity use in one-minute intervals and sub-metered major appliances in 12 single-family homes to show an apparent correlation between the number of occupants and non-HVAC electrical loads. So, to supplement the energy consumption data from utility bills, sub-hourly electricity and natural gas data were collected from the subject building. Additionally, the electricity consumption for several suites was sub-metered to estimate the split between suite-based and common area electricity use. A single PowerHawk power meter/data logger (specifications provided in Table 8) was used to gather this data. The power meter, which was
connected to the natural gas meter, the electricity meter and the sub-metered suites, collected pulse outputs from the building electricity and natural gas meters in the underground parking garage as well as the electrical current from the circuits of the sub-metered suites located in the 12th floor electrical panel.

3.5.3 Suite Conditions Comparison

Regardless of how well the model can predict gross energy-use, it should also generate interior conditions similar to that of the actual building. Kavgic et al. [45] indicated that energy models often use standard temperatures instead of empirical data in their study of the influence of different heating systems on interior temperature and relative humidity. However, interior temperatures are not just the product of thermostat settings but also of occupant behaviour. This was demonstrated by Jian et al. [6] in their observation of the effect of window operation on suite temperature, relative humidity and CO₂ concentrations.

To determine the suite conditions, a number of parameters were monitored. Interior temperature and relative humidity data were captured from the sensors located in the centre of the suite, away from the windows and areas of high internal heat generation such as the kitchen and bathroom. Also, the temperature of the radiator fins was monitored to determine how the heating system responded to the interior and exterior conditions. Displacement sensors were used to observe when occupants opened windows and balcony doors. Finally, the effects of the ventilation and exhaust systems and stack effect were monitored using differential pressure sensors across the exterior envelope, between the suite and the corridor and at the bathroom and kitchen exhaust fans.

3.5.3.1 Suite Selection

Resident permission was required to enter suites for monitoring equipment set-up and maintenance, consequently, participation in the monitoring program was voluntary. To recruit participants, information sheets were circulated to all of the building residents and two information sessions were held in a vacant suite containing a mock set-up of the monitoring equipment. At the project outset, six identical suites were sought: one at the top, middle and bottom of both the north and south facades. Constrained by the suite type and location of the volunteer participants, the wireless technology used to transmit the data and the project budget,
the selected suites were clustered together on the 11th to 15th floors of the building, slightly below the neutral pressure plane. A total of seven suites were monitored for a one-year period.

3.5.3.2 Monitoring Set-up

Three suites were “fully-monitored” with temperature, relative humidity, displacement and differential pressure sensors. Four additional suites were “partially-monitored” with temperature and relative humidity sensors only. Temperature and relative humidity sensors were also located in the corridors of the 3rd, 11th, 12th, 15th and 16th floors. Due to the power panel configuration in the building, the sub-metered electricity consumption, discussed in Section 3.5.2, was only captured for the suites on the 11th, 12th and 14th floors. Table 7 summarizes the location and extent of monitoring for each suite, with suite identifiers based on floor number.

### Table 7: Monitored Suite Details

<table>
<thead>
<tr>
<th>Suite</th>
<th>Bedrooms</th>
<th>Adults</th>
<th>Children</th>
<th>A/C</th>
<th>Orientation</th>
<th>In-Suite Monitoring</th>
<th>Electricity Sub-Metering</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>No</td>
<td>North</td>
<td>Full</td>
<td>Yes</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>Unknown</td>
<td>Unknown</td>
<td>No</td>
<td>North</td>
<td>Full</td>
<td>Yes</td>
</tr>
<tr>
<td>14A</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>Yes</td>
<td>North</td>
<td>Partial</td>
<td>Yes</td>
</tr>
<tr>
<td>14B</td>
<td>2</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Yes</td>
<td>South</td>
<td>Partial</td>
<td>Yes</td>
</tr>
<tr>
<td>14C</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>No</td>
<td>North</td>
<td>Partial</td>
<td>Yes</td>
</tr>
<tr>
<td>15A</td>
<td>2</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Yes</td>
<td>North</td>
<td>Full</td>
<td>No</td>
</tr>
<tr>
<td>15B</td>
<td>2</td>
<td>Unknown</td>
<td>Unknown</td>
<td>No</td>
<td>South</td>
<td>Partial</td>
<td>No</td>
</tr>
</tbody>
</table>

3.5.3.3 Monitoring Equipment

The in-suite monitoring system included a series of wireless data loggers/transmitters with built-in temperature and relative humidity sensors as well as two stereo jack inputs to add other sensor types. The approximate location of the data loggers and sensors in the fully-monitored suites is provided in Figure 22. The details of the equipment used, including the power meter and weather station, are shown in Table 8. A summary of the sensor calibration is provided in Appendix J. A selection of photos of the installed sensors is shown in Appendix I. Each of the
partially-monitored suites had two data loggers measuring temperature and relative humidity only: one in the living room and one in the master bedroom. The total cost of the monitoring equipment installed in the subject building in 2012 dollars was approximately $26,000.

Figure 22: Location of Data Loggers and Sensors

Table 8: Monitoring Equipment Details

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Model Number</th>
<th>Range</th>
<th>Resolution</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wireless data acquisition unit</td>
<td>SMT-A2</td>
<td>See internal temperature and internal RH below and [46] for complete operating details</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal Temperature</td>
<td>Cantherm MF58104F3950 Beta 4390K [46]</td>
<td>-40°C to +70°C</td>
<td>0.1°C</td>
<td>±1°C</td>
</tr>
<tr>
<td>Internal RH</td>
<td>Honeywell HCH-1000-001 [46]</td>
<td>10-95%</td>
<td>0.5%</td>
<td>±5%</td>
</tr>
<tr>
<td>Displacement</td>
<td>Model 404 BI Technologies [47]</td>
<td>14.2mm</td>
<td>0.085mm</td>
<td>±0.38mm</td>
</tr>
<tr>
<td>Differential pressure</td>
<td>SDP1000-L025 [48]</td>
<td>±62Pa</td>
<td>0.1Pa</td>
<td>0.5% (Full Scale)</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-------------------</td>
<td>-------</td>
<td>-------</td>
<td>------------------</td>
</tr>
<tr>
<td>Power Meter</td>
<td>PowerHawk 6312 with 200A-80-mA Solid Core Current Transformers [49]</td>
<td>Measures Wh, VARh, Vah, Vrms, Irms</td>
<td>0.05cu.ft/s for natural gas, 2kW for building level electricity, 10W for suite level electricity</td>
<td>±0.5% (Full Scale)</td>
</tr>
<tr>
<td>Weather Station</td>
<td>Wireless Vantage Pro2 6152</td>
<td>See [50] for details of all weather station sensors</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.5.3.4 Data Collection

The in-suite data loggers collected and transmitted data in 15-minute intervals to a netbook computer located in the electrical closet on the 12th floor where data were uploaded daily to an online database. Wireless repeaters were used on the 11th, 14th and 15th floors to strengthen the signal for the in-suite sensors located on those floors.

Data were collected from April 26th 2012 until April 25th 2013. The weather and electricity data were gathered consistently throughout the year with the exception of a month-long period where one hour (18:00-19:00) of electricity data was not transmitted from the data logger each day. These gaps were filled by averaging the consumption from the hours preceding and following the missing hour. Due to a construction project surrounding the natural gas meter, natural gas monitoring did not begin until February 2013 but continued into the summer of 2013 to establish natural consumption patterns in the absence of space heating. Due to connectivity issues with the netbook and faster-than-anticipated depletion of the batteries in the wireless loggers, there were gaps in the in-suite monitoring data. Even after reducing the data sampling interval following a mid-year recharge of the wireless logger batteries, data gaps still occurred. As gaps for each logger occurred at different times and for varying lengths, there was no consistent way to estimate the missing data. Periods of missing data are discussed in Section 3.5.4, where applicable.

3.5.4 Data Analysis and Discussion

To better understand the influence of the difference in data sources and processing between the two models, the data used as inputs in the Traditional Approach model are compared to the data collected and entered in the Refined Approach model. This section begins by comparing the
different weather files, followed by an exploration of the energy consumption and suite conditions to determine how these parameters are affected by the exterior conditions and occupant behaviour.

3.5.4.1 Weather Data Comparison

Figure 23 shows the average monthly temperatures from the CWEC standard weather file based on historical data from the Toronto International Airport, the actual subject building weather station data and weather data collected from the airport during the monitoring period. Table 9 shows the annual HDD and CDD for the two weather files along with Toronto International Airport data from the monitoring period in 2012-2013 for reference.

![Figure 23: Comparison of Standard Weather Year and Weather Data from the Monitoring Period](image)

**Table 9: Comparison of HDD and CDD**

<table>
<thead>
<tr>
<th></th>
<th>Toronto International Airport (CWEC)</th>
<th>Toronto International Airport (May 2012-Apr 2013)</th>
<th>Subject Building (May 2012-Apr 2013)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDD</td>
<td>4089</td>
<td>3571</td>
<td>3333</td>
</tr>
<tr>
<td>CDD</td>
<td>13</td>
<td>56</td>
<td>68</td>
</tr>
</tbody>
</table>
Clearly the monitoring period data are warmer than the CWEC standard year data. Furthermore, the subject building weather station data shows that the inner-city location of the subject building was warmer than the Toronto International Airport during the monitoring period which is consistent with the urban heat island effect [51]. This means that the energy model based on the Traditional Approach will have a higher variable natural gas load and lower variable electricity load compared to the model based on the Refined Approach. Section 3.5.6 describes the magnitude of the impact of these differences in energy consumption.

3.5.4.2 Energy Consumption Comparison

In this section, comparisons are made between the normalized utility bill data and the data collected from the monitoring period. Next, the sub-metered and sub-hourly data are used to show some of the building and occupant characteristics.

Figure 24 and Figure 25 demonstrate the difference between the monthly energy consumption data sources for natural gas and electricity, respectively. The utility bill data, which were normalized to CWEC, represent the Traditional Approach. Limited metered natural gas data were available during the monitoring period so this was supplemented with billed and calendarized utility bill data from the monitoring period which were not weather normalized. These data from 2012-2013 represent the Refined Approach. Even though metered electricity data was available for the entire monitoring period, the non-weather normalized utility bill data was also shown in Figure 25 to demonstrate the effect that calendarization can have on the data.
Seven out of the twelve months of electricity monitoring data had gaps ranging in length from one to nine days. Where daily data were needed, these gaps were filled with the average of the days preceding and following each gap. Despite gaps in the daily monitored electricity data, the total monthly monitored data logged on the monitoring website appeared complete. To verify this, the monthly totals were compared with the sum of the daily totals scaled up by the
proportion of days missing. The resulting monthly totals varied at most by 2% from the monitored totals with an average annual error of 0.1%. The natural gas consumption profile used for comparison with the energy model included the three monitored months and the remaining nine months from the billing data.

Gap-free monitored data from one natural gas billing period and one electricity billing period were used to verify that the pulse conversion factors for the monitored data were correct. The calendarization process used in the Traditional Approach assumes that the consumption on a given day is equal to the consumption on all other days in the billing period. This is one explanation for why there are differences between the billed and monitored data series in both Figure 24 and Figure 25. Another contributing factor is that the monitored data include the full 24-hour period of each day in the month whereas the billed data are likely collected at different times of the day. The greater number of HDDs in the CWEC data compared to the actual weather data from the monitoring period have contributed to higher natural gas consumption in the CWEC profile, as discussed in Section 3.5.4.1. The increased electricity consumption in December and January is attributed to higher building occupancy during the Christmas holiday break. During this time, no classes are held so students are at home for a greater proportion of the day. This hypothesis is based on an examination of the daily suite-based electricity consumption during those periods.

After comparing the monitored and billed data, the monitored data were analyzed further to determine how different end uses affected energy consumption. Bagge and Johansson [43] showed how the length of the data collection interval dramatically affects the observed peak consumption, so monitored data in intervals ranging from 15 minutes (the shortest available in this project) to one day were examined to identify trends in natural gas and electricity data.

### 3.5.4.3 Natural Gas

Monthly natural gas consumption is presented in Figure 26 along with natural gas consumption data recorded in 15-minute intervals. While the monthly data profile is expected, the 15-minute interval data suggests that controls of the system might not be optimized given the wide range of consumption occurring among these short intervals.
The fluctuations in natural gas consumption by the DHW boilers (2 at 2.4MBtuh each) are observed after May 15, 2013 and range between 0m$^3$ and about 15m$^3$ per 15-minute interval. However, during the coldest month in the monitoring period, February, only one of three space heating boilers (each 2.9MBtuh) appears to be operating continuously while the other two frequently cycled on and off. Figure 27 shows natural gas consumption in 15-minute intervals on the coldest day in the monitoring period together with a typical summer day. By plotting these different time periods on the same graph, the magnitude of the difference between summer and winter natural gas consumption can be seen more clearly. While there are no peak charges for natural gas, frequent cycling can lead to more maintenance, premature failure of the boilers, burner inefficiency and difficulty maintaining set point temperatures [52].
There was no sub-metering of natural gas equipment or hot water delivered to each suite. However, to get a better understanding of how the heating system performed under different exterior conditions, radiator fin surface temperature data were gathered in the fully-monitored suites. Central hydronic baseboard heating systems, such as the one in the subject building, are turned on for the winter season and off during the summer months.

The transition period can be difficult for the building manager to control as temperatures fluctuate during the shoulder season. As shown in Figure 28, there are periods where space heating appears to be required but the system is not operational (lower left quadrant) and other periods where the heating is not required while the system is operating (upper right quadrant).

Figure 27: A Summer and Winter Day of Natural Gas Consumption
3.5.4.4 Electricity

Figure 29 shows how the daily and monthly electricity data vary with the exterior temperature. While the increase in winter consumption can be due to a number of factors including shorter days requiring more lighting, increased occupancy and possibly supplemental heating devices, the summer increase is likely primarily due to A/C use. While the relationship between temperature and electricity use is difficult to discern using the monthly billing data alone, the availability of daily consumption data makes this relationship clearer, as shown in Figure 29.
Figure 29: Whole Building Electricity Consumption

Only 1.6% of the suites were sub-metered for this project because the metering was confined to only those residents on the 12th floor power panel who granted permission to access this data. Nevertheless, within the small sample size, detailed in Table 7, there were both one- and two-bedroom suites as well as suites with and without air-conditioning. As shown in Figure 30 by the average, maximum and minimum daily electricity consumption, there were large variations in suite-level plug and lighting loads, even during the winter when air-conditioning would not be contributing to the electric load.
Based on the average wintertime daily consumption normalized by floor area, the highest consuming suite used more than twice the lowest consuming suite which is consistent with the results from a CMHC study [15]. In the summer, when warmer temperatures prompted the use of window A/C units, as shown in Figure 31, this difference grew to over four times. The variation in daily electricity intensity between the suites in the small subject building sample is also comparable to two other studies [20][53]. For this reason, the data were assumed to be a range that would be representative of the remainder of the suites in the building. That said, collecting sub-metered data from more suites would improve the estimate and increase confidence in the extrapolation of the data to the rest of the building.
Figure 31: Electricity Use with Exterior Temperature for Suites with and without A/C

The average electricity intensity of the monitored suites was 5.0W/m$^2$ during the winter months and 5.6W/m$^2$ in summer (9.7W/m$^2$ for suites with A/C and 4.1W/m$^2$ for those without). Using the number of suites with A/C and the suite orientation, the monitored suite data were extrapolated to estimate the breakdown of electricity use in the building. From the extrapolation it was found that the average annual suite electricity intensity is 45kWh/m$^2$. The exposed exterior wall area of each suite was not considered in this analysis. The total annual electricity intensity of the building is 64kWh/m$^2$ so, using the building floor plans and the suite-based estimate derived from extrapolation, the estimated electricity intensity of the common area is 96kWh/m$^2$. On an annual basis, the suite loads represented 42% of the total building electrical load.

Finding comparable energy intensities from other studies was challenging for a number of reasons including different building vintages, equipment and locations. One study of energy consumption in mid- and high-rise residential buildings in British Columbia [54] found a roughly 2:1 ratio between common area and suite-based electricity use whereas the estimated split in the subject building is about 1.4:1. The BC building is not directly comparable because of some electric space heating and different weather conditions but the greater proportion of common area to suite-based loads is similar to the finding of this study. However, the subject building
results are significantly different from a study conducted by the CMHC [15] where the electrical intensity of six bulk-billed buildings in Toronto with natural gas space heating and no central A/C was 110kWh/m². The authors of the CMHC study suggested that in-suite electricity use in these buildings represented 73% of the overall building electricity consumption. Three of the six CMHC buildings have natural gas driers which, assuming laundry facilities are located in the common areas, would reduce the average common area electrical load. Furthermore the office and daycare on the ground floor of the subject building likely contributes to an increased common area electrical load compared to the CMHC buildings. Looking to Europe for further examples, a study of 77 Swedish buildings [20] yielded similar results to the subject building with a range of 10 to 54kWh/m² for suite-based loads but lower common area loads of 2 to 37kWh/m². Another study of 145 Swedish apartments in seven different buildings [43] yielded an average electricity use of 35kWh/m², but few details were provided about the buildings to determine whether they were comparable to the subject building.

After comparing the electricity consumption of the subject building to other studies, it becomes clear that MURB electricity use can vary dramatically, both in magnitude and in the split between common area and suite-based loads. Without an understanding of the electricity end-use breakdown, the estimated impact of electricity reduction strategies is, at best, an educated guess. While the sub-metering of a selection of apartment loads was helpful in estimating the breakdown between common area and suite-based loads, further sub-metering of major equipment loads could have been used to further refine the model.

### 3.5.4.5 Suite Conditions

When collecting the suite condition data, as detailed in Section 3.5.3, various connectivity and battery issues occurred which affected the quantity of the data acquired. Together with an increase in the sampling interval time, the actual amount of data collected was much less than originally envisioned as shown in Table 10.
Table 10: Data Points Collected

<table>
<thead>
<tr>
<th>Suite</th>
<th>11</th>
<th>12</th>
<th>14A</th>
<th>14B</th>
<th>14C</th>
<th>15A</th>
<th>15B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion of possible data points collected*</td>
<td>16%</td>
<td>39%</td>
<td>55%</td>
<td>61%</td>
<td>20%</td>
<td>14%</td>
<td>32%</td>
</tr>
</tbody>
</table>

*Possible number of data points adjusted to account for change from 15-min to 4hr interval in November 2012.

While effort has been made to choose data periods for comparison that contain similar numbers of points, the results of the suite condition analysis must be viewed in the context of this rather sparse data.

3.5.4.6 Temperature

Temperature and relative humidity can be used to assess how “comfortable” the suites are during different seasons. Although comfort is a relative term, ASHRAE has developed Standard 55 2010 Thermal Environmental Conditions for Human Occupancy [55] to provide a guide to what conditions are considered comfortable. Operative temperature is one of the parameters used to determine the comfort zone but these data were not collected from the subject building. Instead, dry bulb temperatures and an estimate of the mean radiant temperature (MRT) are used to approximate the operative temperature in the suites. Appendix K shows how the MRT and comfort zone were determined and what assumptions were made. This approach assumes a constant monthly MRT. It is important to note that assuming a constant MRT is not reflective of the actual conditions in the suite. This simplifying assumption means that daily variations which could cause thermal discomfort are not captured. Still, the analysis is carried out for illustrative purposes. In future monitoring programs, the MRT should be captured directly to improve the accuracy of this analysis.

The comfort zone, described in Appendix K, forms the basis of assessing the comfort conditions in the monitored suites in the subject building for one winter month and one summer month. Figure 32 and Figure 33 show the dry bulb temperature and relative humidity data for January and July with respect to limits of the ASHRAE comfort zone for the two suites with the largest quantity of data. One is on the north side of the building and the other is on the south side.
Figure 32: Conditions in Suite 14A (North) Relative to Comfort Zone

Figure 33: Conditions in Suite 14B (South) Relative to Comfort Zone
The south-facing suite has higher living room temperatures in both January and July, likely due to solar gains. Using the comfort zone as a guide, it is clear that the south-facing suite 14B is uncomfortably warm during a large portion of July (82% of the data points collected). The south-facing suite also overheats in January (25% of the data points collected are warmer than the comfort zone). The position of the summer and winter comfort zones in Figure 33 is thought to be warmer than they would be in reality. This is because solar radiation was not taken into account when estimating the interior surface temperature of the exterior wall. On the south side in particular, this could have a significant effect. In Suite 14B, the temperature sensor nearest the exterior wall read diurnal temperature swings of approximately 2°C during a week in July. If these temperature swings were taken into account during calculation of the MRT, the comfort zone in Figure 33 would shift to the left, thereby increasing the proportion of time the suite would be considered uncomfortable according to ASHRAE Standard 55 2010.

Through anecdotal evidence gathered through conversations with occupants, including those on the north side of the building, it was clear that overheating created a thermal comfort issue year-round. However, in Figure 33, this is only apparent in the south-facing suite. Part of the reason the conditions described by the occupants were not reflected in this temperature and relative humidity analysis was likely due to the simplifying assumptions made during calculation of the MRT, as described in Appendix K. No formal occupant surveys on thermal comfort were conducted.

By plotting the interior temperatures with the exterior temperatures, as shown in Figure 34, the warmer interior temperature of the south-facing suite is illustrated once again. Furthermore, the particularly low interior temperatures during colder periods indicate that the occupants of Suite 12 likely opened their windows during the winter. This was confirmed by observing the window displacement data during this period. These three data sets were determined to be statistically different using a two-way ANOVA test without replication.
The differences in interior temperature trends can be compared by observing the trend lines for each suite. In addition to the difference in interior temperatures between the north and south elevation, the influence of the A/C in the north-facing suites is apparent when exterior temperatures are above 25°C. To summarize, the south-facing suite overheats in both summer and winter months (based on the January and July analysis) while the conditions of north-facing suite remain primarily within the comfort zone.

The average summer and winter interior temperatures along with the number of suites upon which the average is based (in parentheses) are shown in Table 11. These averages were used to make appropriate adjustments to the suite zone temperatures in the energy model.

Table 11: Average Interior Temperatures in Suites

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Summer with A/C</th>
<th>Summer no A/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>24°C (5)</td>
<td>25°C (3)</td>
<td>26°C (2)</td>
</tr>
<tr>
<td>South</td>
<td>26°C (2)</td>
<td>27°C (1)</td>
<td>27°C (1)</td>
</tr>
</tbody>
</table>

3.5.4.7 Other Parameters

While temperature was really the only suite condition that could be directly incorporated in the energy model, analysis of the additional data collected revealed some interesting findings.

Window opening can be considered an indication of occupants’ dissatisfaction with their interior environment [6]. During periods of cold weather, this behaviour contributes to increased space
heating loads through uncontrolled air leakage driven by stack effect through the large openings. It also makes it even more difficult to control the temperatures within the building in general.

Through window displacement and temperature data, it was determined that residents of the subject building open their windows frequently, even during cold weather periods. These findings are similar to a Serbian study of winter indoor temperatures in apartment buildings [45] where the authors estimated that 85% of occupants opened their windows during the heating season in buildings with district heat (the building type most similar to the subject building in terms of interior temperatures and occupant controllability). With frequent window operation in the subject building during the heating season, it is very difficult to estimate an air leakage rate even if blower door test data were available. Simply reducing the set point temperature of the heating system could be considered but the forces of stack pressure would mean occupants near the ground floor would still be colder than those near the top of the building.

Differential air pressures observed during three periods when the windows appeared to be closed in Suite 12 were compared to find the approximate location of the neutral pressure plane. Table 12 shows the temperature, relative humidity and differential pressure data that were used to solve for the estimated distance of the differential pressure sensor in Suite 12 from the neutral pressure plane.

<table>
<thead>
<tr>
<th>Date</th>
<th>T&lt;sub&gt;ext&lt;/sub&gt;</th>
<th>RH&lt;sub&gt;ext&lt;/sub&gt;</th>
<th>ρ&lt;sub&gt;ext&lt;/sub&gt;</th>
<th>T&lt;sub&gt;int&lt;/sub&gt;</th>
<th>P&lt;sub&gt;ext-int&lt;/sub&gt;</th>
<th>h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan 24</td>
<td>-10.8°C (262.2K)</td>
<td>59%</td>
<td>1.31 kg/m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>20.8°C (293K)</td>
<td>4.7Pa</td>
<td>-3.3m±0.08m</td>
</tr>
<tr>
<td>Feb 8</td>
<td>-7.5°C (265.5K)</td>
<td>89%</td>
<td>1.29 kg/m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>18.7°C (291.7K)</td>
<td>2.1Pa</td>
<td>-1.8m±0.04m</td>
</tr>
<tr>
<td>Feb 12</td>
<td>0.5°C (272.5K)</td>
<td>70%</td>
<td>1.25 kg/m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>21.5°C (294.5K)</td>
<td>2.4Pa</td>
<td>-2.6m±0.06m</td>
</tr>
</tbody>
</table>

These distances were calculated using the basic stack equation presented as Equation 3.
Equation 3

\[ P_s = -\rho g 273h \left( \frac{1}{T_{ext}} - \frac{1}{T_{int}} \right) \]

where:

\[ P_s = \text{pressure differential due to stack [Pa]} \]

\[ \rho = \text{density of the infiltrating or exfiltrating air} \quad \left[ \frac{kg}{m^3} \right] \]

\[ g = \text{gravitational constant} \quad \left[ \frac{m}{s^2} \right] \]

\[ h = \text{distance from neutral pressure plane [m]} \]

\[ T_{ext} = \text{exterior temperature [K]} \]

\[ T_{int} = \text{interior temperature [K]} \]

Obviously the location of the neutral pressure plane is not static. Given the changing temperatures and window operation, Suite 12 appears to be about one to two stories below the neutral pressure plane. The proximity to the neutral pressure plane means that the differential pressures experienced near the top and the bottom of the building will be much greater than the pressures shown in Table 12. Using the data from January 24\textsuperscript{th} and the distances from the estimated neutral pressure plane location to the top and bottom of the building, the pressures driving exfiltration and infiltration are estimated at +26Pa and -50Pa, respectively, with reference to the interior of the building. In calculating these pressure differences it was assumed that there was little resistance to air flow between the floors. Further, it was also assumed that the effect of mechanical equipment on the differential pressures across the envelope was negligible. Stack pressures of the magnitude calculated here are similar to those measured in a study of pressure differences in MURBs conducted by the CMHC [14]. Without the use of an air flow network model, these data cannot be used in the energy model. Nevertheless, it is important to understand how the current systems are functioning prior to contemplating different retrofit measures.
The ventilation system in the subject building is designed to positively pressurize the corridors, primarily to prevent cross-contamination of smoke and odours between suites. However, the effectiveness of this strategy depends on the ability of the supply fan to overcome stack effect. A correlation of the differential pressures between the corridor and the suites and the exterior temperature (Appendix L) showed that, with colder exterior temperatures, corridors became negatively pressurized on the monitored floors, or the opposite of the design intent of the system. However, despite the seemingly ineffectual corridor ventilation system during the colder months, overall the monitored suites still appear to be well ventilated. Based on the monitored negative pressure of the suites with respect to the exterior and the observed window operation, fresh air is likely supplied primarily through uncontrolled infiltration.

While this additional monitoring data provides some insights into building performance, the parameters that can be used directly in the model calibration are limited. The two most important pieces of information gleaned from the monitored data collected are: the interior temperatures and the estimated electricity use breakdown between the suites and common areas. Rather than relying on model defaults in eQUEST, these data can be directly entered into the energy model. It is expected that, with these data, the model accuracy will be improved.

3.5.5 Calibration Using Monitored Data

The Refined Approach model included three major changes from the Traditional Approach model. A weather file reflecting the actual weather conditions that the building experienced during the data collection period was used, instead of a standard weather file. Furthermore, the zone temperatures and the ratio of common area and suite-based electricity use were based on the data collected.

A custom weather file was created using the roof-top weather station data for the monitoring period which extended from April 26\textsuperscript{th}, 2012 to April 25\textsuperscript{th}, 2013. Based on the heating system operation dates provided by the building manager, the winter ‘heating’ model covered April 26\textsuperscript{th}, 2012 to May 14\textsuperscript{th}, 2012 and September 20\textsuperscript{th} 2012 to April 25\textsuperscript{th}, 2013 while the summer model included a single period from May 15\textsuperscript{th} to September 19\textsuperscript{th} 2012.

The zone temperature set points were increased from the defaults so that the average zone temperatures were equal to the average monitored temperatures in each season. Average
temperatures of the monitored suites were assumed constant for the entire building. In reality, since the monitored suites were close to the neutral pressure plane, the suites above would likely be warmer while the suites below the neutral pressure plane would likely be cooler than the suite average during the heating season.

Using the estimates of the split between suite-based and common area electricity consumption, loads assigned to the “residential” zones were decreased while the common area loads including corridors, office space and the day care were increased.

The changes made to the model during re-calibration are summarized in Table 13.

Table 13: Summary of Selected Energy Model Inputs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Traditional Approach</th>
<th>Refined Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Actual</td>
<td>Modeled</td>
</tr>
<tr>
<td></td>
<td>normalized to CWEC</td>
<td></td>
</tr>
<tr>
<td>Electricity intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whole Building</td>
<td>69kWh/m²</td>
<td>68kWh/m²</td>
</tr>
<tr>
<td>Suite</td>
<td>61kWh/m²</td>
<td>45kWh/m²</td>
</tr>
<tr>
<td>Common area</td>
<td>81kWh/m²</td>
<td>96kWh/m²</td>
</tr>
<tr>
<td>Set point temperatures</td>
<td>Default set points:</td>
<td>Average winter</td>
</tr>
<tr>
<td></td>
<td>heating 20°C (68°F)</td>
<td>temperature:24.4°C (76°F)</td>
</tr>
<tr>
<td></td>
<td>and cooling 25.5°C (78°F)</td>
<td>Average summer temperature: 26.1°C (79°F)</td>
</tr>
<tr>
<td>DHW</td>
<td>70 gal/person/day</td>
<td>79 gal/person/day</td>
</tr>
<tr>
<td>Loop capacities</td>
<td>Heating Main Loop:</td>
<td>Heating Main Loop:</td>
</tr>
<tr>
<td></td>
<td>2100kBtu</td>
<td>1500kBtu</td>
</tr>
<tr>
<td></td>
<td>Cooling: 30 tons</td>
<td>Cooling: 430 tons</td>
</tr>
</tbody>
</table>
Changes to electricity intensity and set point temperatures were based directly on the monitored data. However, changes to the DHW consumption and the loop capacities were adjusted without the benefit of data to improve the model fit. The heating- and cooling-related energy consumption from each model was compared with the difference in the HDD and CDD between the model weather files to ensure the incremental changes in energy end use were reasonable. However, during recalibration higher natural gas consumption was required to meet the summertime consumption associated with DHW. It should be noted that occupant density, DHW schedules and DHW equipment are identical in both models. Thus, this component of natural gas consumption should be identical. The author cannot explain why this adjustment to the model was necessary to improve the refined prediction. The modeled energy consumption from the Refined Approach is shown in Figure 35 and Figure 36 along with the actual consumption. For reference, the actual consumption normalized to CWEC from the Traditional Approach model is shown as well.

Figure 35: Monthly Natural Gas Consumption After Calibration with Monitored Data
The CVRMSE and NMBE for the Refined Approach model are shown in Table 14 along with these indicators for the Traditional Approach model, reproduced here from Table 5. Note that the positive and negative errors cancel out during calculation of the NMBE, so the lower NMBE associated with electricity consumption in the Traditional Approach does not necessarily indicate a model that is more reflective of actual building performance. Also shown in Table 14 is a comparison between the Traditional Approach model and the monitored data collected from the subject building. It is clear that the Traditional Approach model is a reasonable representation of the utility data normalized to the standard weather year. However, it is not sufficiently representative of the actual building performance as indicated by the exceeded ASHRAE limits.

Figure 36: Monthly Electricity Consumption After Calibration with Monitored Data
Table 14: Comparison of Modeled with Measured Values Before and After Recalibration

<table>
<thead>
<tr>
<th>Comparison between modeled and measured data</th>
<th>Natural Gas</th>
<th>Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CVRMSE</td>
<td>NMBE</td>
</tr>
<tr>
<td>Traditional Approach Model compared to processed utility data</td>
<td>12.0%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Traditional Approach Model compared to monitored energy consumption</td>
<td>22.3%</td>
<td>-7.1%</td>
</tr>
<tr>
<td>Refined Approach Model compared to monitored energy consumption</td>
<td>10.9%</td>
<td>-0.1%</td>
</tr>
</tbody>
</table>

Shaded cells indicate where the ASHRAE Guidelines have been exceeded

3.5.6 Limitations of Monitored Data

While the aim of the monitoring program was to gather data to characterize the performance of the building, the data collection effort did not cover as much of the building as initially anticipated. As discussed, fewer suites were monitored than planned and the monitored suites were clustered in one area of the building. To complete the model calibration, it was assumed that the monitored suites were representative of all suites in the building. Without more detailed data, this approximation is considered reasonable given that the monitored suites, located near the neutral pressure plane, will likely see ‘average’ interior conditions relative to the suites at the top and bottom of the building. Unfortunately, the data collected by the loggers located in the corridors at the top and bottom of the building was not salvageable. Therefore, it was not possible to confirm the assumption that the monitored suites exhibited ‘average’ interior conditions. The results presented in Section 3.6 should be viewed in the context of these limitations.

3.6 Modeling Results Discussion

Since the objective of this work was to determine the incremental benefit of building monitoring prior to energy model development, this discussion focuses on the two parameters that positively
influenced the accuracy of the energy model: suite temperatures and sub-metered electricity consumption. Use of a weather file with actual data versus standard weather data is also addressed.

The modeled energy end uses from both the Traditional and Refined Approach models are compared in Figure 37.

**Figure 37: Comparison Between Modeled Energy End-uses**

The difference in heating and cooling loads can be attributed to differences in the number of HDD and CDD in the two weather files. The reduced lighting and equipment loads are due to the electricity consumption more closely reflecting the actual electricity use. The averaging technique used to generate the standard weather year electricity consumption, as described in Section 3.4.1 and shown in Figure 36, resulted in a higher-than-actual electricity load which was used for calibration of the Traditional Approach model.

To examine energy-use from a different perspective, Figure 38 shows the contribution of each building component and system to the total building heat losses. The total heat losses are equal to the total energy input including natural gas and electricity, as well as solar, infiltration and occupancy gains. In other words, the total energy-use in Figure 37 is based on only utility
consumption while the total energy-use in Figure 38 is based on utility consumption in addition to solar, infiltration and occupant gains. Envelope component losses, infiltration and DHW losses were determined from the eQUEST simulation reports. Ventilation losses were estimated as the total energy input minus the envelope, infiltration and DHW losses. Due to the method used to determine the ventilation energy loss and the relative magnitude of the infiltration and ventilation energy loss, there was uncertainty about how the model split energy use between these two energy loss categories. The modeled energy consumption for ventilation was compared to another study. A study of ten MURBs in New York [56] found the energy consumption for ventilation varied widely from 2% to 20% of building energy use. The modeled ventilation energy loss was 32% of the subject building energy use. Without any additional data to refine the model, the infiltration and ventilation energy losses were combined, as shown in Figure 38, recognizing that the split between these two energy loss components is not known with a high degree of certainty.

Figure 38: Comparison Between Heat Loss Components
Regardless of uncertainty in the split between energy loss components, the relative difference between the Traditional and Refined Approach models are still examined. There are offsetting effects of higher interior and exterior temperatures in the Refined Approach model which can increase or decrease the total heat loss from the building. As shown by the net reduction in heat loss from the walls and windows, the warmer weather file based on the monitored data appears to have a greater effect than the increased interior set point temperatures. Similarly, the infiltration heat loss component is lower in the Refined Approach model. The suspected reason for the increased ventilation loads is the increased set points temperature requiring air to be delivered at a higher temperature in the Refined Approach model compared to the Traditional Approach model. The difference in DHW load can be attributed to the higher total natural gas consumption required by the model normalized to CWEC because absolute DHW consumption in both models are almost identical. Further analysis of the impact of changes to zone temperature and electricity use are presented here.

3.6.1 Suite-Based Electricity Use

Without extensive sub-metering of major pieces of equipment and individual zones, determining electricity end-uses for the purposes of energy modeling is challenging. With the availability of suite-based electricity consumption data gathered during the monitoring period, the split between common area and suite-based electricity use in the Refined Approach model was found to be different from the eQUEST program defaults used by the Traditional Approach model. As shown in Figure 39, the suite-based load component of the Refined Approach model represented a lower proportion of total electricity use.
A similar result was found by Hanam et al. [36] where suite-based electrical loads were overestimated prior to calibration with metered suite-based data. That said, the program defaults may be appropriate for some buildings and will likely be used when these data are not available. Regardless, the change to the suite-based electricity intensity in this model is an important refinement because it shows that the majority of the electricity use is under the control of the building owner, not the suite occupants. This finding can influence potential retrofit strategies. For example, the building owner may choose to sub-meter major electrical loads to determine the most effective electricity reduction strategy rather than embark on a suite energy-use reduction or light bulb exchange program for the building occupants.

3.6.2 Zone Temperatures

The set point temperature of a building can significantly affect energy consumption [57], so it is important to capture this data for energy modeling purposes. Figure 40 shows how the monitored temperatures in the subject building compare with the temperatures resulting from use of the eQUEST defaults in the Traditional Approach model.
As shown, the temperatures predicted using the Traditional Approach model were up to 5°C lower than the Refined Approach model. For comparison, the Traditional Approach model was run with the actual weather file from the monitoring period and was found to use 26% less natural gas. By comparing the natural gas consumption between this new model and the two existing models, it was determined that about 17% of this natural gas reduction was due to a decrease in HDD. This is consistent with the difference in HDDs shown in Table 9. The remaining 9% was due to a combination of the lower set point temperatures and higher waste heat from suite-based electrical loads.

3.7 Conclusions and Recommendations

For the purpose of evaluating energy retrofit measures, calibrated MURB energy models were developed using two different approaches. The energy end-uses from the model developed using the Traditional Approach were reasonable when compared with average MURB data. However, after analysis of the monitored data, differences in the modeled zone temperatures and the split between suite-based and common area electricity consumption became apparent. With recalibration of the model using the Refined Approach data, the model outputs more closely
matched the actual energy consumption, indicating that the model defaults used initially did not appropriately represent the building performance.

When developing a pre-retrofit monitoring program, the particular model to be calibrated must be considered. Since eQUEST was chosen for this project, the unknown variables included air leakage, lighting and plug loads, interior temperatures and some mechanical system details. While many parameters were monitored to gather data about these unknowns, only the zone temperatures and the estimated energy intensities of different zones could be effectively incorporated into the model.

Sub-metering of suites on different orientations that include suites with and without A/C, was useful in developing an average electricity intensity for all suites in the building. For future monitoring efforts, ideally more sub-metered electricity data would be gathered for suites throughout the building. Sub-metering of major mechanical equipment would also have been helpful in further splitting the common area loads between plug loads, lighting and equipment.

If a more detailed model such as EnergyPlus were used, the differential pressure data could have been used to develop an air flow network. However, a better understanding of the effects of window operation throughout the building would also be required. Regardless, the other trends observed, such as window opening during the heating season and pressure differentials throughout the building, were helpful in determining the effectiveness of the current space conditioning and ventilation systems. This information can be used to establish goals for post-retrofit performance even if it is not incorporated directly into the model. Also, interval data such as natural gas consumption can help building managers improve the operation of the heating system before a retrofit even begins.

Improving the performance of existing buildings is one of the keys to reducing the impact of our built environment. To promote implementation of energy retrofits on a broad scale, estimates of retrofit energy savings must be accurate. Determining an accurate baseline energy model is the first step toward developing a realistic estimate of retrofit measure performance. Additional data such as monitored temperatures and electrical sub-metering can make these estimates more representative of actual performance.
Chapter 4
Testing and Simulation of a Low-Temperature Air-Source Heat Pump Operating in a Thermal Buffer Zone

Chapter 4 examines an air-source heat pump (ASHP) operating within a thermal buffer zone (TBZ) to determine whether this can improve the coefficient of performance (COP) in cold temperatures. However, in a relatively small, enclosed space, the compressor unit may significantly draw down the temperature of this zone, so the limitations of this approach were also investigated.

This chapter begins with a discussion of previous work in the area of low-temperature ASHPs and the use of thermal buffer zones. Then, the procedure used to test a mock-up of the proposed retrofit measure is presented along with the resulting performance data. Finally, an energy model is developed in EnergyPlus and calibrated to the performance data.

4.1 Background

In the moderate climates of Europe and Asia, ASHPs are already a popular means of providing energy-efficient heating and cooling [58]. ASHPs have not been widely adopted in colder climates because of significant reductions in the capacity and COP during cold weather. However, the potential for energy savings associated with ASHP use in colder climates has prompted many researchers to investigate how this performance can be improved.

Roth et al. described the strategies used to improve ASHP performance for cold climates [59], including increasing outdoor coil capacities, the use of CO₂ for refrigerant, and the use of multiple or modulating compressors, among others. They also compared the modeled performance of an ASHP with a two-stage compressor to conventional natural gas furnaces in locations with the following annual heating-degree days: 4200°C·days, 3200°C·days and 2600°C·days. Depending on furnace efficiency, little or no primary energy consumption savings were found, but in some of the cases tested, energy cost savings resulted. However, the study did not include a discussion of the greenhouse gas (GHG) emission reductions associated with switching from natural gas to electricity. This fuel switching could be viewed as a significant benefit in jurisdictions such as Toronto where many multi-unit residential buildings (MURBs)
are heated with natural gas (0.182 kg eCO₂/ekWh assuming 10.3 ekWh/m³). The carbon emission factor for electricity at the time of writing was 0.11 kg eCO₂/kWh and declining each year [28].

Through monitoring of an apartment unit, Bugbee and Swift showed that the energy savings associated with a ductless ASHP were up to 70% compared with electric resistance heating in a climate with over 3000°C·days [58]. However, the unit tested was under-sized and the desired set point temperature in the apartment could not be maintained at all times by the ASHP alone. This more direct comparison between electricity-consuming heat sources illustrates the potential energy savings in the study location (3000°C·days) and is an encouraging prospect for electrically-heated buildings.

Bush et al. conducted laboratory testing of three ASHPs: a single-speed unit, a variable-speed unit and a variable-speed unit designed for low-temperature conditions [60]. They found that, at temperatures as low as -15°C, the low-temperature unit maintained 70% of the rated capacity and achieved a COP of 1.86, reducing the need for energy-intensive electric resistance back-up heating. This was an improvement over the single- and variable-speed units which were only able to maintain 30% and 55% of capacity, respectively, at -15°C. Given the focus on cold climate ASHP performance, a low-temperature variable-speed ASHP was selected for testing in the current study.

In addition to performance testing, there have been many studies suggesting modifications to current ASHP technology to improve cold climate performance. Abdelaziz and Shen described the benefits of multi-stage vapor injection compression cycles for cold climate operation and used an optimization model to suggest changes to capacity and air flow rates for improved performance [61]. Guoyuan et al. developed a prototype of an ASHP with sub-cooling via a supplementary refrigerant circuit which achieved a COP of 2.3 at an ambient temperature of -15°C. Researchers have also investigated pairing solar collectors with air-to-water heat pumps to supplement performance as cited by Liang et al. [62]. Liang et al. also built and tested a solar-assisted heat pump that reduced heat pump energy requirements by 10% over a heating season with a 40 m² solar panel.

After examining the work of others, the motivation behind this part of the work was not to modify an existing ASHP design but rather change the way an “off-the shelf” ASHP is operated. This approach was taken so that energy retrofits could be applied using currently available
technology. The change in operation included moving the outdoor unit into a TBZ to take advantage of solar gains and the heat gain from zones adjacent to the TBZ.

Passively gathering solar gains in a TBZ has been investigated by Hix [63] through his Alpha house and Smith [64] through his “Thermal Envelope House.” Both of these systems rely on natural convective loops to transport heat. This concept for single family homes was adapted by Pressnail et al. [65] when they introduced the operation of an inter-zonal heat pump to transfer heat from the TBZ to the occupied zone. Dixon et al. [12] furthered this work by developing a more robust model in the building energy simulation software EnergyPlus. They demonstrated that COPs of greater than 3.5 could be achieved by operating the compressor in the TBZ. Stahlbrand and Richman [66] modeled the convective loop generated within a TBZ surrounding a detached single-family home using computational fluid dynamics. Their goal was to determine how the location of the ASHP in the convective loop impacted the COP. Thus far, the TBZ/ASHP research at the University of Toronto and Ryerson University has focused on detached single-family home applications and modeling of the ASHP operation. In the current work, the TBZ/ASHP concept is applied for the first time to a common urban building type in need of retrofit: the high-rise MURB. Furthermore, this study extends the work done previously by conducting laboratory testing of the ASHP in a TBZ and developing a calibrated energy model of the ASHP performance.

4.2 Approach

Since Toronto is a heating-dominated climate, the focus of this investigation was on the performance of the ASHP system during winter conditions. In the first part of the study, the baseline “exterior” performance of the ASHP was established by testing it at a range of cold ambient temperatures in a climate-controlled chamber. Then, the ASHP was tested in a TBZ to observe how the TBZ temperature was drawn down by the ASHP operation; the associated changes in COP and power draw were compared to the baseline performance. Next, these TBZ tests were repeated by supplying different rates of heat to the TBZ using electric resistance heaters. The different heat supply rates were used to simulate varying levels of sensible heat gain to the TBZ from solar gains and from the adjacent apartment.

The second part of this study involved the development of an energy model calibrated using the laboratory results to simulate the performance of the ASHP operating in the TBZ.
4.3 Laboratory Testing

This section outlines the laboratory set up including construction of the various zones, selection of the heating, ventilating and air-conditioning (HVAC) and control equipment, and an explanation of the test procedure.

4.3.1 Laboratory Apparatus

Testing of the ASHP in a TBZ required the construction and instrumentation of five different zones in the climate-controlled chamber of the Building Science Laboratory at the Department of Civil Engineering, University of Toronto. Figure 41 shows a schematic plan view of these zones.

![Figure 41: Plan View Schematic of Zones within the Climate Chamber](image)

A model apartment unit with an adjacent enclosed balcony was constructed. A Warm Room zone surrounding the Apartment was maintained at the same temperature as the Apartment (23°C ±1°C). In this way, the Warm Room facilitated the measurement of the heat required to maintain
the Apartment set point temperature. By maintaining the Warm Room at the same temperature as the Apartment, any heat that was added to the Apartment only flowed between the Apartment and the Balcony.

The bounds of the climate simulator constrained the zone sizes, particularly the Apartment. So, while the Balcony dimensions (2.5m by 1.4m) were based on those of the subject MURB from Chapter 3, the Apartment was much smaller than an actual apartment. The total wall area of the Apartment was adjacent to the Balcony and was 5.5m$^2$ compared with the 33m$^2$ wall area of a two-bedroom suite from the subject building which was exposed to the exterior. This resulted in Apartment heating loads which were significantly less than a typical two-bedroom apartment in Toronto. More realistic Apartment heating loads were generated by providing a balanced air exchange between the Apartment and the Cold Room. In other words, the heating load was artificially increased by introducing a chilled air stream into the Apartment. To do this, a modified energy recovery ventilator (ERV) was installed in the Apartment. The ERV was modified by removing the core and then constructing two ducts. One duct ran from the Cold Room air inlet to the Apartment supply air outlet and one duct ran from the Apartment return air inlet to the Cold Room exhaust air outlet. Air flows in the two ducts were balanced to minimize uncontrolled air leakage between zones. Using the maximum ERV fan speed of 61L/s, Cold Room air was supplied to the Apartment. Depending on the Cold Room temperature, this resulted in an estimated increase in the Apartment heating load of between 1kW to 1.6kW. For comparison, the two-bedroom apartment on which the laboratory apparatus was based would lose about 1.3kW at an exterior temperature of 1°C (based on 18.5m$^2$ of remaining exposed wall area after enclosing the balcony). Therefore, this approach was thought to reasonably represent the heating load of the larger space in an actual apartment. Additional transmission losses from the Apartment to the Balcony were estimated to be between 0.1kW and 0.5kW depending on the Balcony temperature during each particular test. Thus, the combination of transmission losses and the balanced supply of cold air led to an Apartment heating load that varied between 1.1kW and 2.1kW. The indoor unit of the ASHP, shown in Appendix M, was located in the Apartment to meet these heating loads. The rated capacity range of the ASHP in heating mode was between 1.3kW and 3.52kW [67].

Initially, the outdoor unit of the ASHP was located in the Cold Room to establish baseline performance. However, the Cold Room chiller cycles resulted in Cold Room temperature
fluctuations of around 6°C depending on the chiller set point temperature. Thus, a guard box surrounding the outdoor unit of the ASHP, also shown in Appendix M, was constructed to dampen the effects of the Cold Room chiller cycles on the ASHP compressor.

During the original experimental design and planning stages, following the baseline performance tests, the outdoor unit was to be moved into the Balcony adjacent to the Apartment. However, after construction and installation of the ASHP, it was decided that, to minimize movement of the refrigerant lines, the compressor would remain in the guard box for all of the tests. Therefore the guard box also served as a model TBZ. Note that, as the guard box is separate from the Apartment as shown in Figure 41, the operation of outdoor unit of the ASHP did not directly affect the temperature of the Balcony or the magnitude of the Balcony heat gains from the Apartment. For the remainder of this chapter, the term “TBZ” will refer to the zone created by the guard box surrounding the outdoor unit of the ASHP. The limitations of this approach are discussed in Section 4.6. (For reference, in Chapter 5, TBZ refers to the enclosed balcony space.)

4.3.2 Equipment Selection

This section outlines the specifications of the ASHP tested as well as all other temperature control and metering equipment used to determine the ASHP performance.

4.3.2.1 ASHP

A ductless mini-split ASHP was chosen because, in a retrofit scenario, refrigerant lines are easier to install than new duct work. A variable-speed low-temperature ASHP with a swing compressor was selected. The ASHP was manufactured by Daikin Industries Ltd., and has a rated heating COP of 4.46 [67]. According to the manufacturer’s specifications, the rated COP was determined using a flow rate of 198L/s. However, operating the ASHP with this air flow rate resulted in excessive cycling because the relatively small Apartment heating load was met quickly, even after maximizing the delivery of Cold Room air using the modified ERV. Therefore, the indoor unit fan of the ASHP was operated at low speed (85L/s) so that longer periods of steady state behaviour could be observed. Thus, for all laboratory tests, the ASHP was operated on the low fan speed which, in turn, contributed to a lower COP than specified by the manufacturer. However, the purpose of the laboratory testing was not to verify the manufacturer’s COP but rather to explore the effect on COP of the ASHP operation in an
enclosed space. The ASHP set point temperature was adjusted between 23.5°C and 25°C to keep the apartment zone temperature as close to 23°C as possible for all of the tests.

4.3.2.2 Temperature Control Equipment

Various types of equipment were required to control the temperatures in the test apparatus. This included thermocouples to measure temperature, a data acquisition unit to collect temperature readings from the thermocouples, and a computer to process the temperature readings and execute the temperature control algorithms. A selection of fans and heaters were controlled by the algorithms to regulate zone temperatures. Climate chamber cooling was provided by a chiller located in the Cold Room.

Type T thermocouples were used to measure both air and surface temperatures. All of the thermocouples were calibrated using a Thermoelectric Pronto 200 thermocouple reader [68], as described in Appendix J. The thermocouples used to measure air temperature were located in pairs approximately 0.3m from the ceiling and the floor in various positions throughout each zone, as denoted by the location of the dots shown in Figure 42. Thermocouples were also located in the air streams of the ASHP and the modified ERV.

![Figure 42: Thermocouple Locations](image)
A Hewlett Packard data acquisition (DAQ) unit was used to read the thermocouples and to provide input to a computer program (HTBasic) which controlled the relay switches for fans and heaters in each zone. Every 15 seconds the DAQ captured a reading from each thermocouple. Average zone temperatures were then calculated and used by the computer program to determine if the heaters should be turned on or off for each 15-second period. Heating was provided by a combination of fans with integrated heaters as well as radiant baseboard heaters. Fans were also used to circulate air to promote relatively uniform zone temperatures.

To summarize the description above, Figure 43 shows the three control loops that were used to maintain the required zone set point temperatures:

1. Thermocouples were used to measure the air temperature in numerous locations throughout each zone. The average of the Warm Room temperature readings was used by the HTBasic computer program which switched heaters on and off via a relay box to maintain the same temperature as the Apartment. Similarly, the TBZ heaters were also controlled in this manner for tests that required TBZ heat gain to simulate solar gains and heat from the Apartment.

2. The ASHP unit was controlled by the integrated thermostat on the indoor unit.

3. The Cold Room temperature was regulated by a chiller controlled by an independent thermostat located on a wall of the climate-controlled chamber.
4.3.2.3 Metering Devices

In addition to the real-time temperature readings required for zone control, the electricity consumption of the fans, heaters and ASHP was metered. To minimize uncontrolled air leakage, spot measurements of differential air pressure were taken to ensure that the air pressure was balanced between zones (less than 0.5Pa difference). The magnitude of the air flows from the ASHP and ERV was also measured. Then, these air flow rates were used with the relevant air stream temperatures to estimate the heat delivered to, and extracted from, the Apartment zone. This section provides the specifications of the equipment used to measure these various parameters.

Two types of electricity meters were used. P4460 Kill A Watt™ EZ meters [69] were used to measure the energy consumption of the fans and heaters. These units were selected because this meter retains energy readings following an electrical interruption to the unit which occurred each time the relay switch opened. These meters, which are accurate to ±0.5% for kilowatt-hour readings [69], were calibrated using a light bulb and a Sangamo K2S electromechanical single phase watt-hour meter from the local electricity utility [70].
Variable-speed compressors, such as the one in the selected ASHP, exhibit irregular current wave forms. As such, the Extech DL160 Dual Input True RMS AC Voltage/Current Datalogger was used to monitor the power drawn by the ASHP. These units measure the current and voltage within a resolution of ±0.1A or V and have an overall accuracy of ±2% [71]. Voltage and current readings were measured and used to determine the power draw every five seconds. This interval allowed for observation of the ASHP operation including compressor speed oscillation and cycling due to defrost requirements and when the Apartment set point temperature was reached.

To determine the air pressure differences between zones and during the ERV balancing process, an Air Instrument Resources Ltd. MP3KDµ micromanometer was used. This micromanometer can be used to detect pressures between 0 Pa and 199.9 Pa with an accuracy of ±1% [72].

The air flow rates from the interior unit of the ASHP and the supply and exhaust of the ERV were measured using an Energy Conservatory Minneapolis Series B Duct Blaster with an accuracy of ±3% [73]. The ASHP air flow at low speed was measured as 85L/s compared to the manufacturer specifications which indicated that the low fan speed should have generated 110L/s of air flow. One reason for this discrepancy may have been due the dust in the filter which had accumulated after about six months of operation. However, the final tests used in this analysis were completed in a one-week period so the increasing influence of a clogged filter is assumed to be minimal over the test period.

4.3.3 Test Procedure

The testing began with establishing the baseline performance of the ASHP. This was followed by testing to determine how the outdoor unit of the ASHP would perform in a confined space or TBZ. Then, various rates of heat gain were applied to the TBZ to determine the potential improvement of the COP with the addition of solar gains and apartment heat gains to the TBZ.

The general test procedure was similar to the steady state and cyclic heating mode tests in ANSI/AHRI Standard 210/240-2008: Performance Rating of Air-Source Heat Pump Equipment. As described, for all tests, the outdoor unit of the ASHP was located in the guard box which also served as the TBZ. The back-up electric resistance heating in the ASHP was disabled so that the performance of the compressor could be observed directly.
The base case tests were intended to represent the typical ASHP operation with the outdoor unit operating outside of the building envelope. This condition, where the exterior acts as an infinite heat source or sink, was achieved by maintaining a constant TBZ temperature during compressor operation. A fan drawing Cold Room air into the TBZ and a heater located in the TBZ operated alternately to maintain this steady TBZ temperature (see control cycle 1 in Figure 43). This fan and heater control minimized the TBZ temperature fluctuations caused by both the chiller cycling and the operation of the ASHP compressor in the enclosed TBZ space.

After establishing the baseline ASHP performance, further tests were used to explore how the ASHP would perform while operating in a limited heat source or sink environment such as a TBZ. The first case tested involved no added heat to the TBZ. This simulated the case where there are no solar gains to the TBZ. Then, different levels of a constant rate of heat gain were applied to the TBZ to simulate varying levels of solar heat gain. Figure 44 shows the rates of heat gain applied to the TBZ in each group of Cold Room temperature tests. For comparison, it also shows the average rate of heat applied to maintain a steady TBZ temperature during the baseline testing. In reality, the rate of heat gain by an enclosed balcony TBZ would be variable throughout the day with the movement of the sun and clouds but these constant heat gain rates were needed to determine ASHP performance trends and to calibrate the suite-based energy model. Note that with the balanced air exchange between the Cold Room and the Apartment, the heating load in the Apartment increased as the Cold Room temperature was decreased.
Figure 44: Tests Conducted

To determine the ASHP performance in each test, power meter and air temperature readings were collected along with periodic air flow measurements. The availability of these data allowed for the calculation of the instantaneous COP of the ASHP using Equation 4.

Equation 4

\[
COP = \frac{Heat \; delivered \; by \; ASHP}{Power \; supplied \; to \; ASHP} = \frac{\rho C Q (T_s - T_r)}{q_s}
\]

where:

\( \rho \) = density of air leaving indoor unit of ASHP \[ \frac{kg}{m^3} \]

\( C \) = heat capacity of air \[ \frac{kJ}{kgK} \]

\( Q \) = flow rate of air leaving indoor unit of ASHP \[ \frac{L}{s} \]

\( T_s \) = temperature of air supplied by indoor unit of ASHP \[ ^\circ C \]

\( T_r \) = temperature of return air entering indoor unit of ASHP \[ ^\circ C \]

\( q_s \) = power supplied to ASHP \[ W \]
All tests were conducted at four different Cold Room temperatures (6°C, 1°C, -4°C and -8°C) and run for a minimum of two hours. Each time the Cold Room temperature was changed, a minimum of 24 hours was allowed between tests. This 24-hour delay was instituted so that the walls, slab and ceiling could equilibrate to the new air temperature.

4.4 Laboratory Results

The overall objective of the testing was to determine how the COP of the ASHP changed during operation under various conditions. Of particular interest was how an ASHP would perform with the outdoor unit located in an enclosed space. It was not known how a rapid change in temperature of the TBZ would affect the COP. In an effort to characterize the ASHP performance in a TBZ, COPs were first calculated using Equation 4 and the methods described in Section 4.4.1. Then, the influence of the TBZ temperature (Section 4.4.2), heat gain rate (Section 4.4.3) and Apartment heating load (Section 4.4.4) on COP were assessed. Finally, ASHP power trends were explored. The influences of available heat energy and TBZ temperature on power draw are presented in Sections 4.4.5 and 4.4.6, respectively. A summary of the laboratory test results can be found in Appendix N.

4.4.1 Calculation of COP

Variable-speed ASHPs have a control algorithm that varies compressor and fan speeds with changing conditions. Therefore, truly steady state tests can be only conducted with the aid of a controller provided by the manufacturer. This controller can be used to override the ASHP control algorithm and operate the compressor and fan at a constant speed for the test period. In this study, without access to the manufacturer’s controller, attempts were made to determine the Steady State COP during periods when the variable-speed compressor of the ASHP operated at a relatively constant speed. These periods were identified by determining regions when the rate of energy consumption was relatively constant, as denoted by the shaded regions in Figure 45.
However, during the course of each test, the “steady state” periods were often short and infrequent. These irregular power consumption patterns, as illustrated in Figure 46, meant that choosing a steady state period from the test data was not a simple task. A selection of data from other tests is presented in Appendix O to show the variability in power consumption patterns between tests.

Figure 45: ASHP Power Consumption from Sample 1°C Test

Figure 46: ASHP Power Consumption from Sample -4°C Test
The Steady State COP involved calculation of an instantaneous COP using Equation 4 for each
five second interval. The average of the instantaneous COPs from the steady state section was
then determined. While attempts were made to choose the most representative steady state
period, power consumption irregularity meant that even within a “steady state” section, the
instantaneous COPs varied between 0.2 and 0.36 standard deviations from the mean, as shown
by the maximum and minimum bars in Figure 47. Of particular note is the high and wide-
ranging Steady State COP of the test where no heat was applied to the TBZ. Also shown in
Figure 47, by the error bars on the average COP value, is the uncertainty associated with the
COP calculation. This uncertainty is based on the accuracy of the T-type thermocouples and the
ASHP power meter shown in Appendix J.

![Figure 47: Average, Minimum and Maximum Steady State COPs for Tests at 1°C](image)

The magnitude and frequency of the variations in power consumption were primarily attributed
to oscillation between the compressor speeds required to maintain the set point temperature.
Other, larger variations (greater than 200W) were attributed to compressor cycling when the set
point temperature was reached or when defrosting of the outdoor unit was required, as confirmed
by the zone temperature readings. This cyclic operation is representative of actual operation, and thus it was the primary interest for this investigation.

To assess ASHP performance during the entire test period including periods of cycling, an Overall COP was developed. The Overall COP was calculated by dividing the total heat delivered by total power drawn over the entire test period. This is similar to the way a heating seasonal performance factor (HSPF) is calculated. Unlike the HSPF, the Overall COP is presented with the same units (kW) in both the numerator and the denominator. The Overall COPs are compared to the Steady State COPs in Section 4.4.2. It is important to note that both the Overall and Steady State COPs are likely overestimated compared to actual field operation which would include electric resistance heating.

4.4.2 Influence of TBZ Temperature on COP

In heating mode, the COP of the ASHP increases when the temperature to which the outdoor unit is exposed increases. This is because there is more energy available for transfer from the outdoor unit to the indoor unit. Figure 48 shows both the Overall and Steady State COPs as determined from each test as well as a plot of the COPs based on the manufacturer’s data for the same interior set point temperature and range of Cold Room temperatures.
Figure 48: Influence of TBZ Temperature on COP

Figure 48 reveals that the Overall and Steady State COPs versus temperature trends are quite similar. It was expected that the Overall COPs would be lower than the Steady State COPs given the cyclic ASHP operation throughout each test, but this was not found. Part of the reason for the similarity of the two measures of COP could be attributed to the period immediately after the compressor had switched off. By observing the temperature of the supply air after the compressor had switched off, it appeared that the refrigerant was still circulating and thus delivering heat for a short period when there was no power draw from the ASHP. With no power draw, and yet with heat still being supplied, this increased the instantaneous COP dramatically, approaching infinity during these short periods.

However, there are some differences between the Overall and Steady State COPs. The steady state data, as shown in Figure 48, exhibits greater variation. This may be attributed to the difficulty in choosing steady state periods for some of the tests.

As discussed, the rated COPs from the manufacturer were determined using an indoor air flow rate of 198L/s [67] while the laboratory tests were conducted at a lower fan speed of 85L/s, for
reasons outlined in Section 4.3.2.1. Therefore, as expected [74], the reduced airflow during the laboratory testing reduced the heating capacity of the ASHP and the resulting COP. However, the rate of change in COP with increased exterior temperatures is almost identical to the manufacturing data as shown by the equations of the lines of best fit in Figure 48.

The purpose of this investigation was not to determine the absolute COPs, so the lower COP found in the laboratory testing was not of concern. In the sections that follow, the computer energy model has been calibrated to the COP trend generated by the laboratory data. However, since the rate of change of the COP with temperature for both the manufacturer and experimental data is the same, as shown in Figure 48, the rated COP in the model can simply be adjusted as needed for future modeling efforts.

Overall, regardless of which measure of COP one chooses, Figure 48 reveals that the increase in TBZ temperature had the anticipated effect of increasing the coefficient of performance of the ASHP.

4.4.3 Influence of TBZ Heat Gain Rate on COP

By operating the ASHP in a TBZ, the temperature of the enclosed space is drawn down as heat is extracted. Gains to the TBZ such as those from the sun can offset this temperature decline. However, if heat is extracted at a rate faster than it is replenished, the temperature of the TBZ will drop below the exterior temperature and thus, there would be no advantage to operating the ASHP in the TBZ. To determine the frequency of this condition, the test results were examined to determine the TBZ heat gain rate and the associated TBZ temperature at which the ASHP COP was improved compared to operation at typical exterior conditions.

Figure 49 shows the TBZ heat gain rate at which it becomes advantageous to operate the ASHP for a given “exterior” or Cold Room temperature. This heat gain rate, where operating the ASHP in a TBZ becomes advantageous, can be found by determining the point where the TBZ temperature is equal to or greater than the Cold Room temperature. The equation for the line of best fit for the TBZ temperature data is shown in Equation 5 which is rearranged in Equation 6 to solve for the location of this point on the x-axis, defined as the minimum TBZ heat gain rate required to make operation of the ASHP in the TBZ worthwhile. To the left of this point is the
region where it would be more advantageous to operate the ASHP in a conventional manner using “exterior” or Cold Room air as a heat source.

Figure 49: Influence of Various TBZ Heat Gain Rates on Zone Temperatures

Equation 5

\[ T_{\text{Coldrm}} = m_{\text{TBZ}} q_{\text{base}} + b_{\text{TBZ}} \]

Equation 6

\[ q_{\text{base}} = \frac{T_{\text{Coldrm}} - b_{\text{TBZ}}}{m_{\text{TBZ}}} \]

where:

\( T_{\text{Coldrm}} = \text{Cold Room Temperature at which the tests were conducted \ (°C)} \)
\( q_{\text{base}} = \text{heat gain rate equal to TBZ heat loss rate} \ [W] \)

\( b_{\text{TBZ}} = \text{y-axis intercept of TBZ temperature profile in Figure 50} \)

\( m_{\text{TBZ}} = \text{slope of TBZ temperature profile in Figure 50} \)

The secondary y-axis in Figure 49 shows the proportion by which the COP improves with changes to the TBZ temperature. This COP improvement was determined by Equation 7.

**Equation 7**

\[
\% \text{ improvement of } COP = \frac{(COP_t - COP_{\text{base}})}{COP_{\text{base}}}
\]

where:

\( COP_t = \text{Overall COP from a particular test} \)

\( COP_{\text{base}} = \text{hypothetical COP when the TBZ temperature matches the Cold Room Temperature} \)

The “base” COP in Equation 7 is a hypothetical COP at the point where the TBZ temperature is equal to the Cold Room temperature as shown in Figure 49. This base COP was determined for each Cold Room temperature to assess relative improvement or deterioration of COP with TBZ temperature changes. The base COP is calculated by solving Equation 6 and then locating the corresponding COP using the equation from the Overall COP line in Figure 48.

For Cold Room temperatures above -5°C, it is more advantageous to operate the ASHP within the TBZ when the rate of heat gain is between 830W and 1000W. However, at -10°C, it is more advantageous to operate the ASHP within the TBZ when the rate of heat gain is at least 740W. To provide perspective, these results are put into the context of the amount of solar heat gain received by the Toronto MURB on which the balcony zone was modeled. For a south-facing suite, shown in Figure 50, the existing living room window which overlooks the balcony has a glazed area of 2.5m\(^2\). This corresponds to a fenestration-to-wall ratio of approximately 50% for this particular wall surface.
Figure 50: Illustration of Suite with Balcony Enclosure

Assuming the inset balcony was enclosed with a similar wall section, as shown in Figure 50, the new south-facing window between the exterior and the balcony space would receive at least 740W in solar gains for 18% of the heating season hours and at least 1000W for 8.8% of the heating season hours. In other words, it would only be advantageous to operate the ASHP within the TBZ during these times. However, the assumed 2.5m$^2$ window size on which this calculation is based is rather modest. In reality, the glazed part of the balcony can extend from the floor to the ceiling to maximize solar gains thereby potentially doubling the estimated number of hours for which operation of the ASHP in the TBZ would be beneficial.

As expected, the COP of the ASHP increased with heat added to the TBZ. With the fenestration ratio contemplated here, the proportion of time that operation of the ASHP in the TBZ is advantageous is limited. While the aim of this work is not to optimize the balcony enclosure design, there is potential for further improvement in performance with changes to the glazing area.

4.4.4 Influence of Apartment Heating Load on COP

With the balanced air exchange between the Apartment and the Cold Room, variations in the Cold Room temperature led to changes in the Apartment heating load. To determine the influence, if any, of changes to the Apartment heating load on the COP, tests with similar TBZ temperatures were compared with different Apartment heating loads, as shown in Figure 51. By
comparing groups of similar TBZ temperatures, the effect of different ambient temperatures on the compressor could be minimized. As expected, for a given TBZ temperature, the magnitude of the Apartment heating load does not have a significant impact on the COP because the variable-speed compressor is able to adjust to a range of heating capacities. However, in an actual application, the ASHP capacity must be appropriately selected for the range of heating loads required for the particular space.

![Figure 51: Influence of Apartment Heating Load on COP](image)

**4.4.5 Heat Transferred Versus Compressor Work**

As the ambient temperature to which the outdoor unit is exposed decreases, the rate of heat extraction by the ASHP goes down. Therefore, to maintain the same heat supply capacity, the compressor must do more work. This relationship is examined by comparing the rate of heat transfer from the TBZ and the power input to the ASHP with changes to the TBZ temperature. Seven tests with similar Apartment heating loads (1300W±50W) were selected for direct comparison and are presented in Figure 52. As expected, the ASHP requires more power as the temperature of the TBZ declines and therefore, the rate of heat extraction from the TBZ decreases.
4.4.6 Power Consumption Variance

The variability in power consumption observed during testing, which indicated frequent oscillations in compressor speeds, was unexpected and required investigation. With the compressor operating in the TBZ, two factors were thought to influence the ASHP power consumption variance: the average TBZ temperature and TBZ temperature variance. A multivariable regression analysis was conducted to determine how each of these parameters affected the power consumption variance. The equation for the curve that relates these parameters is shown in Equation 8.

**Equation 8**

\[
\sigma^2_{\text{ASHP power consumption}} = 22289 + 6765\sigma^2_{T_{TBZ}} - 3651T_{TBZ}
\]

*where:*

\[\sigma^2 = \text{variance}\]

\[T_{TBZ} = \text{TBZ Temperature [°C]}\]
As expected, the variance of the ASHP power consumption is positively affected by variance in TBZ temperature, since the compressor speed must adapt to changes in the TBZ temperature. However, it is important to note that the TBZ temperature changes are actually caused by the compressor operation, so these variables are interdependent. Additionally, there is a negative correlation between the TBZ temperature and the power consumption variance, indicating that the power consumption is more variable as the TBZ temperature drops. Furthermore, by observing the magnitude of the impact of each term on the power consumption variance, it is evident that the variance of the TBZ temperature is a stronger indicator of the power consumption variance than simply the TBZ temperature. In other words, fluctuation of the TBZ temperature appears to affect the ASHP power consumption variance more than the absolute temperature of the TBZ.

This relationship between temperature, temperature variance and power consumption variance will be different for other ASHP models because the control algorithm, which is unique to each model, will dictate how the compressor responds to changes in the operating conditions.

To further explore this relationship, Figure 53 shows the influence of TBZ temperature on the variance of the ASHP power consumption. At the outset of the testing, it was suspected that the ASHP power consumption would be more erratic during tests where the TBZ temperature was drawn down by the compressor operation. It was thought that these rapid temperature drops would cause the compressor to change speeds frequently. In reality, the tests where no heat was added to the TBZ and where the greatest temperature draw down was observed exhibited the highest variances in each Cold Room temperature group, but not the highest variance overall. This indicates that the absolute TBZ temperature is a contributing factor in addition to the TBZ temperature variance. This was confirmed by the multivariable regression analysis presented above. Conversely, it was suspected that the tests where the TBZ temperature was kept reasonably constant would result in the most steady state compressor operation as indicated by power consumption variance. However, the tests with a steady TBZ temperature did not exhibit a lower power consumption variance than the other tests in each Cold Room temperature group. This reveals that operating the compressor of the ASHP in a confined space does not appear to significantly increase compressor speed oscillation or cycling.
Analysis of the laboratory test results in Section 4.4 provided insight into how to best calibrate an energy model. In this section, an energy model was developed and calibrated so that the laboratory results could be incorporated into a whole-building simulation. By developing such a model, an ASHP operating in a TBZ could be modeled to determine the impact of this proposed retrofit option on an entire building. The building energy simulation program EnergyPlus was selected to model the laboratory testing conditions, primarily because code modifications to allow a heat pump to function between two zones had already been developed [12].

This section begins with a brief discussion of the code modifications followed by details of the model set up. Then, the model calibration technique is outlined. Finally, a comparison of the modeling results to the laboratory data is presented.
4.5.1 Code Modifications

For the work done by Dixon et al., described in Section 4.1, source code modifications to EnergyPlus were required. In 2009, Dixon et al. [12] modified the version 4.0.0 source code of EnergyPlus to enable the heat pump object to operate between two zones as opposed to pumping heat to and from the exterior as shown in Figure 54.

Figure 54: Original and Modified ASHP Components [12]

However, these code changes were not incorporated into future release versions of EnergyPlus. At the time of writing, the current version of EnergyPlus was 8.0.0. Thus, the first step in modeling the laboratory performance of the ASHP was to transfer the previous source code modifications from version 4.0.0 to the current 8.0.0 version. Once the ASHP operation could be modeled between two zones, a model of the laboratory set up was developed.

4.5.2 Model Set-Up

The energy model was constructed as a simplified version of the laboratory set up with three adjacent zones, shown in Figure 55. The thermal resistance values shown here were determined following calibration of the model described in Section 4.5.3. The ceiling and floor of each zone was assumed to be adiabatic.
In the model, two thermostats were used: one in the Apartment to control the ASHP and one in the TBZ to control the electric resistance baseboard heater. The capacity of the electric resistance heater in the TBZ was then modified to match the metered energy consumption from the actual TBZ heaters in the laboratory during each particular test.

Following establishment of the model geometry, construction and basic controls, a challenge with the ASHP part of the model was encountered. The source code modifications enabled a working single-speed ASHP model using the ‘AirLoopHVAC:UnitaryHeatPump:AirToAir’ object in EnergyPlus. However, the laboratory tests were conducted with a variable-speed ASHP. Time and resource constraints did not allow for further development of the code required for a working variable-speed model so other methods of using the existing code modifications were sought.

One strategy would have been to assign multiple single-speed ASHPs to the zone. Each ASHP could have been assigned the performance curves from a different speed. Then, a schedule could have been created so that different ASHPs were called depending on the TBZ temperature to which the compressor was exposed. However, the test data showed that the compressor speed...
varied even when the TBZ temperature was reasonably constant, as discussed in Section 4.4.6. In fact, the compressor speed would often fluctuate dramatically during what appeared to be steady state parts of the test as indicated by zone temperature profiles, as shown in Figure 46. Also, there was insufficient manufacturer data available to generate all of these performance curves. Accordingly, this strategy was not adopted.

Another contemplated strategy involved entering performance curves for the variable-speed ASHP into the single-speed model. Performance curves for the variable-speed ASHP, based on manufacturer data, were generated using the EnergyPlus preprocessor Curve Fit Tool. There are four performance curves (Equation 9, Equation 10, Equation 11, Equation 12) that are influenced by the manufacturer test data [75].

**Equation 9**

\[
\text{TotCapTempModFac} = a + b(T_{db,i}) + c(T_{db,i})^2 + d(T_{db,o}) + e(T_{db,o})^2 + f(T_{db,i})(T_{db,o})
\]

**Equation 10**

\[
\text{TotCapFlowModFac} = a + b(ff) + c(ff)^2
\]

**Equation 11**

\[
\text{EIRTTempModFac} = a + b(T_{db,i}) + c(T_{db,i})^2 + d(T_{db,o}) + e(T_{db,o})^2 + f(T_{db,i})(T_{db,o})
\]

**Equation 12**

\[
\text{EIRFlowModFac} = a + b(ff) + c(ff)^2
\]

where:

\[
\text{TotCapTempModFac} = \text{Total heating capacity modifier curve as a function of temperature}
\]

\[
\text{TotCapFlowModFac} = \text{Total heating capacity modifier curve as a function of flow fraction}
\]
Given particular air flow rates and temperature conditions, the equation for each curve produces a factor. The “TotCap” factors are applied to the rated capacity while the “EIR” factors are applied to the Energy Input Ratio (EIR), which represents the inverse of the rated COP, to produce an estimate of the actual capacity or EIR at the particular temperature and flow conditions.

A persistent error, apparently caused by the code modifications, prevented the incorporation of the coefficients from the variable-speed ASHP into the single-speed model. However, the model appeared to be functioning as expected with the curves from a single-speed ASHP used in earlier work. So the final strategy, which was adopted, was to compare the single- and variable-speed curves to determine if the model was still usable for calibration using the laboratory data.

There is little difference between the single- and variable-speed curves for the relationship between the temperature of the air entering the outdoor unit and the capacity (Equation 9), as shown in Figure 56. Thus, a single-speed heat pump could be used to model this aspect of the variable-speed ASHP performance.
Only two flow rates were available from the variable-speed ASHP manufacturer to plot the relationships between the mass flow rate of the entering air and the capacity (Equation 10) and EIR (Equation 12). Due to this lack of data, these relationships appeared linear. When comparing the single- and variable-speed curves, the flow-EIR relationship was similar while the flow-capacity relationship was not. However, all laboratory tests were operated at a constant interior air flow rate. Therefore, once the model was calibrated, the difference between these curves is negligible because the air flow rate does not change. The only issue here is that the model input air flow determined by calibration may not be the same as the flow rate measured in the laboratory.

The most significant concern was the difference between the single- and variable-speed air temperature-EIR relationships which was substantial over the range in temperatures, as shown in Figure 57. Essentially, the COP of the variable-speed ASHP was less affected by exterior temperature than the single-speed ASHP. Recognizing that the performance of the single- and variable-speed ASHPs near the intersection of the two lines would be similar, the laboratory test series with a TBZ temperature range that centred around this intersection (the 1°C test series) was chosen for the model calibration. Ideally, the model would have been calibrated with all of the laboratory data, but without a variable-speed model, full calibration of the model was not possible at the upper and lower extremes of the range of temperatures tested. While less than...
ideal, the calibration was still carried out for all of the 1°C tests for illustrative purposes. An alternative strategy has to be developed for future modeling efforts including development of a whole-building model.

![Graph: Variation in EIRTTempModFac with Exterior Temperature](image)

**Figure 57: Variation in EIRTTempModFac with Exterior Temperature**

The default EnergyPlus time step is 15 minutes and the modified version 4 model with an ASHP operating in a TBZ functioned with this time step. However, the version 8 model was unstable during initial testing until the time step was decreased to one minute. This instability could have been a result of the version 8 code modifications. Once the model produced consistent results between runs, it was calibrated using the data collected from the laboratory testing.

### 4.5.3 Model Calibration

To begin calibrating the model, first all known data were entered into the model including Apartment and Cold Room temperatures as well as the TBZ heat gain rates. The Apartment temperature from the laboratory testing data was incorporated into the thermostat schedule. Also, a custom weather file was generated from the laboratory temperature data so that the exterior conditions in the model were the same as the conditions in Cold Room of the laboratory. The rate of heat applied by the TBZ heaters, shown in Figure 44, was determined from the electricity metering during the laboratory testing, as described in Section 4.5.2.
The model variables including infiltration, wall conductivity and ASHP coil capacity as well as rated COP were adjusted until the modeled data approached the measured test data including ASHP power consumption, air temperatures and heat gain and loss rates. The calibration process involved a trade-off between matching the model to the measured COP or the TBZ temperature. Priority was placed on calibration to the COP because this parameter would have the greatest effect on building energy-use in future modeling efforts.

During the calibration process key parameters were extracted from the model results and compared with the available laboratory data as shown by the sample test schematic in Figure 58. Following calibration, the ASHP parameters that yielded the best fit to the laboratory data were a rated heating capacity of 2200W and a rated COP was 2.7.

![Figure 58: Temperature and Power Comparison between Laboratory Data and Model Output](image)

### 4.5.4 Model Results Compared with Laboratory Results

Once the model was calibrated with one test, all remaining tests from the 1°C series were entered into the model to determine if the changes in zone temperature and COP could be accurately predicted. As shown in Figure 59, the model was able to reasonably predict the Balcony temperature. As discussed in Section 4.3.1, the Balcony was not used for its originally intended purpose: a TBZ in which the ASHP could operate. Instead, the temperature of the Balcony
zone simply floated between the Apartment and Cold Room temperatures. The temperature of the actual TBZ, or guard box, on the other hand was not accurately predicted by the model. The TBZ temperatures were overestimated with increasing rates of heat added to the zone.

![Figure 59: Comparison Between Modeled and Measured Zone Temperatures](image)

This could be due to the small volume of air and the associated complex heat transfer relationships in the TBZ space. The model could have been made to more closely represent the TBZ temperatures by increasing the infiltration and conductivity of the TBZ walls. However, introducing these variable changes resulted in a poorer calibration for the COP which, as discussed, was the priority for the calibration exercise. Through prioritization of the COP, the model results from the colder conditions appear to match the laboratory COP data well. However, in warmer temperature tests, the model underestimates the COP, as shown in Figure 60.
The deviation in the warmer temperature region cannot be explained based on the performance curve inputs, particularly the EIRTempModFac curve. Thus, review and refinement of the source code is required. Nevertheless, the model data reasonably matched the laboratory results in the colder temperature region, which is the focus of this study.

4.6 Discussion and Recommendations

The work presented here was comprised of two main parts: laboratory testing of an ASHP operating in a TBZ and then the calibration of an energy model of the laboratory apparatus using the data collected. This section first discusses some of the sources of error in the laboratory work and opportunities to refine the results with future testing. This is followed by a discussion of how the results of the laboratory work can be applied. Finally, the energy modeling challenges are summarized.

Despite attempts to extract “steady state” periods from the test data, the ASHP power consumption was not constant during these periods. In a given “steady state” period, the compressor still appeared to oscillate between speeds as indicated by the ranges of power consumption within each steady state period (from 25W up to 400W). Obtaining a controller from the manufacturer would likely result in steady state tests with a more constant compressor
speed. This would have allowed for calculation of a true steady state COP. Without such a controller and the ability to determine true steady state behaviour, the Overall COP is the best measure of COP performance.

If a larger artificial heating load had been applied to the Apartment zone, the indoor fan speed and set point temperature could have been set higher to observe more realistic COPs. This would have also increased the capacity of the ASHP. In the current work, most of the testing occurred at the lower end of the capacity range for this particular ASHP resulting in a lower estimate of the COPs compared to those that could be expected in an actual apartment application.

The accuracy of the heat flow calculations could have been improved by using data from a grid of thermocouples in each air flow stream as indicated in Section 2.5.4 of ANSI/AHRI Standard 210/240-2008. However, the position of the thermocouples used to measure the flowing air temperature was not changed between the tests so the relative difference in temperature, which is the primary focus of this study, would be indicative of the relative difference in heat flow.

The overall objective of the laboratory testing was to show whether or not the COP of the ASHP could be improved by locating the outdoor unit in a TBZ. In Section 4.4.3, it was shown that the impact of a TBZ on the COP of an ASHP is positive if the TBZ is warmer than the exterior temperature and negative if the TBZ is colder than the exterior temperature. To maximize the benefit and eliminate the penalty of operation within a TBZ, the ASHP should be designed to be able to extract heat from either the TBZ or the exterior, as needed. One possibility would be to supply air to the outdoor unit using a split duct, with one side drawing air from the TBZ and the other drawing air from the exterior. A control algorithm could then be used to operate a motorized damper that changes the air source depending on the temperature differential between the TBZ and the exterior.

For all tests, the outdoor unit was located in the guard box TBZ which was not connected to the Apartment. Had the outdoor unit of the ASHP been moved into the Balcony for the TBZ tests, the influence of the temperature drawdown by the compressor on the Balcony heat gains from the Apartment could have been observed. Since the TBZ was separate from the Balcony, this aspect of the model could not be calibrated. Instead, the Balcony temperature was allowed to
float. However, the energy model was capable of simulating heat flows associated with this arrangement, as shown in Figure 61, so this is included in the analysis presented in Chapter 5.

![Figure 61: Heat Flow Rates and Zone Temperature Model](image)

Figure 61: Heat Flow Rates and Zone Temperature Model

The primary goal for developing and calibrating an energy model was to extend the suite-based laboratory testing to a whole-building model in the future. Had the calibrated model functioned as intended, the energy savings associated with replacing traditional hydronic and electric baseboards with suite-based ASHPs operating in TBZs could be estimated for different buildings in different locations. Instead, an alternative method is proposed in Section 4.7.

### 4.7 Future Work

Aside from developing the source code necessary to model the variable-speed ASHP operating in a TBZ, the development of a model output processor is used to further the work presented in this chapter. This tool, described in Chapter 5, can apply factors to the energy consumption outputs of an energy model to approximate the effect of the inter-zonal ASHP. After using an
energy modeling program to simulate the apartment heating load and the solar gains to the TBZ, the model output processor takes the outputs from the suite-based energy model and simulates the effect of the ASHP operation based on the laboratory data from this chapter. Finally, the resulting energy-use reduction factors are applied to the space heating component of the calibrated whole-building model from Chapter 3.

4.8 Conclusions

With the development of lower temperature heat pumps, ASHPs show promise for reducing the energy consumption required for heating and cooling in a cold climate such as Toronto. The objective of this part of the work was to show that the COPs of ASHPs could be improved further in cold climates by placing the outdoor unit in a TBZ. The specific application contemplated here involves enclosing MURB balconies to create this TBZ while providing suite-based, demand-controlled space conditioning.

Laboratory testing of an ASHP operating in a TBZ was conducted across a range of exterior temperatures and TBZ heat gain rates to characterize performance trends. The rate of change of the COP with respect to the temperature to which the outdoor unit was exposed was found to be the same in the laboratory as the manufacturer data suggested. However, the COPs presented here are lower than the manufacturer data due to several factors including lower interior unit air flow rates. Also established were the required TBZ heat gain rates needed to improve the COP compared to typical exterior operation. Finally, the variance in the power consumption of the ASHP appears to be correlated with the temperature and the temperature variance to which the outdoor unit was exposed.

Attempts were made to model the laboratory test results so that these suite-level findings could be applied on a whole-building scale. While a working EnergyPlus model was generated, the single-speed ASHP model could not be adequately calibrated to match all of laboratory data derived from the operation of the variable-speed ASHP testing. Nevertheless, the model reasonably predicted the COPs and the balcony temperatures below 10°C. However, the model was not a good predictor of the TBZ temperatures.

To further the work presented here, a hybrid approach to modeling this potential retrofit strategy on a whole-building level has been proposed. The approach includes the development of a
model output processor that uses the solar gains from a whole-building energy model and the COPs from the laboratory data to modify suite-based heating loads by an energy consumption reduction factor. This approach can be used to determine the impact on energy-use of retrofitting an existing MURB with suite-based ASHPs operating in enclosed balconies and is described in Chapter 5.
Chapter 5
Evaluating the Proposed Retrofit of a Multi-Unit Residential Building Using an Air-Source Heat Pump Operating in an Enclosed Balcony Space

In Chapter 4, it was shown that the coefficient of performance (COP) of an air-source heat pump (ASHP) in cold weather can be improved by operating the ASHP within a thermal buffer zone. This chapter describes how the findings of the laboratory testing are applied to the calibrated energy model of the subject multi-unit residential building (MURB) described in Chapter 3. The goal of this part of the work is to determine the whole-building energy-use impacts of retrofitting a centrally heated MURB with suite-based ASHPs operating in thermal buffer zones created by enclosing balcony spaces. As Toronto is a heating-dominated climate, the discussion of the retrofit impact is focused on the wintertime condition.

This chapter begins by describing the proposed retrofit measure in more detail including a summary of the energy flows. This is followed by a description of the development of the suite-based energy model in EnergyPlus and the process by which this model was harmonized with the whole-building eQUEST model of the subject MURB. Next, the modifications made to the suite-based model output using a model output processor are discussed and the subsequent results are presented. Finally, the suite-based modeling results are used to determine energy-use reduction factors that are applied to the output of a calibrated whole-building model to determine the impact of this proposed retrofit measure. Beyond energy-use, this chapter concludes with a broader discussion of other retrofit considerations including the qualitative benefits.

5.1 Proposed Retrofit Strategy

As previously described, the retrofit strategy investigated in this work involves enclosure of the existing balconies of a MURB as well as the installation of an ASHP in each suite to provide space conditioning. The outdoor unit of each ASHP is located within the thermal buffer zone (TBZ) created by installing a retractable enclosure for the existing balcony space. Based on the results of the analysis in Chapter 4, the TBZ enclosure modeled here is primarily glass to maximize the solar gains to the space. While the TBZ is most advantageous on the south side,
solar gains to the TBZ can also be beneficial for east and west orientations. On the north side of a building, the TBZ creates a tempered air space without the benefit of solar gains but it can still provide a marginal increase in the overall thermal resistance of the wall.

Since the suites in the subject building face north and south, the ASHP will only operate in the TBZ on the south side. The north-side suites will also be conditioned by an ASHP but it will only be used to extract heat from the exterior air. An ASHP extracting heat from the exterior is denoted as $\text{ASHP}_{\text{EXT}}$ for the remainder of the thesis.

In the south-facing suites, operation of the outdoor unit of an ASHP in the enclosed balcony will draw down the temperature of that space. This results in complex heat flows between the apartment, the balcony and the exterior, the investigation of which is presented in this section.

The laboratory testing, presented in Chapter 4, showed that operation of the ASHP inside a TBZ is only advantageous under certain conditions defined by the temperature to which the outdoor unit is exposed. Equation 13, derived from the laboratory testing and shown in Figure 48, describes how the COP of the ASHP used in this work changes with the ambient temperature.

**Equation 13**

\[
COP = 0.069T_{\text{amb}} + 2.24
\]

where:

$COP = \text{coefficient of performance of the ASHP}$

$T_{\text{amb}} = \text{ambient temperature surrounding the outdoor unit}$

Once the COP has been determined from Equation 13, it can be used to determine the relationship between the power required by the ASHP for pumping and the total heat delivered by the interior unit as shown in Equation 14 and Equation 15.
Equation 14

\[ \text{COP} = \frac{q_d}{q_{\text{Power}}} \]

Equation 15

\[ q_d = q_p + q_{\text{Power}} \]

where:

\[ q_d = \text{heat delivered by ASHP [W]} \]

\[ q_{\text{Power}} = \text{electrical power required by ASHP [W]} \]

\[ q_p = \text{heat energy extracted or pumped by ASHP [W]} \]

The heat available in the TBZ, \( q_p \), is a function of: the incoming solar gains; the heat gains/losses from/to the apartment depending on the TBZ temperature resulting from the solar gains; the ASHP operation; and the losses from the TBZ to the exterior. Therefore, favourable conditions for using the ASHP to pump heat from the TBZ are dependent on sufficient solar gains and the time-delayed re-radiation of these solar gains from the thermally-massive concrete slab and brick veneer in the enclosed balcony TBZs. Given the variability of solar gains throughout the day, the configuration in the proposed retrofit involves an outdoor unit of an ASHP that can draw air from the TBZ or the exterior to maximize the COP depending upon the TBZ conditions. This ASHP which is able to adapt to changing conditions will be denoted as ASHP\textsubscript{Hybrid}. For the ASHP\textsubscript{Hybrid}, the ambient temperature (\( T_{\text{amb}} \)) can be the TBZ temperature (\( T_{\text{TBZ}} \)) or the exterior temperature (\( T_{\text{EXT}} \)). For the ASHP\textsubscript{EXT}, the ambient temperature is always equal to the exterior temperature. Figure 62 summarizes the energy flows that are considered in the analysis of the performance of the south-facing suite.
As discussed, exposure to solar radiation varies according to suite orientation. A south-facing suite in Toronto will see a significantly lower heating load than a north-facing suite due to the space heating benefit of the incident solar radiation. However, uncontrolled solar gains can also result in overheating of the south-facing suites. The observed overheating of the subject building was described in Chapter 3. This overheating can lead to occupants opening windows and,
consequently, increased energy losses. The idea of transferring solar gains from the south to the north side of an apartment building has been explored previously. Melih [76] investigated the passive transfer of warm air from a south-facing sunspace through ducts to the north-side of an apartment building. However, the inter-suite heat transfer in the proposed retrofit contemplated here is assisted by the ASHP.

To reduce the instance of overheating on the south façade and to provide the north-facing suites with more equitable access to the heating benefits of solar gains, the proposed retrofit involves the use of a multi-head heat pump that can transfer heat from the south side to the north side of the building. Excess heat from the south side of the building will be delivered to the north side when available. For the remainder of the time, the north suites will be heated with an ASHP drawing heat exclusively from the exterior. For periods when the solar gains exceed the space heating requirements of both the north and the south suites, the excess heat will be directed to hot water storage. This can either be used for domestic hot water (DHW) or for space heating at a later time. In this chapter, it will be assumed that this energy is directed to DHW.

A summary of the components of the proposed system is depicted in Figure 63 including the variables assigned to each component which will be used for the remainder of the thesis to describe these energy flows. The prioritization of delivery of the energy extracted from the TBZ is also shown.
While only the heating season operation is contemplated here, the retractable enclosure allows for the TBZ to be restored to an open-air balcony during the summer months. Then, when the ASHP is switched into cooling mode, the heat is expelled directly to the exterior rather than being captured in the TBZ and further adding to the apartment cooling load.
5.2 Subject Building

The impact of the proposed retrofit strategy is modeled for the subject building described in Chapter 3. Since the details of the building required for the whole-building model have already been introduced in Section 3.2, only further details required for the suite-based model are presented here and discussed. Two-bedroom suites are the most common suite type in this building and were selected as the basis for the energy modeling study. The two-bedroom suite floor plan is shown in Figure 64.

![Figure 64: Subject Suite Floor Plan](image)

The envelope of the subject building consists of a brick façade with a concrete block backup wall (no insulation) finished with gypsum board on the interior. Based on these components, the total thermal resistance of this wall section is estimated to be $0.58m^2K/W$. The windows, which were replaced in 2004 and 2005, are double-glazed, low-emissivity units with thermally-broken frames and have an estimated overall thermal resistance of $0.41m^2K/W$.

The subject building also has inset balconies, as opposed to balconies that project beyond the exterior envelope. This configuration limits the findings of this work because MURBs with balconies projecting from the building envelope are also common. The position of the balconies...
(inset or projected from the envelope) impacts the ratio between the wall area enclosing the TBZ and the wall area that separates the apartment from the TBZ. In other words, the inset balconies in the subject building have a greater proportion of wall adjacent to a conditioned space compared to the exterior. This ratio, in addition to the thermal resistance of the respective walls, affects the total rate of solar gains transmitted to the TBZ and heat flow to/from the apartment. This relationship for the general case (inset or projected) is discussed in Section 5.7 so that the impact of using inset balconies for this work is understood.

5.3 Energy Model Development

A hybrid approach was required to determine the whole-building energy-use impact of the proposed suite-based retrofit measures. The results of two separate energy models, a suite-based model and a whole-building model, were combined to estimate this impact. The building energy simulation program eQUEST 3.64 was used for the whole-building simulation, as described in Chapter 3, and EnergyPlus version 8.0.0 was used for the suite-based model. This section begins by describing the need for two models in this analysis. Next, the details of the model set up and calibration are discussed. To determine the heat available from the TBZ for the north- and south-facing suite heating demand and the hot water storage, processing of the suite-based data was required and is described. Finally, the details of the modeled retrofit measures are presented.

5.3.1 The Need for Two Models

There were two reasons for choosing to work with two different software packages. First, an eQUEST energy model of the subject building calibrated with detailed energy-use and interior condition data had been developed as described in Chapter 3. Second, EnergyPlus source code modifications to allow operation of the ASHP between two confined zones had been completed. These modifications are described in Chapter 4.

Due to the popularity of eQUEST in the energy modeling community, it was selected for the analysis of the subject MURB. Furthermore with the availability of eQUEST design “wizards” containing many default values, it was thought that the results of calibrating the model with detailed monitoring data could also help inform the energy modeling community about the appropriateness of using default values, as discussed in Chapter 3. Furthermore, the amount and
type of data used for calibration of this model is not common and the calibration process was extensive. Therefore, the calibrated model was used as the base building on which to test the proposed retrofit. However, the drawback of using the existing whole-building model in eQUEST was that it did not allow for the operation of an ASHP between two enclosed spaces. This meant that the proposed retrofit measure could not be modeled directly using this program. Attempts were made to model the TBZ as a sunspace within eQUEST but unrealistically high sunspace temperatures resulted [77]. Thus, EnergyPlus was chosen to model the TBZ and ASHP.

Data collected from the laboratory testing of an ASHP operating in a TBZ were used to calibrate the EnergyPlus model. Unfortunately, using the laboratory data revealed that the calibrated performance of the ASHP in the energy model was limited to a rather narrow temperature range. However, the model of the TBZ, without ASHP operation, calibrated to the laboratory data well, as shown in Figure 59. Thus, given the suspect results from the eQUEST sunspace model, even with the ASHP calibration problem, use of a suite-based EnergyPlus model was pursued to determine the TBZ operation. Furthermore, the highly-customizable, detailed EnergyPlus output allowed for sub-hourly observation of the interaction between the exterior, the TBZ and the Apartment which was not possible in eQUEST. Without an adequate means of directly modeling the ASHP within the TBZ, the EnergyPlus output data were used to calculate the impact of the ASHP performance using a spreadsheet program.

Given the benefits of both of these models, the whole-building impact of the retrofits was therefore determined using a hybrid approach that combined the outputs of the suite-based EnergyPlus model and the whole-building eQUEST model. The general approach was to first develop the two base case models, one in each program, and then harmonize the models so that the suite-level temperatures, heat gain and loss components, and energy-use were the same. The eQUEST model had previously been calibrated to actual suite temperature and energy-use data and was thought to serve as an accurate representation of the actual subject building. As such, the model harmonization was achieved by calibrating the EnergyPlus model to the eQUEST model. The development and calibration of the EnergyPlus model is presented in more detail in Sections 5.3.2 and 5.3.3.
5.3.2 Suite-Based Energy Model Set-Up

Since details of the eQUEST model can be found in Chapter 3, this section focuses on the development of the suite-based EnergyPlus model. The OpenStudio Trimble Plug-in (version 0.15.0.10520) for SketchUp (version 8.0.16846) was used to set up the geometry and the thermal zones for two suite-based models: a one-zone apartment model and a two-zone apartment that includes an enclosed balcony model as shown in Figure 65 and Figure 66, respectively.

Solar shading was added to the middle window of the one-zone model to ensure the shading effect from the existing balcony slab of the suite above was modeled correctly. To maximize solar gains, the panel used to enclose the TBZ of the two-zone model consisted of 100% glazing.
The walls adjacent to the adjoining suites and the interior corridor as well as the ceiling and floor of the subject suite were assumed to be adiabatic. The adjacent zones in the eQUEST model were maintained at the same set point temperature and the inter-suite heat transfer was minimal so this assumption is reasonable.

An identical single-apartment zone was added to the whole-building eQUEST model and a “LV-C Detail of Space” report from the DOE-2.2 simulation results file was compared with the EnergyPlus IDF Editor inputs to ensure the single-apartment zone models were equivalent in terms of geometry and envelope performance.

For simplicity when developing the energy reduction factors associated with the retrofit, the EnergyPlus model included electric baseboards as opposed to hydronic baseboards and a natural gas boiler. The method used to compare the actual natural gas-based heating system modeled in eQUEST with the electric heating system modeled in EnergyPlus is described in Section 5.5.1.

5.3.3 Model Calibration

Once the EnergyPlus model was generated, both the EnergyPlus and eQUEST models were run with the same weather file. Then, the outputs were compared to ensure the suite-based EnergyPlus model was representative of the single-suite zone in the whole-building eQUEST model. Lighting, equipment and occupancy schedules were adjusted in the EnergyPlus model until the resulting internal gains were the same as the eQUEST model. Using the single-suite zone in the eQUEST model for comparison, the heating season loads were compared with the EnergyPlus model to ensure they were similar. A comparison between the eQUEST and EnergyPlus heating season gains and losses for the south-facing suite are shown in Figure 67.
Figure 67: Comparison Between eQUEST and EnergyPlus Heating Season Gains and Losses

The difference in the sum of the heat losses in Figure 67 was less than 2% and the difference between the sum of the heat gains was less than 1%. Each of heat gain and loss elements were then examined to ensure that the time sensitivity of the loads was captured the same way in both models across the days and months. The energy transfer profiles in the eQUEST and EnergyPlus models for most of the parameters was very similar such as the window heat gains and losses as shown in Figure 68.
The differences in the peak loads between the two models, shown in Figure 68, can be attributed to a difference in the length of the time steps between the two models. Hourly data are available in eQUEST while the number of time steps in EnergyPlus can range from one to 60 per hour. For each retrofit scenario, the EnergyPlus time steps were varied until the model stabilized or, in other words, produced the same results when the scenario was re-run. To reduce computation time and output data file size, the largest possible time step that resulted in a stable model was chosen for each scenario. This resulted in different time steps for different modeled scenarios as shown in Table 15.

**Table 15: Model Time Steps**

<table>
<thead>
<tr>
<th>EnergyPlus Model Type</th>
<th>Time Steps Per Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>No enclosed balcony</td>
<td>4</td>
</tr>
<tr>
<td>Enclosed balcony</td>
<td>30</td>
</tr>
</tbody>
</table>

The wall heat transfer profile in EnergyPlus was significantly different from that in eQUEST despite a reasonable calibration between the models on an aggregate scale, as shown in Figure 67. The same wall material properties including emissivity, thickness, conductivity, heat capacity and density were entered in both models but the EnergyPlus model predicted much greater swings in heat gains and losses, as shown in Figure 69, which would suggest a lower heat capacity than the walls in the eQUEST model.
The discrepancy could be due to a difference in how the models handle thermal mass. Several unsuccessful attempts were made to calibrate the EnergyPlus model to the eQUEST model at this hourly time scale. However, because the focus of this work was to determine the overall energy and energy cost savings of implementing the retrofit measures, the model was left as is. Given the comparison between energy gain and loss components shown in Figure 67, the EnergyPlus model was considered to be a reasonable estimate of the suite-based energy flows in eQUEST. Furthermore, the reductions in space heating energy-use determined from the EnergyPlus model would be applied to the eQUEST model as a percentage reduction to the space heating component of the whole-building model rather than absolute reduction in equivalent kilowatt-hours.

5.3.4 Processing the EnergyPlus Output Data

The inability to accurately model the ASHP operating within a TBZ in either software program necessitated the development of a model output processor to determine the energy-use impact of this retrofit strategy. Additionally, the benefit of operating the ASHP in the TBZ is the ability to put excess solar heat gains to use elsewhere which could not be modeled in EnergyPlus. Even if the ASHP-TBZ model developed following the laboratory testing was fully calibrated across the entire temperature range, the single-speed compressor EnergyPlus object used with the ASHP is controlled by one zone thermostat [78]. However, the difference in the heating load between the north and south sides of the building resulting from solar gains means that independent control of the indoor units in each suite is required to maintain the set point temperature without over- or
under-heating one of the suites. Thus, neither the performance of the ASHP in the TBZ nor the benefit of sharing the south-facing solar gains between two zones could be modeled with EnergyPlus, hence the need for the model output processor.

The model output processor takes energy flows generated by energy models from both north- and south-facing suites and outputs values for each of the variables shown in Figure 63. The equations used to modify the energy model output and the algorithm employed are detailed here.

5.3.4.1 Energy Flows

This section describes the cases considered by the model output processing algorithm and then details the governing equations. As described previously, only the heating season case is considered here.

The heat available for removal from the TBZ by the ASHP is a function of solar gains and the heat gains and losses to and from the TBZ. In the heating season, there are three operating conditions to be considered with reference to the energy flows shown in Figure 62. These cases are presented in Table 16 with the relationship between the zone temperatures and the resulting energy flows in and out of the TBZ. The sign convention for all energy flows in Table 16 is positive if energy is added to the TBZ and negative if energy is removed.

<table>
<thead>
<tr>
<th>Case Description</th>
<th>Temperature Conditions</th>
<th>Energy Flow Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess solar gains (bright sun)</td>
<td>$T_{\text{EXT}} &lt; T_{\text{APT}} &lt; T_{\text{TBZ}}$</td>
<td>$+$ $-$ $-$</td>
</tr>
<tr>
<td>Moderate solar gain (cloudy or high angle of incidence)</td>
<td>$T_{\text{EXT}} &lt; T_{\text{TBZ}} &lt; T_{\text{APT}}$</td>
<td>$+$ $+$ $-$</td>
</tr>
</tbody>
</table>
The first step in determining how much heat could be removed from the TBZ was to quantify the effective solar gains transmitted to the TBZ. The term “effective” is used to denote the solar gains available to the ASHP\textsubscript{Hybrid} after accounting for the losses due to air leakage from the TBZ to the exterior and the energy stored in the thermal mass of the TBZ structure. For these reasons, the effective solar gains are lower than the solar radiation transmitted through the TBZ window in the energy model output. The effective solar gains \( q_{solar,eff} \) were determined by conducting an energy balance on the TBZ using the heat flows in and out of the TBZ \( (q_{TBZ-APT} \text{ and } q_{TBZ-EXT}) \), as shown in Equation 16.

\textbf{Equation 16}

\[ q_{solar,eff} + q_{TBZ,APT} + q_{TBZ,EXT} = 0 \]

\textit{where:}

\[ q_{solar,eff} = \text{effective solar gains [W]} \]

\[ q_{TBZ,APT} = \text{heat flow from Apartment to TBZ when TBZ temperature is floating [W]} \]

\[ q_{TBZ,EXT} = \text{heat flow from Exterior to TBZ when TBZ temperature is floating [W]} \]

The heat flows in and out of the TBZ \( (q_{TBZ,APT} \text{ and } q_{TBZ,EXT}) \) were determined from the output of the two-zone apartment EnergyPlus model run with a floating TBZ temperature. Then, Equation 16 was rearranged to solve for the effective solar gains.

With the effective solar gains established, the next step was to determine the heat available to be pumped from the TBZ or \( q_{\text{avail}} \). When operating, the ASHP\textsubscript{Hybrid} removes energy from the TBZ. This effect was achieved by cooling the TBZ to a set point temperature using the ZoneHVAC:IdealAirLoadsSystem object in EnergyPlus [78]. The effective solar gains from the floating TBZ temperature case were then combined with the resulting heat flows from the cooled TBZ case (denoted by the prime symbol) to quantify the amount of heat available to the ASHP\textsubscript{Hybrid}, as shown in Equation 17.
Equation 17

\[ q_{\text{solar,eff}} + q'_{\text{TBZ,APT}} + q'_{\text{TBZ,EXT}} = q_{\text{avail}} \]

where:

\[ q'_{\text{TBZ,APT}} = \text{heat flow from Apartment to TBZ when TBZ is cooled} \ [W] \]

\[ q'_{\text{TBZ,EXT}} = \text{heat flow from Exterior to TBZ when TBZ is cooled} \ [W] \]

\[ q_{\text{avail}} = \text{heat available to be pumped by ASHP from TBZ} \ [W] \]

Note that this estimate of effective solar gains, described in Equation 17, is conservative because the energy losses associated with air leakage from the TBZ to the exterior would decrease with the reduction in TBZ temperature associated with the ASHP operation.

As the TBZ temperature is drawn down below the apartment temperature, the heat loss from the apartment to the TBZ increases. The ASHP_{\text{Hybrid}} was modeled using the modified source code version of EnergyPlus to illustrate this effect. Figure 70 shows the TBZ temperatures and associated heating loads for two suite-based models for one week in January: one with electric baseboard heating and one with the ASHP operating in the TBZ drawing down the temperature.
The case where the ASHP draws down the TBZ temperature below the apartment temperature cannot be directly compared to the electric heating case because the resulting apartment heating load is different, as shown in Figure 70. To ensure a like-to-like comparison between the cases, the additional heat load in the apartment must be accounted for. This was done by returning a proportion of the $q_{avail}$ to the apartment equal to the increased heating load when the TBZ temperature is drawn down ($q'_{TBZ,TBZ}$). Therefore, the net heat pumped by the ASHP in the TBZ ($q_{p,TBZ,Total}$) is determined by Equation 18.

**Equation 18**

$$q_{p,TBZ,Total} = q_{avail} - q'_{TBZ,TBZ}$$

where:

$q_{p,TBZ,Total}$ = net heat pumped by ASHP from TBZ [W]

$q'_{TBZ,TBZ}$ = additional heat flow from Apartment to TBZ when TBZ is cooled [W]

This net heat removed from the TBZ is available to meet the north and south suite heating demands. If the rate at which the net heat is removed exceeds the instantaneous north and south suite heating demands, it is directed to hot water storage.

### 5.3.4.2 Coefficient of Performance of ASHP

The Overall COP data determined through the laboratory testing is lower than the manufacturer curves indicate, as shown in Figure 71 which has been reproduced from Figure 48 for reference. As discussed in Chapter 4, this difference is because the fan on the indoor unit of the ASHP was operated at a lower speed than that which was used to generate the manufacturer performance curves due to the limitations of the artificial loads used in the test apparatus.
As well, the manufacturer data were derived from steady state testing with the aid of a controller to override the ASHP operating algorithm which is not necessarily reflective of actual performance. However, there is a large body of research documenting the performance of ASHPs operating in milder climates where the COP measured in field research is often significantly lower than the COP determined by laboratory testing. There are a number of reasons for this including poor controls or sizing of equipment, excessive use of electric resistance heating and incorrect refrigerant charge [84]. The laboratory testing was conducted without the availability of a controller to override the ASHP control algorithm so it is suspected that the actual operating COP of the ASHP is closer to the experimental data than the manufacturer’s data. Without additional data to verify that the laboratory data is representative of actual performance, the experimental data were used to derive the curve that defines the COP based on the ambient temperature to which the ASHP outdoor unit is exposed (the TBZ or exterior temperature) for the remainder of this work. With the use of this experimental data curve, it is acknowledged that the results presented here may be overestimating the actual COP if operating in the field.
As shown in Figure 71, the established relationship between the COP and the ambient temperature appeared linear within the temperature range tested. However, the TBZ and exterior temperatures sometimes fell outside of this air temperature range during the ASHP operation. Figure 72 shows the frequency of the ambient air temperature to which the ASHP was exposed, in 5°C bins for the four different TBZ temperatures modeled. These four scenarios are termed High, Mid, Low and Ext and are described further in Section 5.3.5. Also shown in Figure 72 are the temperature ranges from Figure 71 in which the COP performance curves had been established.

Figure 72: Frequency of TBZ and Exterior Temperatures During Heating Season

For the purposes of this analysis, the equation for the line describing the relationship between COP and the ambient temperature (Equation 13) has been assumed to be valid for the entire temperature range in which the ASHP was modeled, even though this may not be the case. This assumption is considered valid for the lower TBZ and exterior temperatures given the temperature range for which manufacturer testing was completed, shown in Figure 72. However, the validity of this assumption could not be tested directly for the warmer TBZ and
exterior conditions so other ASHP performance data, external to this study, were sought to identify general trends for performance in warmer temperatures [79][80]. After consulting studies of ASHP performance in warmer temperatures, in lieu of actual data, it was concluded that the simplifying assumption of an extrapolated COP-ambient temperature curve was reasonable for determination of the $COP_{TBZ}$.

### 5.3.4.3 Model Output Processing Algorithm

Once the net heat pumped by the ASHP had been established along with the COP at the given operating conditions, the heat delivered was assigned to the south and/or north heating load and any excess heat was directed to hot water storage. The flow chart in Appendix P summarizes the outputs required from the energy models and the steps taken to determine the magnitude of the energy flows from Figure 63. As shown in Appendix P, the ASHP$_{Hybrid}$ is modeled by using the $COP_{EXT}$ when there is no heat pumped from the TBZ (e.g. overnight).

### 5.3.5 Modeled Scenarios

The primary goal of this work was to demonstrate the potential energy savings of the proposed retrofit measure: the operation of an ASHP in an enclosed balcony or TBZ. However, it is useful to present these savings in the context of other incremental improvements to the building envelope and heating, ventilating and air-conditioning (HVAC) system, as shown in Table 17.

**Table 17: Model Scenarios**

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Balcony</th>
<th>Heat Source</th>
<th>Model type</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoTBZ–ElecBB</td>
<td>Open air</td>
<td>Electric baseboard</td>
<td>Base Case</td>
</tr>
<tr>
<td>NoTBZ–ASHP$_{EXT}$</td>
<td>Open air</td>
<td>ASHP with $COP_{EXT}$</td>
<td>Incremental Retrofit</td>
</tr>
<tr>
<td>TBZ–ElecBB</td>
<td>Enclosed</td>
<td>Electric baseboard</td>
<td>Incremental Retrofit</td>
</tr>
<tr>
<td>TBZ-ASHP$_{EXT}$</td>
<td>Enclosed</td>
<td>ASHP with $COP_{EXT}$</td>
<td>Incremental Retrofit</td>
</tr>
<tr>
<td>TBZ-ASHP$_{Hybrid}$</td>
<td>Enclosed</td>
<td>Hybrid ASHP ($COP_{TBZ}$ or $COP_{EXT}$ depending on $q_{p,TBZ,Total}$)</td>
<td>Proposed Retrofit</td>
</tr>
</tbody>
</table>
For example, while the proposed retrofit solution includes an ASHP operating in an enclosed balcony, it is important to recognize the energy benefit of simply enclosing a balcony space or switching from electric resistance heating to an ASHP. Furthermore, the combined effects of the ASHP\textsubscript{EXT} and the TBZ were examined to isolate the benefit of operating an ASHP in hybrid mode switching between the COP\textsubscript{EXT} and the COP\textsubscript{TBZ} depending on the TBZ conditions.

All scenarios, except the TBZ-ASHP\textsubscript{Hybrid}, were run with a north- and south-facing version of the two-bedroom unit shown in Figure 65 and Figure 66. The two orientations were modeled to identify the impact of solar gains. The heating set point for the building was 23.5°C which resulted in average north and south side zone temperatures that approached the actual temperatures observed in the subject building suites, shown in Table 11. While this set point temperature is higher than the typical set point temperature in an average cold climate building, the whole-building model had been calibrated using this interior condition. Arbitrarily lowering the set point temperature to a more realistic level would reduce the space heating load and artificially lower the projected retrofit energy savings.

The TBZ-ASHP\textsubscript{Hybrid} was only tested on the south side because of the requirement for solar gains. For this case, the TBZ was cooled to various set point temperatures. This range of TBZ temperatures was tested because the net heat removed by the ASHP is dependent on the TBZ temperature. All TBZ set points were between the interior apartment temperature and the exterior and are shown in Table 18. As the TBZ set point temperatures are a function of the interior and exterior air temperatures, they are expressed as equations with these two variables.

**Table 18: TBZ Cooling Set Point Temperatures**

<table>
<thead>
<tr>
<th>Temperature Case</th>
<th>TBZ Temperature =</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>( T_{\text{APT}} - (T_{\text{APT}} - T_{\text{EXT}})/4 )</td>
</tr>
<tr>
<td>Mid</td>
<td>( T_{\text{APT}} - (T_{\text{APT}} - T_{\text{EXT}})/2 )</td>
</tr>
<tr>
<td>Low</td>
<td>( T_{\text{APT}} - 3(T_{\text{APT}} - T_{\text{EXT}})/4 )</td>
</tr>
<tr>
<td>Exterior</td>
<td>( T_{\text{EXT}} )</td>
</tr>
</tbody>
</table>
5.4 Suite-Based Modeling Results

This section presents the results of the suite-based modeling completed in EnergyPlus and modified by the model output processor. First, the energy consumption and the overall COP for the TBZ-ASHP\textsubscript{hybrid} models are compared with the TBZ-ASHP\textsubscript{EXT} model to determine the influence of the ambient temperature on the COP of the ASHP. This is used to determine the optimal TBZ cooling set point temperature which will be used in the remainder of the TBZ-ASHP\textsubscript{Hybrid} analysis. Then, the changes to apartment heating load with the various retrofit measures are examined along with the associated frequency of overheating in the south-facing suite. Finally, the power requirements of all of the modeled scenarios are compared with the optimal TBZ-ASHP\textsubscript{hybrid} case. The power consumption reduction factors derived here are then applied to the whole-building model in Section 5.5. As discussed previously, the purpose of operating the ASHP in a TBZ created by enclosing a balcony space is to improve cold weather performance so the analysis will focus on the winter condition. A summary of the complete modeling results are shown in Appendix Q.

5.4.1 ASHP Coefficient of Performance

The ASHP\textsubscript{Hybrid} modeled using the model output processing algorithm, operates at different times to supply different loads (south space heating, north space heating and excess heat directed to hot water storage). As the variable temperatures of the TBZ and exterior affect the real-time COP of the ASHP\textsubscript{Hybrid}, the different loads are provided with different overall COPs in a heating season. For example, the ASHP\textsubscript{Hybrid} only draws heat from the TBZ when it is advantageous compared to drawing heat from the exterior. This occurs most often during periods of solar gain. During periods of solar gain, the south suite heating loads are often minimal, meaning that almost all of the heat removed from the TBZ goes to the north side or to hot water storage. This also means that the average COP of the heat pumped to the north side and hot water storage is higher. So, to determine the COP of each component of the heat delivered, an Overall COP based on the total seasonal performance was determined. The method for calculating the Overall COP is described in Section 4.4.1. The Overall COP was used instead of an average of the instantaneous COPs because the Overall COP provides a weighted-average of the COP based on the total amount of heat delivered. To demonstrate the differences in COP, a bubble plot of the heating energy delivered to the south-facing suite is shown in Figure 73. The area of the bubbles is proportional
to the total heat delivered while the bubble position along the y-axis indicates the Overall COP at which it was pumped.

Figure 73: Heat Delivered to the South-side Suite

The electric resistance heating in the base case and the backup electric resistance heating in the ASHP cases is supplied at 100% efficiency, shown by the COP of 1. In Figure 73, the performance of the ASHP\textsubscript{Hybrid} is split into two components: ASHP\textsubscript{TBZ} and ASHP\textsubscript{EXT} depending on where heat is being drawn from. With cooler TBZ temperatures, the average ASHP\textsubscript{EXT} COP increases. This occurs because the reduction in TBZ temperature increases the heating load of the south-facing suite. This increase means the ASHP\textsubscript{EXT} operates more often and therefore the operating time extends into periods of warmer temperatures. This warmer overall average temperature of ASHP operation increases the COP.

Figure 73 also shows the improvement in COP of the ASHP\textsubscript{TBZ} compared to the ASHP\textsubscript{EXT}. Note that when the TBZ temperature is drawn down to the exterior temperature, the COP of the ASHP\textsubscript{TBZ} is lower than the COP of the ASHP\textsubscript{EXT}. This is because the thermal resistance benefit of the TBZ is essentially removed and more heat must be returned to the apartment to account for this ($q'_{\text{TBZ,APT}}$). However, the algorithm continues to remove heat from the TBZ under these
conditions because the south-facing suite is overheating. This is discussed further in Section 5.7.1.

Note the relatively small proportion of heat delivered by the ASHP\textsubscript{TBZ} in Figure 73. This is because almost all heat drawn from the TBZ occurs during periods of excessive solar gains on the south side of the building. This means that most of the heat removed from the TBZ is delivered to the north-facing suite and the hot water storage, as shown in Figure 74 and Figure 75.

Figure 74: Heat Delivered to North-facing Suite
Figure 75: Heat Delivered to Hot Water Storage

The COPs generated by the model output processing algorithm are based on inputs from the suite-based model calibrated to the conditions of the monitored suites near the neutral pressure plane in the subject building. As described in Section 3.5.5, the suites above and below the monitored suites would be warmer and cooler, respectively, in the heating season due to the effects of stack action. This temperature difference would, in turn, affect the COP of the ASHPHybrid. However, without monitored data available from the top and bottom of the building, the conditions in the monitored suites of the subject building and the associated COP of the ASHPHybrid are assumed to be equal to the average conditions in the entire building.

Figure 76 shows how the total energy consumption of the ASHP, or the total heating energy required, increases with a lower TBZ set point temperature due to the increased losses from the apartment. However, this increasing energy consumption can be offset by the net excess heat available for hot water storage in the ASHPHybrid case which was not possible to capture in the ASHPExt case. This offsetting effect is shown by the bars representing the total energy consumption minus the heat pumped to hot water storage.
Also shown in Figure 76 is the Overall COP for the space heating delivered along with the Overall COP for the total energy delivered including space heating and hot water storage. As indicated by the maximum point on both COP curves, there is an optimal TBZ set point temperature at which to maximize both COPs. Cases where the COP curves are maximized align with the cases where the total energy consumption, net of the energy pumped to hot water storage, is minimized. Note that the two COP curves exhibit different peaks which indicate that the optimum TBZ set point temperature is likely between these two cases. For the purpose of this analysis, the priority is given to the Overall COP of the total energy delivered. Thus the “Low” temperature case is considered the optimal TBZ operating condition. Identification of the actual optimum point is discussed in Section 6.2.
5.4.2 TBZ Temperature and Associated Apartment Heating Demand

As previously established, the ASHP\textsubscript{Hybrid} operation in the TBZ draws down the TBZ temperature. Once the TBZ temperature falls below the apartment temperature, the heat transfer from the apartment to the TBZ increases. This effect is demonstrated in Figure 77 which shows how the total heating season losses from the apartment change with the modeled scenarios.

![Figure 77: Apartment Heating Demand](image)

The north and south scenarios without an enclosed balcony space exhibit the same total heat loss over the winter simulation but the lower heat loss of the south-facing walls is due to the offsetting effect of solar gains. As shown here, simply enclosing the balcony space is a very effective strategy for reducing heat loss. Enclosure of the balcony resulted in a reduction in space heating of over 68% on the south side and over 44% on the north side. Furthermore, the switch from electric resistance heating to an ASHP\textsubscript{EXT} will also significantly reduce the heating power requirement, whereas the introduction of an ASHP\textsubscript{Hybrid} into the TBZ increases the apartment heat losses to the balcony. However, the ASHP\textsubscript{Hybrid} algorithm, shown in Appendix P, accounts for this loss by reducing the heat available for removal from the TBZ by the amount...
that was lost by the apartment because of the temperature draw down. Additionally, during periods of overheating, the additional heat loss from the apartment to the TBZ can have a beneficial cooling effect, the need for which is established in Section 5.4.3. It should be noted that the thermal resistance of the subject building envelope is relatively low. Improving the thermal resistance of the separation between the TBZ and the apartment, which is discussed in Section 6.2, could improve the overall performance of this retrofit measure.

### 5.4.3 Apartment Overheating

The average monthly apartment zone temperatures are presented in Figure 78 and Figure 79. The zone temperature profiles for the models with enclosed balconies (TBZ) are higher than the open-air balcony models (No TBZ) because of the increased thermal resistance associated with adding the TBZ. As observed in Chapter 3, overheating of the suites on the south side of the subject building is a problem. While this issue is likely due, in part, to poor heating controls, it is also exacerbated by solar gains on the south façade. Similar to the subject building, overheating was observed in the modeled suite as well. As these are heating-only models, any need for cooling was not met by window opening or air-conditioning which explains the extreme south-facing suite temperatures in the shoulder seasons, as shown in Figure 78. Note that the operation of the ASHP\textsubscript{Hybrid} yields lower apartment temperatures than the ASHP\textsubscript{EXT} as mentioned in the previous section.

![Figure 78: South-facing Apartment Temperatures](image)
As shown in Figure 79, overheating is not an issue for the north-facing suites.

![North-facing Apartment Temperatures](image)

**Figure 79: North-facing Apartment Temperatures**

Table 19 shows the proportion of time when the south-facing suite is overheating with each of the modeled scenarios. The various TBZ cooling set point cases have also been included here for comparison purposes.

**Table 19: Proportion of Time Overheating Occurs in South-facing Suite with Various TBZ Temperatures**

<table>
<thead>
<tr>
<th></th>
<th>No TBZ</th>
<th>TBZ</th>
<th>ASHPhybird drawing down TBZ to various temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>High</td>
</tr>
<tr>
<td>JAN</td>
<td>6%</td>
<td>29%</td>
<td>24%</td>
</tr>
<tr>
<td>FEB</td>
<td>6%</td>
<td>35%</td>
<td>31%</td>
</tr>
<tr>
<td>MAR</td>
<td>18%</td>
<td>68%</td>
<td>64%</td>
</tr>
<tr>
<td>APR</td>
<td>44%</td>
<td>95%</td>
<td>92%</td>
</tr>
<tr>
<td>OCT</td>
<td>66%</td>
<td>100%</td>
<td>99%</td>
</tr>
<tr>
<td>NOV</td>
<td>19%</td>
<td>48%</td>
<td>44%</td>
</tr>
<tr>
<td>DEC</td>
<td>5%</td>
<td>21%</td>
<td>18%</td>
</tr>
</tbody>
</table>

The intent of the multi-head ASHP is to allow for the distribution of some of the excess solar energy to the north suite and/or hot water storage. When comparing the overheating in the
ASHP\textsubscript{Hybrid} models, Table 19 shows how effective this redistribution of energy can be on reducing overheating on the south side of the building as the TBZ temperature is drawn down further. For example, setting the TBZ temperature equal to the exterior temperature reduces overheating more than the “optimal” Low TBZ temperature case, but there is an energy efficiency penalty for this operating mode, as described previously. Therefore, although Table 19 shows that there is more potential for moving excess heat from the south to the north, there is a limit to how low the TBZ temperature can be drawn down before it becomes more advantageous to extract heat from the exterior. One alternative to this excessive overheating is to pump heat directly from the south-facing suite to the north-facing suite when it is no longer beneficial to draw heat from the TBZ. However, this arrangement goes beyond the scope of the proposed retrofit and will be left for future work.

5.4.4 Apartment Heating System Electricity Consumption

To modify the whole-building model, reductions to space heating and DHW energy consumption must be determined. Figure 80 shows the total energy required for space heating in the north and south suites for each modeled scenario. As shown, the combined effect of the TBZ-ASHP\textsubscript{Hybrid} case yields the most significant reduction in space heating energy for the north-side suite. However, increased energy consumption for the TBZ-ASHP\textsubscript{Hybrid} case on the south-side appears to cancel this north-side benefit.

![Figure 80: Heating System Electricity Consumption per Suite](image-url)
It is not until the impact of the retrofit measure on space and DHW heating energy consumption are examined together that the benefit of capturing this heat from the TBZ is realized. Figure 81 shows the total energy consumption for one north- and one south-facing suite for each of the modeled scenarios. It also includes the amount of heat pumped to hot water storage and a balance line indicating the net energy consumed. By including only the heat pumped to hot water storage as opposed to the heat delivered, the energy required to power the ASHP_{Hybrid} has been accounted for in the savings.

Figure 81: Combined Heating System Energy for One North and One South Suite

Table 20 shows the space heating energy-use reduction factors based on the energy consumption in Figure 81. Details of how these factors and the DHW savings are applied to the whole building model are presented in Section 5.5.
Table 20: Energy-use Reduction Factors for Retrofit Measures Relative to ‘No TBZ-ElecBB’ Case

<table>
<thead>
<tr>
<th></th>
<th>North</th>
<th>South</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>No TBZ - ASHP&lt;sub&gt;EXT&lt;/sub&gt;</td>
<td>52%</td>
<td>53%</td>
<td>52%</td>
</tr>
<tr>
<td>TBZ - ElecBB</td>
<td>56%</td>
<td>32%</td>
<td>47%</td>
</tr>
<tr>
<td>TBZ – ASHP&lt;sub&gt;EXT&lt;/sub&gt;</td>
<td>30%</td>
<td>17%</td>
<td>25%</td>
</tr>
<tr>
<td>TBZ - ASHP&lt;sub&gt;hybrid Low Temp&lt;/sub&gt;</td>
<td>28%</td>
<td>25%</td>
<td>27%</td>
</tr>
</tbody>
</table>

5.5 Derivation of the Whole-Building Energy-Use Estimates

To generate an estimate of the impact of the retrofit measures on whole-building energy-use, the results from the two models were merged. The relative suite-level impacts of adding an enclosed balcony and an ASHP to an apartment heated with electric baseboards were explored in the previous section. Next, these suite-level impacts were translated to a whole-building model. This section first discusses the need for modifications to the original whole-building model and then describes how the heating energy-use reduction estimates were derived and applied to the whole-building model.

5.5.1 Modifications to the Calibrated Whole-Building Model

As described in Chapter 3, the subject building was the focus of a previous modeling exercise which utilized detailed suite condition and energy-use data for calibration. The accuracy of this calibration was one of the reasons that this model was used to determine the impact of the retrofit measures proposed in this work. This subject building, on which the whole-building eQUEST model was based, is heated with hydronic baseboards fed by natural-gas fired boilers. The suite-based EnergyPlus models, described in Section 3.5.6, included electric baseboard heating so, to use the energy-use reduction factors in Table 20, the whole-building eQUEST model also had to include suite-based electric baseboard heating. Thus, a new whole-building model with electric baseboards was required to allow for direct application of the energy-use reduction factors. However, this model had to be equivalent to the existing calibrated whole-building model with
hydronic baseboards. The need for this calibration and development of the model is described in Appendix R.

### 5.5.2 Merging the Suite-Based Results with the Whole-Building Model

The energy reduction factors associated with the contemplated retrofits are limited to space heating and so were only applied to this part of the whole-building model output. Though the reduction factors obviously differ between the suites on the north and south facades, as shown in Table 20, there are an equal amount of suites on each façade so these factors were simply averaged together and multiplied by the total electric annual space heating energy consumption in the whole-building model. The results of this modification are presented and discussed in Section 5.6.

It is important to note that by applying an average of the north and south energy-use reduction factors, shading on the south façade and reflection of solar radiation onto the north façade and the associated impact on energy-use is being ignored. While this rather isolated condition is not exactly representative of the subject building or other MURBs in densely populated areas, this method of estimation was pursued because the performance of the ASHP is thought to be conservative based on the test conditions from which the COP-Ambient temperature curve was derived and the estimate of effective solar gains. Furthermore, access to solar gains is highly site specific. Rather than arbitrarily converting some of the south-facing suites to north-facing ones, the whole building estimate was developed using the average of the north and south façade factors.

As DHW heating was not modeled in the suite-based EnergyPlus model, an estimate of the excess heat available for hot water storage was made based on the number of suites in the building and the total kilowatt-hours of excess heat per suite as determined by the model output processing algorithm. As a test, the natural gas DHW system modeled in the calibrated eQUEST model was switched to an electric water heater. This resulted in a reduction in equivalent kilowatt-hours used for DHW heating of about 25%. Therefore, the estimate of the absolute number of kilowatt-hours of excess heat was applied as a reduction to the remaining natural gas DHW load assuming a 75% efficient system.
5.6 Whole-Building Model Results

The results of applying the suite-based energy reduction factors to the whole-building model are presented here. In this section, these factors are first applied to the suite-based heating loads and then the impact is extended to the building common areas assuming the heating system throughout the building can be retrofitted using ASHPs operating in TBZs.

5.6.1 Retrofit Applied to Suites Only

The impact of applying the proposed retrofit measure in the suites was compared to the original calibrated whole-building model which included hydronic baseboards fed by natural gas boilers. The energy consumption from each of these cases, expressed in term of annual energy intensity, is presented in Figure 82.

![Figure 82: Annual Energy Intensity of the Retrofit Measures Applied in the Suites Only](image)

The “NoTBZ–ElecBB” case shown in Figure 82 is not a proposed retrofit measure. Instead, it is included here to show the difference in total energy consumption between having hydronic versus electric baseboards in the suites. In these suite-only retrofits, the common areas are still heated by natural gas-fired appliances. This arrangement is not uncommon in Toronto. Some
older buildings with electric baseboards located underneath the windows in the suites have a central air handling unit with a natural gas burner providing conditioned air to the common areas.

As shown in Figure 82, the application of the retrofit measures in the suites only appears to have a relatively minor effect on the whole-building energy consumption. Here, the reduction in natural gas consumption from the hydronic baseboard model to the other models is due in part to a shift in the suite-based space heating energy source from natural gas to electricity. The remaining natural gas in the four other models is used for DHW and common area space heating. A further natural gas reduction is shown in the TBZ-ASHP\textsubscript{Hybrid} case where the excess heat pumped from the TBZ has been used to offset a portion of the DHW heating load.

The majority of the electricity loads are due to the energy consumption of the fans, pumps and plug, lighting and cooling loads. Note that the transition from a hydronic baseboard heating system to an electric resistance system also yielded some pump energy savings.

The next section examines the impact of replacing the heating system in both the suites and the common areas. Since the TBZ–ASHP\textsubscript{EXT} and the TBZ-ASHP\textsubscript{Hybrid} resulted in the greatest reduction in energy-use, only these retrofit measures are considered going forward.

### 5.6.2 Retrofit Applied to Whole Building

In this section the original model with hydronic baseboards is compared to the TBZ–ASHP retrofits applied to the suites only as well as the suites and the common areas. Note that, in the case of applying the TBZ–ASHP\textsubscript{Hybrid} retrofit throughout the building, a TBZ would be required for the common area ASHPs. This could be achieved in a few different ways. The waste heat from a mechanical penthouse could be an option. A space like this provides access to excess heat 24 hours a day. Depending upon the building configuration, naturally lit corridors, atria or lobbies could also be used as a TBZ. Otherwise, the excess heat on the south façade could possibly be used to condition both the north-side suites and the common areas. All of the data in this section is presented in terms of the suite-only retrofit case and the suite-and-common-area retrofit case, denoted as “TBZ-ASHP Apt” and “TBZ-ASHP WhlBldg”, respectively.

The results, which follow, are presented in terms of energy savings, energy cost savings and reduction in greenhouse gas (GHG) emissions because the decision to pursue a building energy retrofit can include any one or perhaps all of these metrics. Energy cost savings can be a major
driver as these savings are used to offset the capital cost of the retrofit measures. Furthermore, adherence to codes, local building standards or incentive programs can require a measure of absolute energy saved or GHG emissions avoided. As such, the results of this work should be viewed through all three lenses.

5.6.2.1 Energy-Use Impact

The TBZ-ASHP retrofits are first considered in terms of space heating (both hydronic and ASHP) and the pumping energy associated with the hydronic baseboard system. Then the impact on whole-building energy intensity is examined. Figure 83 shows the dramatic reduction in the total amount of energy attributed to the space heating system by switching the entire building to heating through ASHPs. Note that the ASHP_{Hybrid} actually shows less space heating savings, as previously discussed.

![Graph showing energy consumption](image)

**Figure 83: Annual Space Heating and Pump Energy Consumption**

Figure 84 shows the total annual energy intensity of the TBZ–ASHP retrofits applied in the suites only and in the whole building compared with the original hydronic baseboard model. Application of the TBZ–ASHP retrofit to the suites only results in a reduction in annual energy
intensity of between 50-60kWh/m² while using this retrofit measure to replace the entire central heating system leads to a reduction of 110-130kWh/m². Note that these estimates of energy-use reduction are based on the COP derived from laboratory testing. While the control algorithm of the ASHP was not overridden during the laboratory testing and apartment set point temperatures were maintained throughout each test, the electric resistance heating was disabled. As such, the effect of the control algorithm over the electric resistance heat was not tested, thus these results are likely overestimated. However, without field testing data, these estimates will continue to be used.

Figure 84: Annual Energy Intensity

These reductions are a combination of the reduced heating load by enclosing the balcony space, the COP of the ASHP, the efficiency gains inherent in the switch from natural gas to electricity and a small reduction in the electricity used for the pumps in the hydronic heating system.
5.6.2.2 Energy Cost Impact

Energy modeling of proposed retrofit measures is often used to estimate the potential energy savings to calculate the payback period of the capital cost for the measure. Therefore it is important to consider the proposed retrofit in terms of energy cost savings. The total energy costs were calculated using the rates in Table 21 and are shown in Figure 85.

Table 21: Utility Unit Cost

<table>
<thead>
<tr>
<th>Utility</th>
<th>Quantity</th>
<th>Rate</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>-</td>
<td>$0.109/kWh [81]</td>
<td>Mid-peak rates at all times</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>First 170m$^3$ per month</td>
<td>$53.34 [82]</td>
<td>Includes gas supply, transportation, delivery charge ($20/month customer charge has been omitted)</td>
</tr>
<tr>
<td></td>
<td>Over 170m$^3$</td>
<td>$0.24/m$^3 [82]</td>
<td></td>
</tr>
</tbody>
</table>

Figure 85: Annual Energy Costs
The electricity rate per kilowatt-hour at the time of writing was 4.7 times greater than the cost per equivalent kilowatt-hour of natural gas (using a conversion factor of 10.3ekWh/m$^3$). With this significant difference in energy cost rates, the energy savings shown in Section 5.6.2.1 do not translate to a comparable decrease in cost ($3,500 to $10,000 annually). Unfortunately, with the utility pricing at the time of writing, it would likely be impossible to justify this type of retrofit on the basis of payback period alone. It is outside the scope of this work to project future energy prices but as natural gas prices increase with a decrease in supply or carbon taxation, the savings shown here will increase. In the meantime, the next section provides an indication of the magnitude of these savings if energy prices were to directly reflect the associated GHG emissions.

### 5.6.2.3 GHG Emissions Impact

Figure 86 and Figure 87 show the estimated annual reduction in CO$_2$ emissions associated with the proposed retrofit measures. Figure 86 shows the impact relative to space heating and pump energy, while Figure 87 shows the impact in relation to the total annual building energy-use.

---

**Figure 86: GHG Emissions Associated with Space Heating and Pump Energy-use**
Figure 87: GHG Emissions Associated with Total Building Energy-use

At the time of writing, the GHG emissions factor for natural gas was 1.6 times that of electricity in the City of Toronto, based on an equivalent kilowatt-hour. This determination is based on factors of $0.11 \text{kg eCO}_2/\text{kwh}$ of electricity and $1.891 \text{kg eCO}_2/\text{m}^3$ of natural gas [28]. This means that natural gas use has a greater impact on the atmosphere per equivalent kilowatt-hour than electricity use. So, the impact of the retrofits on the building GHG emissions is proportionally greater than the reduction in equivalent kilowatt-hours as seen in Figure 83 and Figure 84. In the future, if utility pricing reflects the GHG emissions impact associated with the particular energy source, the case for the TBZ-ASHP retrofit based on energy cost savings would become more compelling. This is because the TBZ-ASHP retrofit involves switching from emission-intensive natural gas to electricity for space heating.

5.7 Discussion

By combining the suite-based and whole-building energy models, the impact of the proposed retrofit measure was determined on the total building energy-use, the energy cost and the
associated GHG emissions. The performance of the ASHP\textsubscript{Hybrid} was found to be better than using the ASHP\textsubscript{EXT} exclusively, if the energy directed to hot water storage is taken into account. Furthermore, the frequency of overheating in the south-facing suite is reduced with use of the ASHP\textsubscript{Hybrid}.

During the development of the suite-based model, the impact of the relationship between the wall area and the thermal resistance for the TBZ enclosure and the balcony walls was identified. The inset balconies in the subject building influence the amount of solar gains available to the TBZ and the heat exchange between the apartment and the TBZ. Balconies that project beyond the plane of the exterior building envelope are also common in Toronto so it is worthwhile to explore how the TBZ-ASHP\textsubscript{Hybrid} retrofit benefits change with this alternative balcony configuration. During construction of the model output processor, equations to determine $q_{\text{solar,eff}}$ and $q_{p,\text{TBZ,Total}}$ from the energy model outputs were developed. A new term, effective COP, was used to describe the COP of the ASHP\textsubscript{Hybrid} after accounting for the heat returned to the apartment when necessary, $q'_{\text{TBZ-APT}}$. In Appendix S it is shown that the effective COP is related to product of the wall-area-to-thermal-resistance (A/R) ratio of the walls separating the apartment and the TBZ and the inverse of the A/R ratio for the TBZ enclosure itself. Based on this algebraic relationship between the thermal resistance and area of the walls enclosing the TBZ, balconies projecting from building envelope are thought to reduce energy-use even further, as discussed in Section 6.2.

5.7.1 Future Work

Aspects of the proposed retrofit strategy that require further consideration include refinement of the energy model, the addition of hygrothermal modeling, the assessment of the performance in different building configurations and an estimate of the implementation cost.

To appropriately model the variable-speed ASHP operating in the TBZ as well as model multiple zones with the TBZ–ASHP\textsubscript{Hybrid} arrangement, which would require variable refrigerant flow, access to an energy modeling program with greater functionality is required. One possible path would be to proceed with further code modifications in EnergyPlus. With a fully functional model, the cooling case can also be easily tested. A hygrothermal assessment of the new double envelope arrangement is also required to determine the condensation potential in the TBZ.
throughout the year. Of particular concern is the occupants’ ability to open the window between the apartment and the TBZ during winter allowing warm moist air to enter the colder zone.

Continued overheating of the south-facing suite, even after drawing the TBZ temperature below the exterior temperature, means there is still excess heat that can be used. Strategies and technologies for moving this heat easily from the south- to the north-side of the building should be investigated.

While beyond the scope of the work presented here, the algebraic relationships presented in Appendix S will be expanded in the future to develop a relationship for the general case.

Finally, a detailed estimate of the TBZ enclosure and ASHP equipment and installation cost is required. Ideally this would be compared with the cost to replace existing, aging HVAC equipment and offset against a projected increase in rental income and future energy prices.

5.8 Conclusions

This chapter presented the energy, energy cost and GHG emissions impacts of applying the proposed energy retrofit strategy to the subject MURB. A suite-based energy model of the retrofit measure was harmonized with an existing calibrated whole-building energy model. Then, a model output processor was developed to allow for modeling the delivery of energy from the TBZ to meet the south and north heating loads. Excess heat beyond these loads was added to hot water storage. Using this approach, the proposed retrofit measure was found to increase apartment heating loads relative to operating the ASHP exclusively with exterior air. However, the hybrid operating mode resulted in excess heat being captured to offset DHW loads as well as a reduction in the overheating of the south-facing suite. Applying the proposed retrofit measure to replace the heating system of the subject MURB is estimated to reduce the annual energy intensity by 39% and reduce the associated GHG emissions by 45%. Unfortunately, given the current cost of energy, this retrofit strategy could not likely be justified based on the energy cost savings alone. However, if future utility prices are proportional to the GHG emissions of natural gas and electricity on an equivalent kilowatt-hour basis, the case for energy cost savings becomes more compelling. There are also a number of additional benefits to the proposed retrofit measure which will be considered in Chapter 6.
Chapter 6
Discussion

The papers that combine to form this thesis each summarize one part of the investigation that led to estimating the energy savings associated with applying the proposed retrofit measure to a subject multi-unit residential building (MURB). This chapter provides a broader discussion of the impacts of this proposed retrofit to the MURB stock in Toronto and how different thermal buffer zone (TBZ) configurations in other buildings can affect the energy performance of the air-source heat pump (ASHP) operating in the TBZ. This chapter concludes with a discussion of the qualitative benefits that complement the predicted energy savings presented in this thesis and then a summary of the broader impact of the work.

6.1 Impact on MURB Stock in Toronto

To generate a realistic estimate of the performance of the proposed retrofit measure, the energy modeling was based on the actual energy consumption and interior conditions of a subject MURB. The subject building was selected, in part, because of the characteristics it shares with many post-war MURBs. However, based on the findings presented in Chapter 2, it is clear that MURB energy-use in Toronto is highly variable. Therefore, it is important to place the estimated impact of the proposed energy retrofit strategy in the larger context of the Toronto MURB stock.

The weather-normalized energy consumption of the subject building was found to be greater than the median energy intensity of the MURBs sampled in Chapter 2. Figure 88 shows the pre- and post-retrofit energy consumption of the subject MURB. The energy reductions resulting from replacement of the space heating system with the TBZ-ASHP configuration have moved the subject building below the median energy intensity of the sample.
Next, the impact of applying the proposed retrofit to numerous buildings was estimated using the Refined Data Set from Chapter 2. Only the Refined Data Set was used because the breakdown between base and variable natural gas and electricity energy-use was available. For buildings heated with natural gas, the energy reduction factor from Chapter 5 was applied to the variable natural gas consumption. For electrically heated buildings, the energy reduction factor was applied to the variable electricity load. The resulting natural gas reduction is an underestimate because the efficiency of the natural gas boilers was not accounted for and the reduction in electricity use is slightly overestimated because the factor also reduces any space cooling load in the building. However, with a lack of more detailed data for these buildings, the estimated impact is considered conservative because of the prevalence of buildings in the sample that are heated with natural gas.

It has been assumed that only the worst performing buildings will be targets for an energy retrofit. Therefore, the energy reduction factor was only applied to the variable loads of the buildings that had a pre-retrofit energy intensity greater than the median. The estimated post-retrofit energy intensities of the Refined Data Set are presented in Figure 89.
Figure 89: Projected Impact of the Retrofit on MURB Stock

By applying the energy reduction factors associated with the proposed retrofit measure, the median energy intensity of the Refined Data Set has been reduced from 300ekWh/m² to 236ekWh/m². In reality, buildings with specific characteristics such as high air leakage rates, pressurized corridor systems, and difficulty controlling interior temperatures would likely be the most appropriate candidates for this type of retrofit measure.

6.2 Improving the Energy Performance of the Retrofit Measure

During the development of the model output processor, equations to determine the heat flows between the TBZ, ASHP, apartment and exterior were developed. During this process, the relationship between the areas and the thermal resistances (A/R ratio) of the walls enclosing the TBZ was revealed. It was shown that the effective coefficient of performance (COP_{eff}) of the ASHP operating in the TBZ is related to product of the A/R ratio of the walls separating the apartment and the TBZ and the inverse of the A/R ratio for the TBZ enclosure itself as shown in Equation 19. The derivation of this relationship can be found in Appendix S.
**Equation 19**

\[
\text{COP}_{\text{eff}} \propto \left( \frac{1}{1 + \frac{A_{\text{APT}} R_{\text{TBZ}}}{R_{\text{APT}} A_{\text{TBZ}}}} \right)
\]

where:

\( A_{\text{APT}} = \text{wall area between TBZ and Apartment } [m^2] \)

\( A_{\text{TBZ}} = \text{wall area of balcony enclosure } [m^2] \)

\( R_{\text{APT}} = \text{thermal resistance of wall between TBZ and Apartment } \left[ \frac{m^2 K}{W} \right] \)

\( R_{\text{TBZ}} = \text{thermal resistance of wall between TBZ and Exterior } \left[ \frac{m^2 K}{W} \right] \)

Table 22 shows the factors influencing the COP_{eff} that result from the characteristics of the TBZ in the subject building. The COP_{eff} factor for the subject building has been compared to three different scenarios including the subject building walls but with a projected balcony. The other two “modified R_{SI}-value” scenarios include inset and projected versions of a TBZ with a single-glazed balcony enclosure and an apartment wall with an R_{SI} value of 5m^{2}K/W and a triple-glazed window.

**Table 22: Impact of TBZ Enclosure Characteristics on COP_{eff}**

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<th>Case</th>
<th>Balcony Type</th>
<th>( A_{\text{APT}} ) (m(^2))</th>
<th>( R_{\text{APT}} ) (m(^2)K/W)</th>
<th>( A_{\text{TBZ}} ) (m(^2))</th>
<th>( R_{\text{TBZ}} ) (m(^2)K/W)</th>
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<td>0.43</td>
<td>0.35</td>
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<td>value</td>
<td>Projected</td>
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<td>0.53</td>
<td>14.0</td>
<td>0.43</td>
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<tr>
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<tr>
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<td>0.2</td>
<td>0.96</td>
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The increasing COP_{eff} factors with changes to the TBZ enclosure configuration, as shown in Table 22, indicate the potential for improved performance of the ASHP operating in the TBZ, as
per Equation 19. However, improvement of the thermal resistance between the TBZ and the apartment would reduce the heat transfer between these two zones. Thus, the excess heat driven from the apartment to the TBZ during overheating would be reduced. The algebraic relationships described will be developed further in the future to establish an equation for the general case which includes the apartment heating load and overheating conditions. These new equations will be used to establish the real-time optimum TBZ temperature for different exterior conditions and space heating needs.

6.3 Other Consequences of the Proposed Retrofit Measure

The results of the proposed retrofit measure have been presented in terms of the potential energy savings, energy cost savings, and GHG emission avoidance in Chapter 5. While these savings are readily quantifiable with the energy models and the model output processing algorithm, the proposed retrofit measure does not function in isolation. Buildings are complex systems and the retrofit contemplated in this work must be viewed in the context of the rest of the building and the relevant stakeholders. There are also a number of qualitative benefits that can be realized by implementing the proposed retrofit measure, though some of these benefits require further modifications to the building to achieve the maximum impact. However, ASHPs are also complicated systems which require appropriate sizing, installation, control and maintenance in order to function at maximum efficiency. This section describes the proposed retrofit measure in the context of these additional considerations.

A major influencing factor in determining building energy-use, particularly in the residential context, is occupant behaviour. In previous work by the author and others [6], it has been observed that occupants will periodically open their windows during cold weather periods. It is presumed that they are not satisfied with the air quality or temperature in their suite [6] and resort to opening the window if they lack control of the space conditioning system. For example, in the subject building, the radiator controls have been disabled which make it difficult to control space temperatures. Unfortunately, this occupant behaviour can significantly increase uncontrolled air leakage thereby increasing the building heating load.

A suite-based conditioning system with in-suite controls, such as the proposed retrofit, would allow occupants to adjust the set point temperature as desired. To some extent, this can also reduce overheating which can occur in a centrally-heated system, by not providing heat to a
space that has exceeded the set point temperature. It also provides occupants with a sense of control.

To improve indoor air quality, a suite-based heat recovery ventilator or energy recovery ventilator could be installed while maintaining the existing central kitchen and bathroom exhaust equipment in place to prevent contamination of incoming fresh air. The supply of fresh air directly to the suite would mean that the pressurized corridor ventilation system would only be needed for fire and smoke control. Additionally, re-circulating air through an in-suite ASHP allows the opportunity for filtration of the interior air.

Without reliance on the corridor air to provide a pressure differential and ventilation, weather stripping could be applied to the corridor doors to make them more air-tight thereby reducing the energy required for positive corridor pressurization. This, along with air-sealing around vertical penetrations throughout the building, could significantly reduce the effects of stack and therefore uncontrolled air leakage. In turn, this would lead to more comfortable suites and lower building heating loads which would reduce ASHP operation or the necessary capacity. By effectively compartmentalizing suites and reducing the stack effect in the building, the suites at the top and bottom of the building will not see extreme differences in the COPs for the ASHP Hybrid operation which would otherwise be observed in the warmer and cooler suites above and below the neutral pressure plane.

To further reduce loads, occupancy sensors can be used to lower set point temperatures and air flow rates when occupants are away.

By providing heating, cooling, ventilation and possibly part of the DHW, using equipment located in the suites and presumably connected to the suite circuit, occupants could be billed directly for their energy-use rather than paying the same as their neighbours. There have been numerous studies showing that shifting the financial responsibility for energy-use from building owners to occupants can reduce energy-use significantly [83]. Beyond billing for plug and lighting loads, this type of billing strategy would be very challenging to implement in buildings with a central space conditioning system such as the subject building. However, the issue that arises with the proposed retrofit strategy is the inequitable access to the sun depending on the suite orientation. This has been partially addressed by transferring excess heat from the south-
side TBZ to the north-side suite but the persistent overheating of the south-facing suites, even with the proposed retrofit, indicates that more heat is available for transfer.

The space heating equipment in many of the older MURBs in the Toronto is in need of replacement. While developing a capital cost estimate for the retrofit was beyond the scope of this work, this estimate should be viewed in terms of the incremental cost over and above replacement of the existing equipment such as boilers, pumps, fans, tanks, piping and controls. Furthermore, this type of in-suite retrofit can, to a certain extent, can be carried out on a suite-by-suite basis over a longer period of time. For example, north and south suite pairs can have the ASHP and retractable balcony enclosure installed separately, when vacancy permits. Then once the retrofit is completed for both suites, the exterior unit in the south suite can be connected to the interior unit of the north suite. By staging the installation over a longer period, retrofit project financing may be easier to arrange. If the retrofit done during a vacancy, there is minimal disruption to occupants and it may be possible to increase the rental rate for the improved post-retrofit suite. Additionally, the improved appearance of the building (with balcony enclosures) and the reduced energy consumption can potentially increase the property value.

There are many positive aspects to switching from a centralized space conditioning system to a suite-based system but the challenges of operating an ASHP to maximize efficiency and occupant comfort must also be recognized. ‘Cold blow’ is a term used to describe the flow of air from the indoor unit of the ASHP before the coils have warmed sufficiently [84]. This can be uncomfortable for occupants during the heating season. To mitigate this issue and to ensure the provision of heat even when outdoor temperatures are low, an electric resistance back-up heater is included as part of the indoor unit [84]. The operation of this resistance heating (COP=1) obviously has a negative effect on the overall COP of the ASHP and must be minimized. Further, other issues such as improper equipment sizing, refrigerant flow, and refrigerant pipe length can also negatively impact COP. The ASHP would also take up usable floor space on the balcony but by operating the ASHP within the thermal buffer zone, the heat exchanger surfaces may see less dirt and debris build-up over time possibly improving the COP compared to a typical installation.
The proposed TBZ–ASHP<sub>Hybrid</sub> retrofit shows promise as a retrofit strategy that can reduce energy consumption in cold-climate MURBs along with the associated GHG emissions, though the savings presented in this work may be overestimated. Furthermore, there are potential benefits for the occupants in terms of comfort and controllability. To maximize the energy savings benefits of TBZ–ASHP<sub>Hybrid</sub> retrofit, operational characteristics of the ASHP as well as other aspects of the building operation must be considered, as discussed. However, with the utility prices in the City of Toronto at the time of writing, it is unlikely that the case for retrofit could be based on energy cost savings alone. Instead, the benefits to occupants, increased property income and reduction in GHG emissions would likely be the drivers for change.

6.4 Broader Impact of the Work

While the thesis has focused on only one particular retrofit strategy for the Toronto MURB sector, the methodology developed to test the TBZ-ASHP retrofit can be used as a comprehensive strategy for assessing other potential retrofit strategies. The approach used in Chapter 2 to characterize the MURB stock in Toronto can be applied to other regions and building types in order to identify the building characteristics associated with the worst energy performers in a particular sample. The comparison between the outputs of the Traditional Approach model compared to the Refined Approach model in Chapter 3 highlights the need to monitor variables beyond utility data in order to generate a model that reflects actual building performance. While the calibration of the suite-based energy model in Chapter 4 was not completed across the entire range of temperatures tested, this work lead to the development of the model output processor to ensure the results of the laboratory testing were incorporated in the whole-building model. It is important to test the contemplated retrofit strategy and develop a model of the observed performance because it may not be appropriate to rely on data provided by manufacturer. Finally, Chapter 5 presents an approach for scaling up the zone-based testing and modeling to the building-level.
Chapter 7
Conclusions

There is no single solution to reducing multi-unit residential building (MURB) energy-use since there are a variety of retrofit measures that can be applied. This thesis proposed one novel energy retrofit strategy that involved the operation of an air-source heat pump (ASHP) in a thermal buffer zone (TBZ) and, more broadly, presented a methodology by which to assess building energy retrofit measures.

First, an assessment of MURB energy-use in Toronto was conducted to determine the reduction potential. The results revealed a wide range of energy intensities in the MURB stock with a median value of 300ekWh/m$^2$ when normalized to a standard weather year. Most of this energy consumption was GHG emission-intensive natural gas combustion for space heating.

Next, a subject building with characteristics common to post-war MURBs was selected for a detailed investigation. Energy-use and interior condition data were collected over a one-year period and used to calibrate an energy model of the building. It was shown that using this detailed data for calibration yielded a model that was more representative of the actual building performance. The two most valuable parameters captured from the monitoring program were the sub-metered suite electricity loads and interior temperatures.

Then, the proposed retrofit measure was tested in a climate-controlled chamber by operating an ASHP in a TBZ modeled after the subject MURB balcony. The results showed that the COP of the ASHP could be improved during operation in the TBZ when solar gains were available. This prompted the need for consideration of a hybrid ASHP that could draw air from the TBZ or the exterior depending on the TBZ conditions. Due to limitations with the available modeling software, it was not possible to fully calibrate an energy model of the ASHP operating in the TBZ which necessitated the development of a model output processor.

Finally, the impact of the proposed retrofit on the energy-use of the subject MURB was determined using the calibrated whole-building energy model and the results from the laboratory testing. By replacing the central heating system in the subject MURB with the proposed retrofit measure, it was estimated that energy savings of 39% and a reduction in GHG emissions of 45% could be achieved assuming the ASHP operated at the COPs observed in the laboratory testing.
Furthermore, the frequency of overheating in the south-side suite was reduced depending on the temperature to which the TBZ is drawn down. However, given the utility prices at the time of writing, it is likely that the proposed retrofit measure cannot be justified based on energy cost savings alone until the utility prices are more in line with the associated GHG emissions of each energy source.

Implementation of the proposed retrofit where an ASHP is operated within a TBZ must be considered within the broader context of Toronto MURBs that already require retrofit. If the improvements to building operation and the incremental cost of implementation are considered along with the energy savings estimate established by this thesis, the proposed energy retrofit measure shows promise as an option for aging MURBs.
References


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[41] Canada Mortgage and Housing Corporation, Analysis of the Annual Energy and Water Consumption of Apartment Buildings in the CMHC HiSTAR Database, Technical Series 01-142


[57] C. Leung, H. Ge, Sleep thermal comfort and the energy saving potential due to reduced indoor operative temperature during sleep, Building and Environment, 59 (2013) 91-98.


Appendix A: Details of Journal Publications
Chapter 2

Title: Correlating Energy Consumption with Multi-Unit Residential Building Characteristics in the City of Toronto

Authors: M. Touchie, C. Binkley, K. Pressnail

Status: Published in Energy and Buildings

C. Binkley conducted the literature review, gathered, processed and analyzed the data and wrote some sections of the text. These contributions were submitted as part of her M.A.Sc. thesis which was supervised by K. Pressnail. M. Touchie expanded the literature review, revised the GHG emissions estimate and wrote the remaining part of the manuscript. K. Pressnail guided, supervised and reviewed the work.

Chapter 3

Title: Using Suite Energy-Use and Interior Condition Data to Improve Energy Modeling of a 1960's MURB

Authors: M. Touchie, K. Pressnail

Status: Under review by Energy and Buildings

M. Touchie developed the monitoring program; sourced, calibrated and installed the equipment; analyzed the data collected; developed and calibrated the model; wrote the manuscript. K. Pressnail guided, supervised and reviewed the work.

Chapter 4

Title: Testing and Simulation of a Low-Temperature Air-Source Heat Pump Operating in a Thermal Buffer Zone

Authors: M. Touchie, K. Pressnail
Status: Published in Energy and Buildings

M. Touchie designed and built the laboratory apparatus; conducted the testing; analyzed the data; developed and calibrated the energy model, wrote the manuscript. K. Pressnail guided, supervised and reviewed the work.

Chapter 5

Title: Evaluating the Proposed Retrofit of a Multi-Unit Residential Building Using an Air-Source Heat Pump Operating in an Enclosed Balcony Space

Authors: M. Touchie, K. Pressnail

Status: To be submitted in Energy and Buildings

M. Touchie developed the energy model and model output processor; analyzed the modeling results; wrote the manuscript. K. Pressnail guided, supervised and reviewed the work.
Appendix B: Meta-Analysis Data Summary
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Appendix D: Determination of Moving Average
To determine the changes in building characteristics over time, a moving average trend line was used. However, the spread of data points, one for each building, was not uniform over the time period examined. For example, some years included multiple buildings while other years had none. As the trend line was intended to show changes over time, simply applying a moving average to the existing data points would not have calculated the average over time but instead over the number of data points.

To compensate for these uneven data, smoothing of the building vintage data was undertaken. For years with multiple buildings, one data point was generated based on the average of all the buildings in that year. For years without a single building, the data point was determined by linear interpolation from the last year with available data to the next year with available data.

In the charts which include a moving average, Figure 9, Figure 10 and Figure 13, the original data points are shown in blue and the smoothed data are presented in grey. Two moving average trend lines are presented in each graph: one based on five years and one based on ten years. These moving average ranges were selected because the building code cycle time falls within this range.
Appendix E: Additional Correlations and Correlation Summary
Figure 90: Influence of Fenestration Ratio on Electricity Intensity in Building with A/C and Double-Glazed Windows

Figure 91: Influence of Glazing U-value on Variable Natural Gas Intensity
Figure 92: Influence of Glazing U-value on Electricity Intensity in Building with A/C

Figure 93: Influence of Boiler Age on Variable Natural Gas Intensity
### Table 23: Summary of Correlation Analyses

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<td>General Shell Information</td>
<td>Building Type</td>
<td>Multi-family, high-rise (interior Entries)</td>
<td>Drawings</td>
</tr>
<tr>
<td></td>
<td>Building Area (Units)</td>
<td>Total 309,301ft² (AG=267,409ft² [24,842m²], BG=41,892ft² [3892m²])</td>
<td>Drawings</td>
</tr>
<tr>
<td></td>
<td>Number of Floors Above Grade</td>
<td>20</td>
<td>Drawings</td>
</tr>
<tr>
<td></td>
<td>Number of Floors Below Grade</td>
<td>3</td>
<td>Drawings</td>
</tr>
<tr>
<td></td>
<td>Analysis Year</td>
<td>April 26, 2012 to April 25, 2013</td>
<td>Data collected</td>
</tr>
<tr>
<td></td>
<td>Daylighting Controls</td>
<td>No</td>
<td>Building manager</td>
</tr>
<tr>
<td></td>
<td>Usage Details</td>
<td>Hourly Enduse Profiles</td>
<td>Default</td>
</tr>
<tr>
<td>Building Footprint</td>
<td>Footprint shape</td>
<td>Custom</td>
<td>Drawings</td>
</tr>
<tr>
<td></td>
<td>Building Orientation / Plan North</td>
<td>NNW</td>
<td>Google maps</td>
</tr>
<tr>
<td></td>
<td>% Perimeter Zone</td>
<td>84.80%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Floor heights</td>
<td>Flr-to-Flr: 8.75ft, Flr-to-Cell: 8.25ft</td>
<td>Drawings</td>
</tr>
<tr>
<td></td>
<td>Estimated Total Envelope Area (ft²)</td>
<td>154157</td>
<td>Drawings</td>
</tr>
<tr>
<td></td>
<td>Estimated Wall Envelope Area</td>
<td>140783</td>
<td>Drawings</td>
</tr>
<tr>
<td></td>
<td>Estimated Roof Area (ft²)</td>
<td>13370</td>
<td>Drawings</td>
</tr>
<tr>
<td>Building Envelope Constructions</td>
<td>Roof Surfaces - Construction</td>
<td>6&quot; concrete</td>
<td>Building manager</td>
</tr>
<tr>
<td></td>
<td>Roof Surfaces - Ext Finish/colour</td>
<td>Roof, built up</td>
<td>Building manager</td>
</tr>
<tr>
<td></td>
<td>Roof Surfaces - Ext Insulation</td>
<td>2&quot; polyurethane</td>
<td>Building manager</td>
</tr>
<tr>
<td></td>
<td>Above Grade Walls -</td>
<td>6&quot; CMU</td>
<td>Drawings</td>
</tr>
<tr>
<td></td>
<td>Above Grade Walls - Ext Finish/colour</td>
<td>Red brick</td>
<td>Drawings</td>
</tr>
<tr>
<td></td>
<td>Above Grade Walls - Ext Finish/colour</td>
<td>none</td>
<td>Building manager</td>
</tr>
<tr>
<td></td>
<td>Above Grade Walls - Addtl Insulation</td>
<td>hollow CMU</td>
<td>Drawings</td>
</tr>
<tr>
<td></td>
<td>Ground Floor - Exposure</td>
<td>over parking garage</td>
<td>Drawings</td>
</tr>
<tr>
<td></td>
<td>Ground Floor- Cap &amp; Finish</td>
<td>vinyl siding</td>
<td>Site Visit</td>
</tr>
<tr>
<td></td>
<td>Ground Floor- Construction</td>
<td>6&quot; concrete, slab penetrates wall plane</td>
<td>Drawings</td>
</tr>
<tr>
<td></td>
<td>Ground Floor- Ext/Cav Insul:</td>
<td>None</td>
<td>Building manager</td>
</tr>
<tr>
<td></td>
<td>Ground Floor- Interior Insul</td>
<td>none</td>
<td>Building manager</td>
</tr>
<tr>
<td></td>
<td>Below Grade - Construction</td>
<td>6&quot; concrete</td>
<td>Site Visit</td>
</tr>
<tr>
<td></td>
<td>Below Grade- Insulation</td>
<td>none</td>
<td>Site Visit</td>
</tr>
<tr>
<td></td>
<td>Infiltration</td>
<td>Perim: 0.3, Core 0.001</td>
<td>Estimate, based on [34] and assuming better than average tightness because of the window replacements</td>
</tr>
<tr>
<td>Building Interior Finishes</td>
<td>Ceilings - Int. Finish</td>
<td>Drywall</td>
<td>Site Visit</td>
</tr>
<tr>
<td></td>
<td>Ceilings - Batt Insulation</td>
<td>none</td>
<td>Building manager</td>
</tr>
<tr>
<td></td>
<td>Vertical Walls - type</td>
<td>Mass</td>
<td>Drawings</td>
</tr>
<tr>
<td>Menu Location</td>
<td>Parameter</td>
<td>Model input</td>
<td>Source, Calculation or Assumption</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------</td>
<td>-------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Vertical Walls - batt insulation</td>
<td>none</td>
<td>Building manager</td>
<td></td>
</tr>
<tr>
<td>Floors - Interior Finish</td>
<td>Vinyl</td>
<td>Site Visit</td>
<td></td>
</tr>
<tr>
<td>Floors - Construction</td>
<td>6in concrete</td>
<td>Drawings</td>
<td></td>
</tr>
<tr>
<td>Floors - Concrete Cap</td>
<td>none</td>
<td>Estimate</td>
<td></td>
</tr>
<tr>
<td>Slab Penetrates Wall Plane?</td>
<td>Yes</td>
<td>Drawings</td>
<td></td>
</tr>
<tr>
<td>Slab Edge Insulation</td>
<td>none</td>
<td>Site Visit</td>
<td></td>
</tr>
<tr>
<td>Slab Edge Finish</td>
<td>none</td>
<td>Site Visit</td>
<td></td>
</tr>
</tbody>
</table>

**Exterior Doors**

| Door #1 - Type | opaque | Drawings |
| Door #1 - # of Doors By Orientation | 152S, 152N | Drawings |
| Door #1 - Dimensions | 6.7'x 2.5' | Drawings |
| Door #1 - Construction/ Glass Definition | Wood, solid core flush | Drawings |
| Door #2 - Type | Glass | Drawings |
| Door #2 - # of Doors By Orientation | 1E, 1W | Drawings |
| Door #2 - Dimensions | 7'x3.5' | Drawings |
| Door #2 - Construction/ Glass Definition | Double low-e, Alum with break | Drawings |
| Door #3 - Type | overhead | Drawings |
| Door #3 - # of Doors By Orientation | 1S | Drawings |
| Door #3 - Dimensions | 7'x6' | Drawings |
| Door #3 - Construction/ Glass Definition | uninsulated steel | Drawings |

**Exterior Windows**

<p>| Window Area Specification Method | Percentage of gross floor wall area (floor to floor) | Drawings |
| Window #1 - Glass Category and Type | Double low-e | Drawings |
| Window #1 - Frame Type and Width | Alum w/brk, oper, metal spacer | Drawings |
| Window #1 - Dimensions | 8.75'x6.6' | Drawings |
| Window #1 - Sill Ht. | 0.5 | Drawings |
| Window #1 - % Window By Orientation | 19S, 19N | Drawings |
| Window #2 - Glass Category and Type | Double low-e | Drawings |
| Window #2 - Frame Type and Width | Alum w/brk, oper, metal spacer | Drawings |
| Window #2 - Dimensions | 7.33'x4.58' | Drawings |
| Window #2 - Sill Ht. | 1.5 | Drawings |
| Window #2 - % Window By Orientation | 22S, 22N | Drawings |
| Window #3 - Glass Category and Type | Double low-e | Drawings |
| Window #3 - Frame Type and Width | Alum w/brk, oper, metal spacer | Drawings |
| Window #3 - Dimensions | 3.5'x4.5' | Drawings |
| Window #3 - Sill Ht. | 3 | Drawings |</p>
<table>
<thead>
<tr>
<th>Location</th>
<th>Parameter</th>
<th>Model input</th>
<th>Source, Calculation or Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window #3 - % Window By Orientation</td>
<td>4E, 4W</td>
<td>Drawings</td>
<td></td>
</tr>
<tr>
<td>Estimated Building-wide gross flr-to-flr</td>
<td>26.30%</td>
<td>Drawings</td>
<td></td>
</tr>
<tr>
<td>Estimated Building-wide gross flr-to-cell</td>
<td>27.9</td>
<td>Drawings</td>
<td></td>
</tr>
<tr>
<td>Exterior Window Shades and Blinds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overhangs - Dist from Win</td>
<td>0</td>
<td>To account for the shading of the inset balconies</td>
<td></td>
</tr>
<tr>
<td>Overhangs - Shade Depths</td>
<td>2.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windows with Overhangs</td>
<td>Type 1 (Windows on balcony)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity Areas Allocation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area #1 Type and Percent</td>
<td>Residential 81%</td>
<td>Drawings</td>
<td></td>
</tr>
<tr>
<td>Area #1 Assign First To</td>
<td>Mid/Top/Per</td>
<td>Drawings</td>
<td></td>
</tr>
<tr>
<td>Corridor</td>
<td>Area #2 Type and Percent</td>
<td>Corridor 14.2%</td>
<td>Drawings</td>
</tr>
<tr>
<td>Corridor</td>
<td>Area #2 Design Max Occu and Ventilation</td>
<td>2000/551 Adjusted to be 874cfm/er to equal 16000cfm ventilation and exhaust</td>
<td>Using average square footage of each corridor and the estimated corridor ventilation supply rate from [33]</td>
</tr>
<tr>
<td>Corridor</td>
<td>Area #2 Assign First To</td>
<td>1st/Mid/Top/Core</td>
<td>Exhaust fans 15HP from site visit and 18240L/s based on 53L/s per exhaust fan per suite [33]</td>
</tr>
<tr>
<td>Storage</td>
<td>Area #3 Type and Percent</td>
<td>Storage 0.8</td>
<td>Drawings</td>
</tr>
<tr>
<td>Storage</td>
<td>Area #3 Design Max Occu and Ventilation</td>
<td>2000/0</td>
<td>Assumed no vent air supplied directly</td>
</tr>
<tr>
<td>Storage</td>
<td>Area #3 Assign First To</td>
<td>1st/Core</td>
<td>Drawings</td>
</tr>
<tr>
<td>Laundry</td>
<td>Area #4 Type and Percent</td>
<td>Laundry 0.2</td>
<td>Drawings</td>
</tr>
<tr>
<td>Laundry</td>
<td>Area #4 Design Max Occu and Ventilation</td>
<td>2000/25</td>
<td>Default</td>
</tr>
<tr>
<td>Laundry</td>
<td>Area #4 Assign First To</td>
<td>Top/Perim</td>
<td>Drawings</td>
</tr>
<tr>
<td>Office</td>
<td>Area #5 Type and Percent</td>
<td>Office 1.7</td>
<td>Drawings</td>
</tr>
<tr>
<td>Office</td>
<td>Area #5 Design Max Occu and Ventilation</td>
<td>500/20</td>
<td>Default</td>
</tr>
<tr>
<td>Office</td>
<td>Area #5 Assign First To</td>
<td>1st/Core/Perim</td>
<td>Drawings</td>
</tr>
<tr>
<td>Classroom</td>
<td>Area #6 Type and Percent</td>
<td>Classroom/Lecture 2.1</td>
<td>Drawings</td>
</tr>
<tr>
<td>Classroom</td>
<td>Area #6 Design Max Occu and Ventilation</td>
<td>200/15</td>
<td>Default</td>
</tr>
<tr>
<td>Classroom</td>
<td>Area #6 Assign First To</td>
<td>1st/Core/Perim</td>
<td>Drawings</td>
</tr>
<tr>
<td>Classroom</td>
<td>Occupancy Profiles By Season</td>
<td>EL1 Occ Profile (S1)</td>
<td>Drawings</td>
</tr>
<tr>
<td>Parking Garage</td>
<td>Area #7 Type and Percent</td>
<td>Parking Garage 1</td>
<td>Drawings</td>
</tr>
<tr>
<td>Parking Garage</td>
<td>Area #7 Design Max Occu and Ventilation</td>
<td>41899/36000</td>
<td>Default</td>
</tr>
<tr>
<td>Parking Garage</td>
<td>Area #7 Assign First To</td>
<td>Blw</td>
<td>Drawings</td>
</tr>
</tbody>
</table>

Zone Group Definitions
- AGGround Floor Core: 50% Corridor, 50% Storage, Main Loop, no exhaust
- AGGround Floor Perimeter: 9% Storage, 41% Office, 50% Classroom, Main Loop, 3000cfm, high
- AGTypical Floor(s) Core: 100% Corridor, Corridor MAU, 16000cfm, standard
- AGTypical Floor(s) Perimeter: 100% Residential, unconditioned
- AGTop Floor Core: 100% Corridor, Corridor MAU, no exhaust
<table>
<thead>
<tr>
<th>Menu Location</th>
<th>Parameter Code</th>
<th>Model input</th>
<th>Source, Calculation or Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG Top Floor Perimeter</td>
<td>94% Residential, 6% Laundry, unconditioned</td>
<td>94% Residential, 6% Laundry, unconditioned</td>
<td></td>
</tr>
<tr>
<td>BG Parking Garage</td>
<td>100% Parking, Ventilator, exhaust 36,000cfm</td>
<td>Based on 2x5HP fans on each parking garage level operating 24hrs per day based on conversation with building electrician</td>
<td></td>
</tr>
</tbody>
</table>

### Non-HVAC End Uses to Model

<table>
<thead>
<tr>
<th>Parameter Code</th>
<th>Model input</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior End Uses (Contributing to space loads)</td>
<td>Interior (ambient) lighting, misc equip. motors</td>
<td>Building manager</td>
</tr>
<tr>
<td>Exterior End Uses (Not contributing to space loads)</td>
<td>Exterior lighting, DHW</td>
<td>Building manager</td>
</tr>
<tr>
<td>Laundry Facilities - Location of Equipment</td>
<td>Common</td>
<td>Drawings</td>
</tr>
<tr>
<td># of Dwelling Units Per Floor</td>
<td>16</td>
<td>Drawings</td>
</tr>
<tr>
<td>Laundry Loads/Unit/Wk</td>
<td>3.1</td>
<td>Default</td>
</tr>
<tr>
<td>Washer Type</td>
<td>Vertical axis</td>
<td>Building manager</td>
</tr>
<tr>
<td>Dryer Fuel</td>
<td>Electricity</td>
<td>Building manager</td>
</tr>
</tbody>
</table>
Appendix G: Energy Model Inputs – Traditional Approach Model
<table>
<thead>
<tr>
<th>Menu Location</th>
<th>Parameter</th>
<th>Model input</th>
<th>Source, Calculation or Assumption</th>
<th>Model input</th>
<th>Source, Calculation or Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Shell Information</td>
<td>Cooling Equipment</td>
<td>None</td>
<td>Main Loop for A/C units; PTAC (sys per site); Corridor Unit ventilator (no cool); Suite without A/C. Unconditioned, Parking Garage. Unit ventilator (no cool)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heating Equipment</td>
<td>Main Loop: HW Baseboard with NO zone vent (sys per site); Corridor MUA; HW Furnace with zone vent (sys per site); Parking Garage unit ventilator (no heat); Ground Floor: HW Baseboards with zone vent</td>
<td>System that most resembles actual</td>
<td>None</td>
<td>System that most resembles actual</td>
</tr>
<tr>
<td>Building Footprint</td>
<td>Zones: apts, corridor, ground floor</td>
<td>Zones: A/C apts, non-A/C apts, corridor, ground floor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activity Areas Allocation</td>
<td>Area #1 Design Max Occup and Ventilation</td>
<td>Area #1 Design Max Occup and Ventilation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Activity Areas Allocation</td>
<td>Area #1 Design Max Occup and Ventilation</td>
<td>215,004sqft/760people = 356sqft per 600 people because no fresh air delivered directly to building manager. Typically 700 but around 600 during summer months</td>
<td>235,004sqft/800people = 350sqft per 600 people because no fresh air delivered directly to building manager. Typically 700 but around 600 during summer months</td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>Area #1 - Lighting</td>
<td>1.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corridor</td>
<td>Area #2 - Lighting</td>
<td>1.18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laundry</td>
<td>Area #4 - Lighting</td>
<td>2.45</td>
<td>Calibrated to monthly electricity consumption</td>
<td>2.45</td>
<td>Calibrated to monthly electricity consumption</td>
</tr>
<tr>
<td>Office</td>
<td>Area #5 - Lighting</td>
<td>2.54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Classroom</td>
<td>Area #6 - Lighting</td>
<td>2.96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscellaneous Loads and Profiles</td>
<td>Area #1 Electric Load</td>
<td>Area #1 Electric Load</td>
<td>Scaled up default loads until electricity consumption matched bills</td>
<td>0.62</td>
<td>Scaled up default loads until electricity consumption matched bills</td>
</tr>
<tr>
<td>Residential</td>
<td>Area #3 Electric Load</td>
<td>Area #3 Electric Load</td>
<td></td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>Laundry</td>
<td>Area #4 Electric Load</td>
<td>Area #4 Electric Load</td>
<td>Default: 0.15, based on average running watts, 6 hours operation and quantity of equipment provided by Fraser divided by 450sqft</td>
<td>47.7</td>
<td>47.7</td>
</tr>
<tr>
<td>Office</td>
<td>Area #5 Electric Load</td>
<td>Area #5 Electric Load</td>
<td>1.54</td>
<td>1.54</td>
<td></td>
</tr>
<tr>
<td>Classroom</td>
<td>Area #6 Electric Load</td>
<td>Area #6 Electric Load</td>
<td>1.03</td>
<td>1.03</td>
<td></td>
</tr>
<tr>
<td>DHW</td>
<td>DHW Hourly Profiles</td>
<td>70 gal/person/day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HVAC System Definition</td>
<td>[System 1 - Cooling Source: DX coils]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[System 1 - Heating Source: none]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[System 1 - Hot Water Src: Packaged Terminal AC]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[System 1 - System Per Area: System per site]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HVAC Zones: Temperature and Air Flows</td>
<td>[System 1 - System Type: All above grade zones]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>[System 1 - Occupied Cool/Heat: Main Loop: Cool 78/Heat 71]</td>
<td>Increased heating set point to get zone temperature to be the default set point</td>
<td>Main Loop: Cool 78/Heat 68</td>
<td>Default</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[System 1 - Minimum Design Flow]</td>
<td>0 no air circulation in suites</td>
<td>0 no air circulation in suites</td>
<td></td>
</tr>
</tbody>
</table>

**WINTER MODEL**

**SUMMER MODEL**
<table>
<thead>
<tr>
<th><strong>WINTER MODEL</strong></th>
<th><strong>SUMMER MODEL</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System 1 - Occupied Cool/Heat</strong></td>
<td><strong>System 1 - Occupied Cool/Heat</strong></td>
</tr>
<tr>
<td><strong>System 2 - Minimum Design Flow</strong></td>
<td><strong>System 2 - Minimum Design Flow</strong></td>
</tr>
<tr>
<td><strong>System 3 - Occupied Cool/Heat</strong></td>
<td><strong>System 3 - Occupied Cool/Heat</strong></td>
</tr>
<tr>
<td><strong>System 4 - Minimum Design Flow</strong></td>
<td><strong>System 4 - Minimum Design Flow</strong></td>
</tr>
</tbody>
</table>

**HVAC System Fans**

- **Fan Details**
  - Main Loop: Power = 10HP; efficiency = 16000cfm; ground floor heating 2800cfm; high efficiency fans, 8000cfm at 20% of 10% of OA
  - Building manager

- **HVAC System Fan Schedules**
  - Corridor and parking garage fans 24/7; main loop: 24hrs/day; ground floor heating during the day on weekdays only
  - Building manager

**HVAC Zone Heating, Vent and Economizers**

- **System 1 - Occupied Cool/Heat**
  - Main Loop: -2100kBTu, Corridor MAU: -1160 kBTu; ground floor heating: -400 kBTu
  - Through calibration with actual NO consumption

- **System 2 - Minimum Design Flow**
  - Main loop: 30 kBTu
  - Through calibration with summer electricity use

**Heating Primary Equipment**

- **Hot Water System - Head and Design DT**
  - 41.6, 40.0
  - Default

- **Hot Water System - Pump Configuration**
  - Single System Pump
  - Building manager: pumps only on loop not in boiler

- **Hot Water System - Number of System Pumps**
  - 4

- **Hot Water System - HW Loop Flow**
  - Constant
  - Building manager

- **Hot Water System - Loop Pump (Head and Flow)**
  - Blank
  - Default

- **Hot Water System - Motor Efficiency**
  - Standard
  - Building manager

- **Boiler Type/Fuel**
  - Condensing HW Boiler, Natural Gas
  - From nameplate

- **Boiler - Count/Output**
  - 1, 2934
  - From nameplate

- **Boiler Efficiency**
  - 95%
  - Calibration and fairly new boilers

- **Electric Demand**
  - 2.06
  - Default
Appendix H: Energy Model Inputs – Refined Approach Model
<table>
<thead>
<tr>
<th>Menu Location</th>
<th>Parameter</th>
<th>Model input</th>
<th>Source, Calculation or Assumption</th>
<th>Model input</th>
<th>Source, Calculation or Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WINTER MODEL</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>SUMMER MODEL</strong></td>
<td></td>
</tr>
<tr>
<td>Interior Lighting Loads and Profiles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residents Area #1 - Lighting</td>
<td>0.51</td>
<td>Calibrated with the submetered suite loads by scaling default values in each zone</td>
<td>0.51</td>
<td>Calibrated with the submetered suite loads by scaling default values in each zone</td>
<td></td>
</tr>
<tr>
<td>Corridor Area #2 - Lighting</td>
<td>2.1</td>
<td></td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage Area #3 - Lighting</td>
<td>4.41</td>
<td></td>
<td>4.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laundry Area #4 - Lighting</td>
<td>4.32</td>
<td></td>
<td>4.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Office Area #5 - Lighting</td>
<td>4.32</td>
<td></td>
<td>4.32</td>
<td></td>
<td></td>
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<tr>
<td>Classroom Area #6 - Lighting</td>
<td>4.93</td>
<td></td>
<td>4.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscellaneous Loads and Profiles</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residents I Area #1 Electric Load</td>
<td>0.41</td>
<td>Calibrated with the submetered suite loads by scaling default values in each zone</td>
<td>0.41</td>
<td>Calibrated with the submetered suite loads by scaling default values in each zone</td>
<td></td>
</tr>
<tr>
<td>Corridor Area #2 Electric Load</td>
<td>0</td>
<td>Default: 0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage Area #3 Electric Load</td>
<td>0</td>
<td>Default: 0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Office Area #5 Electric Load</td>
<td>5.05</td>
<td>Calibrated with the submetered suite loads by scaling default values in each zone</td>
<td>5.05</td>
<td>Calibrated with the submetered suite loads by scaling default values in each zone</td>
<td></td>
</tr>
<tr>
<td>Classroom Area #6 Electric Load</td>
<td>5.03</td>
<td>Calibrated with the submetered suite loads by scaling default values in each zone</td>
<td>5.03</td>
<td>Calibrated with the submetered suite loads by scaling default values in each zone</td>
<td></td>
</tr>
<tr>
<td><strong>DHW</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DHW Hourly Profiles: 79 gal/day</td>
<td>DHW Hourly Profiles: 79 gal/day</td>
<td></td>
</tr>
<tr>
<td><strong>HVAC Zones: Temperature and Air Flows</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System 1 - Occupied Cool/Heat</td>
<td>Main Loop: Cool 78/Heat 78</td>
<td>Calibration to get the apt temperatures to match the monitored temperatures</td>
<td>Main Loop: Cool 80/Heat 76.1</td>
<td>Calibration to get the apt temperatures to match the monitored temperatures</td>
<td></td>
</tr>
<tr>
<td>System 1 - Minimum Design Flow</td>
<td>0</td>
<td>no air circulation in units</td>
<td>0</td>
<td>no air circulation in units</td>
<td></td>
</tr>
<tr>
<td>System 2 - Occupied Cool/Heat</td>
<td>Corridor MAU: Cool 78/Heat 77.5</td>
<td>Calibration to get the apt temperatures to match the monitored temperatures</td>
<td>Corridor MAU: Cool 78/Heat 76.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System 2 - Minimum Design Flow</td>
<td>0.8</td>
<td>default</td>
<td>0.8</td>
<td>default</td>
<td></td>
</tr>
<tr>
<td>System 3 - Occupied Cool/Heat</td>
<td>Ground Floor Heating: Cool 78/Heat 80</td>
<td></td>
<td>UNCONDITIONED Non-A/C units</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System 3 - Minimum Design Flow</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>HVAC Zone Heating: Vent and Economizers</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating, vent and economizer details</td>
<td>Main Loop: 150kW, Corridor MAU: 1160 kBtu; Ground floor heating: auto-tuned</td>
<td>Through calibration with actual NG consumption</td>
<td>Main Loop: 430kW</td>
<td>Through calibration with summer electricity use</td>
<td></td>
</tr>
</tbody>
</table>
Appendix I: Photos of Sensor Installation
Figure 94: Roof-top Weather Station
Figure 95: Reed Switch for Door Operation

Figure 96: Plunger Sensor for Window Operation (closed position)
Figure 97: Plunger Sensor for Window Operation (open position)

Figure 98: Reed Switch for Window Operation
Figure 99: Plunger Sensor for Window and Temperature Sensor for Baseboard

Figure 100: Differential Pressure Sensor across Exterior Envelope
Figure 101: Differential Pressure Sensor for Bathroom Fan

Figure 102: Differential Pressure Sensor between Apartment and Interior Corridor
Appendix J: Sensor Calibration
This section briefly describes the calibration procedure for the sensors and measurement equipment used in the study.

**Temperature Sensor Calibration**

All of the thermocouples were calibrated using an ice bath. Thermocouple readings were taken using a Thermoelectric Pronto 200 thermocouple reader and compared to thermometer readings. With Type-T thermocouples, the reader can measure temperatures between -200°C and 400°C and is accurate to ±0.2°C [68].

The Cantherm MF58104F3950 Beta 4390K temperature sensors were calibrated by co-locating all of the sensors along with a series of thermocouples in the Apartment zone of the laboratory set up. The thermocouple readings were compared to the Cantherm sensor readings over time.

**Relative Humidity Sensor Calibration**

Calibration of the Honeywell HCH-1000-001 relative humidity sensors was completed by locating all of the sensors in a sealed box with two different salt solutions. First, a magnesium nitrate solution was used to generate a mid-range relative humidity (55% at 20°C) and then a potassium nitrate solution was used to generate a high relative humidity (93% at 20°C). Readings were collected by the SMT-A2 wireless data loggers over a two-day period and compared to the control curve for each salt solution.

**Displacement Sensor Calibration**

Due to the limited range of the plunger-type displacement sensor, the sensors could not track the entire motion of the window. Of primary interest was whether the window was open or closed. These sensors were calibrated by manually depressing each plunger and recording the time spent “open” and “closed”. These readings were then compared to the readings collected by the SMT-A2 wireless data loggers to determine if the plungers were functioning properly.

**Differential Pressure Sensor Calibration**

The SDP1000-L025 differential pressure sensors were calibrated by arranging all the sensors to read the pressure difference between the Apartment zone and the Balcony zone in the laboratory. A pressure difference was generated by unbalancing the air flow of the energy recovery...
ventilator operating between the Cold Room and the Apartment. This pressure difference was measured with the Air Instrument Resources Ltd. MP3KDµ micromanometer. This micromanometer can be used to detect pressures between 0 Pa and 199.9 Pa with an accuracy of ±1% [72]. The manually collected readings were then compared to the data collected by the SMT-A2 wireless data loggers.

**Power Meter Calibration**

P4460 Kill A Watt™ EZ meters [69] were calibrated using a light bulb and a Sangamo K2S electromechanical single phase watt-hour meter from the local electricity utility [70].

Table 24 summarizes which sensors and measurement equipment were calibrated and how the accuracy observed during the calibration differed from the accuracy stated in the manufacturer literature. Where equipment was not calibrated, the manufacturer accuracy was assumed. Where the accuracy observed was better than the manufacturer accuracy, the manufacturer accuracy was assumed, to be conservative. Conversely, when the manufacturer accuracy was better than the observed accuracy, the observed accuracy was assumed.

**Table 24: Summary of Sensor and Equipment Accuracy**

<table>
<thead>
<tr>
<th>Sensor or measurement equipment type</th>
<th>Model Number</th>
<th>Manufacturer Accuracy</th>
<th>Calibrated?</th>
<th>Observed Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Cantherm MF58104F3950 Beta 4390K [46]</td>
<td>±1°C</td>
<td>Yes</td>
<td>±0.3°C</td>
</tr>
<tr>
<td></td>
<td>Type T Thermocouples [85]</td>
<td>±0.03°C*</td>
<td>Yes</td>
<td>±0.28°C</td>
</tr>
<tr>
<td></td>
<td>Wireless Vantage Pro2™ 6152: Outside Temperature [50]</td>
<td>±1°C</td>
<td>Yes</td>
<td>±0.3°C</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Honeywell HCH-1000-001 [46]</td>
<td>±5%</td>
<td>Yes</td>
<td>±15% below 60% RH</td>
</tr>
<tr>
<td></td>
<td>Wireless Vantage Pro2™ 6152: Outside Relative Humidity [50]</td>
<td>±3%</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Accuracy/Range</th>
<th>Validity</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>Model 404 BI Technologies [47]</td>
<td>±0.38mm</td>
<td>Yes</td>
<td>Able to measure “open” and “closed” with 100% accuracy</td>
</tr>
<tr>
<td>Differential</td>
<td>SDP1000-L025 [48]</td>
<td>0.5% (Full Scale) or ±0.31Pa</td>
<td>Yes</td>
<td>0.34Pa</td>
</tr>
<tr>
<td>Pressure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Meter</td>
<td>P4460 Kill A Watt™ EZ meters [69]</td>
<td>±0.5% for kilowatt-hour readings</td>
<td>Yes</td>
<td>±4.5%</td>
</tr>
<tr>
<td></td>
<td>DL160 Dual Input True RMS AC Voltage/Current Datalogger [71]</td>
<td>±2%</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PowerHawk 6312 with 200A-80-mA Solid Core Current Transformers [49]</td>
<td>±0.5%</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Air flow</td>
<td>Energy Conservatory Minneapolis Series B Duct Blaster [73]</td>
<td>±3%</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

*Reference Type-T thermocouple accuracy was derived from more extensive calibration conducted by a previous Ph.D. candidate on the actual thermocouples used in the laboratory testing [85].
Appendix K: Determination of Comfort Zone
ASHRAE Standard 55-2010 Thermal Environmental Conditions for Human Occupancy requires operative temperature in order to define comfortable conditions for occupants. Operative temperature can be approximated by the average of the dry bulb temperature and the mean radiant temperature (MRT) [26] when the air speed is less than 0.4m/s and the MRT is less than 50°C which has been assumed for the interior of the subject building.

The MRT was not collected during the monitoring program however the dry bulb temperature was. The dry bulb temperature data collected from the interior wall of the living room were thought to be the most appropriate for this analysis because these temperature sensors were located furthest from the window, kitchen and bathroom, relative to the other temperature sensors.

The MRT can be approximated by using angle factors to generate a weighted average of the interior surface temperatures of the zone being considered [26]. Figure 13.2 from [26] was used to determine the angle factors based on the location of the temperature sensor on the inner wall of the living room, as shown in Figure 103.

\[\text{Operative temperature} = \frac{\text{Dry bulb temperature} + \text{Mean radiant temperature (MRT)}}{2}\]

Figure 103: Schematic of Living Room Zone
The interior surface temperatures are constantly changing, particularly the exterior wall due to solar radiation, but calculating the changing MRT for each 15 minute period for which dry bulb temperature data was not feasible. Instead average monthly conditions are assumed.

The temperature of all surfaces adjacent to other suites or the common area corridor (interior walls) is assumed to be equal to the average suite temperature. The temperature of the interior surface of the exterior wall was determined by solving for the temperature difference across the interior air film (Equation 20 [26]) and subtracting this from the interior temperature. Once the wall surface temperatures and angle factors were determined, Equation 21 [26] was used to estimate the MRT.

**Equation 20**

\[
\frac{\Delta T_{if}}{\Delta T_{tot}} = \frac{R_{if}}{R_{tot}}
\]

*where:*

\(\Delta T_{if} = \text{temperature difference across interior surface film}\)

\(\Delta T_{tot} = \text{temperature difference between interior and exterior}\)

\(R_{if} = \text{thermal resistance of interior air film } \left( \frac{m^2K}{W} \right)\)

\(R_{tot} = \text{thermal resistance of exterior wall } \left( \frac{m^2K}{W} \right)\)

**Equation 21**

\[MRT \cong T_1^4 F_1 + T_2^4 F_2 + \cdots + T_N^4 F_N\]

*where:*

\(MRT = \text{mean radiant temperature } (\degree C)\)

\(T = \text{temperature of surface } N (\degree C)\)
\[ F = \text{angle factor for surface N} \]

The MRT was calculated for January and July for the two suites which had the most data collected: 14A and 14B. These suites were also selected because one suite faces north and the other faces south to allow for a comparison between suites on different orientations.

A summary of the interior surface temperatures for the living room zones in suites 14A and 14B determined by Equation 20 and the resulting MRTs determined by Equation 21 is presented in Table 25 along with the air temperatures used in the calculations. The thermal resistance of the exterior wall was estimated at 0.3m\(^2\)K/W based on the components of the wall as detailed in the building plans [86] and a building audit report [87]. The thermal resistance of the interior surface film was assumed to be 0.12m\(^2\)K/W based on Table 8.2 from [26].

**Table 25: Average Monthly MRT for Suites 14A and 14B**

<table>
<thead>
<tr>
<th>Average Monthly Values</th>
<th>Exterior</th>
<th>Suite 14A</th>
<th>Suite 14B</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>-2.8°C</td>
<td>23.3°C</td>
<td>25.6°C</td>
<td>Monitored data</td>
</tr>
<tr>
<td>Jan 2013</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interior wall temperature</td>
<td>23.3°C</td>
<td>25.6°C</td>
<td>Assumed</td>
<td></td>
</tr>
<tr>
<td>Exterior wall temperature</td>
<td>12.9°C</td>
<td>14.3°C</td>
<td>Calculated</td>
<td></td>
</tr>
<tr>
<td>MRT</td>
<td>23.2°C</td>
<td>25.5°C</td>
<td>Calculated</td>
<td></td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>74%</td>
<td>31%</td>
<td>31%</td>
<td>Monitored data</td>
</tr>
<tr>
<td>Jul 2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air temperature</td>
<td>24.0°C</td>
<td>26.7°C</td>
<td>28.0°C</td>
<td>Monitored data</td>
</tr>
<tr>
<td>Interior wall temperature</td>
<td>26.7°C</td>
<td>28.0°C</td>
<td>Assumed</td>
<td></td>
</tr>
<tr>
<td>Exterior wall temperature</td>
<td>25.6°C</td>
<td>26.4°C</td>
<td>Calculated</td>
<td></td>
</tr>
<tr>
<td>MRT</td>
<td>26.7°C</td>
<td>28.0°C</td>
<td>Calculated</td>
<td></td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>59%</td>
<td>47%</td>
<td>45%</td>
<td>Monitored data</td>
</tr>
</tbody>
</table>
The Thermal Comfort Tool developed by the Centre for the Built Environment [55] was then used to determine the range of dry bulb temperatures and relative humidities that is considered comfortable. The tool requires MRT, air speed, and the metabolic rate and clothing level of the occupants. The MRT was assumed constant throughout the month of January and July and is equal to the values shown in Table 25. The air speed and metabolic rate were assumed constant at 0.1m/s and 1 met. The January and July clothing levels were assumed to be 1clo and 0.5clo, respectively [55].

The resulting range of temperatures and relative humidities considered acceptable for comfort based on the assumed MRT is shown in Table 26.

**Table 26: Thermal Comfort Ranges for Suites 14A and 14B in January and July**

<table>
<thead>
<tr>
<th></th>
<th>Suite 14A</th>
<th></th>
<th>Suite 14B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td><strong>Jan 2013</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp at 100% RH</td>
<td>18.3°C</td>
<td>24.0°C</td>
<td>16.8°C</td>
</tr>
<tr>
<td>Temp at 0% RH</td>
<td>22.6°C</td>
<td>30.5°C</td>
<td>20.3°C</td>
</tr>
<tr>
<td><strong>Jul 2012</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp at 100% RH</td>
<td>21.6°C</td>
<td>25.9°C</td>
<td>20.7°C</td>
</tr>
<tr>
<td>Temp at 0% RH</td>
<td>25.4°C</td>
<td>31.0°C</td>
<td>24.0°C</td>
</tr>
</tbody>
</table>
Appendix L: Differential Pressure and Exterior Temperature
Figure 104: The Influence of Exterior Temperature on the Differential Pressure between the Corridor and the Suite
Appendix M: Photos of the ASHP Laboratory Set-Up
Figure 105: Outdoor Unit of ASHP in TBZ

Figure 106: Indoor Unit of ASHP in Apartment
Appendix N: Laboratory Test Summary
<table>
<thead>
<tr>
<th>Cold Room Temp</th>
<th>Avg Guard Heat</th>
<th>Avg Cycle Time</th>
<th>Guard Temp Analysis of Test Times</th>
<th>Overall COP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg Max Variance</td>
<td>Avg Max Min</td>
<td>Avg C C</td>
<td>Steady State COP</td>
</tr>
<tr>
<td>W</td>
<td>W</td>
<td>W</td>
<td>W</td>
<td>W</td>
</tr>
<tr>
<td>6.0</td>
<td>0</td>
<td>Off</td>
<td>507</td>
<td>1210</td>
</tr>
<tr>
<td>6.2</td>
<td>541 On</td>
<td>423</td>
<td>538</td>
<td>1640</td>
</tr>
<tr>
<td>6.0</td>
<td>868 On</td>
<td>410</td>
<td>552</td>
<td>23.01</td>
</tr>
<tr>
<td>6.1</td>
<td>1226 On</td>
<td>313</td>
<td>565</td>
<td>36.49</td>
</tr>
<tr>
<td>6.0</td>
<td>1612 On</td>
<td>312</td>
<td>535</td>
<td>33.34</td>
</tr>
<tr>
<td>5.7</td>
<td>531 Thermostat</td>
<td>385</td>
<td>538</td>
<td>23.10</td>
</tr>
<tr>
<td>1.1</td>
<td>0 Off</td>
<td>684</td>
<td>1320</td>
<td>69.32</td>
</tr>
<tr>
<td>1.1</td>
<td>492 On</td>
<td>679</td>
<td>1363</td>
<td>77.92</td>
</tr>
<tr>
<td>1.1</td>
<td>909 On</td>
<td>582</td>
<td>1295</td>
<td>48.68</td>
</tr>
<tr>
<td>1.4</td>
<td>1250 On</td>
<td>520</td>
<td>1324</td>
<td>16.91</td>
</tr>
<tr>
<td>1.7</td>
<td>1431 On</td>
<td>463</td>
<td>590</td>
<td>19.09</td>
</tr>
<tr>
<td>1.7</td>
<td>1778 On</td>
<td>357</td>
<td>568</td>
<td>34.18</td>
</tr>
<tr>
<td>1.3</td>
<td>644 Thermostat</td>
<td>540</td>
<td>1162</td>
<td>30.20</td>
</tr>
<tr>
<td>-4.2</td>
<td>0 Off</td>
<td>808</td>
<td>1209</td>
<td>84.43</td>
</tr>
<tr>
<td>-3.3</td>
<td>514 On</td>
<td>802</td>
<td>1257</td>
<td>68.65</td>
</tr>
<tr>
<td>-3.4</td>
<td>1001 On</td>
<td>737</td>
<td>1305</td>
<td>61.46</td>
</tr>
<tr>
<td>-3.4</td>
<td>1231 On</td>
<td>730</td>
<td>1468</td>
<td>60.67</td>
</tr>
<tr>
<td>-3.5</td>
<td>1476 On</td>
<td>575</td>
<td>1434</td>
<td>25.29</td>
</tr>
<tr>
<td>-4.1</td>
<td>1892 On</td>
<td>592</td>
<td>1328</td>
<td>22.32</td>
</tr>
<tr>
<td>-3.9</td>
<td>627 Thermostat</td>
<td>668</td>
<td>1276</td>
<td>88.68</td>
</tr>
<tr>
<td>-8.9</td>
<td>0 Off</td>
<td>1153</td>
<td>1000</td>
<td>91.91</td>
</tr>
<tr>
<td>-8.3</td>
<td>526 On</td>
<td>827</td>
<td>1241</td>
<td>166.21</td>
</tr>
<tr>
<td>-8.9</td>
<td>738 On</td>
<td>375</td>
<td>823</td>
<td>79.05</td>
</tr>
<tr>
<td>-8.3</td>
<td>1128 On</td>
<td>675</td>
<td>1350</td>
<td>173.95</td>
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Appendix O: Power Consumption Data from a Selection of Tests
Figure 107: ASHP Power Consumption from 1°C Test (1430W heat added)

Figure 108: ASHP Power Consumption from 1°C Test (492W heat added)
Figure 109: ASHP Power Consumption from -4°C Test (1892W heat added)

Figure 110: ASHP Power Consumption from -4°C Test (steady temperature)
Appendix P: Flow Chart of Model Output Processing Algorithm
From cooled TBZ model:
\[ q_{\text{TRZ Ext}} \text{ and } q_{\text{TRZ APT}} \]
\[ \text{COP}_{\text{TRZ}} = 0.069 \times T_{\text{TRZ}} + 2.24 \]
\[ \text{COP}_{\text{Ext}} = 0.069 \times T_{\text{Ext}} + 2.24 \]
\[ q_{\text{req, SH}} = \text{south APT heating load} \]

From float TBZ model:
\[ q_{\text{wall, SH}} = q_{\text{TRZ Ext}} - q_{\text{TRZ APT}} \]
\[ q_{\text{req, SH}} = \text{north APT heating load} \]

\[ q_{\text{wall}} = q_{\text{wall, SH}} + q_{\text{TRZ Ext}} + q_{\text{TRZ APT}} \]

\[ q_{\text{wall}} > 0 \]

\[ q_{\text{power, TRZ, Total}} = q_{\text{wall}} / (\text{COP}_{\text{TRZ}} - 1) \]
\[ q_{\text{TRZ, Total}} = (q_{\text{power, TRZ, Total}}) / (\text{COP}_{\text{TRZ}}) \]

\[ q_{\text{req, SH}} = q_{\text{TRZ, Total}} \]
\[ q_{\text{TRZ, SH}} = 0 \]
\[ q_{\text{TRZ, DHW}} = 0 \]

\[ q_{\text{TRZ, SH}} = q_{\text{req, SH}} - q_{\text{TRZ, SH}} \]
\[ q_{\text{TRZ, SH}} = q_{\text{TRZ, SH}} (1 - 1 / \text{COP}_{\text{TRZ}}) \]

\[ q_{\text{wall}} > (q_{\text{req, SH}})(1 - 1 / \text{COP}_{\text{TRZ}}) \]

\[ q_{\text{TRZ, SH}} = q_{\text{req, SH}} (1 - 1 / \text{COP}_{\text{TRZ}}) \]

\[ q_{\text{TRZ, SH}} > q_{\text{req, SH}} \]

\[ q_{\text{TRZ, DHW}} = q_{\text{TRZ, DHW}} (1 - 1 / \text{COP}_{\text{TRZ}}) \]

\[ q_{\text{TRZ, DHW}} = q_{\text{TRZ, DHW}} / (\text{COP}_{\text{TRZ}}) \]

\[ q_{\text{power, TRZ, DHW}} = q_{\text{TRZ, DHW}} / (\text{COP}_{\text{TRZ}}) \]

End
Appendix Q: Summary of Suite-Based Modeling Results
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<td>21%</td>
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| Excess Heat used for DHW                            | 422             | 977               | 1991         | 3878           |      |     |     |     |
| DHW total Power                                     | 101             | 269               | 664          | 1889           |      |     |     |     |
| DHW COPoverall                                      | 4.19            | 3.64              | 3.00         | 2.05           |      |     |     |     |

| Total Space heating delivered                       | 12748           | 12683             | 5989         | 5955           | 6152 | 6390 | 6794 | 7230 |
| Total space heating power required                  | 12748           | 6581              | 5989         | 3148           | 3128 | 3206 | 3466 | 3842 |
| COPoverall                                          | 1              | 1.93              | 1            | 1.89           | 1.97 | 1.99 | 1.96 | 1.88 |

| Space heating savings from base                     | 48%             | 53%               | 75%          | 75%            | 75%  | 73%  | 70%  |     |

| Total Heat Delivered (north, south, DHW)            | 5955            | 6574              | 7367         | 8785           | 11108|     |     |     |
| Total power required (north, south, DHW)            | 3148            | 3228              | 3474         | 4130           | 5731 |     |     |     |
| COPoverall (north, south, DHW)                      | 2.04            | 2.12              | 2.13         | 1.94           |      |     |     |     |

| Net of DHW pumped                                   | 2907            | 2766              | 2802         | 3742           |      |     |     |     |
Appendix R: Conversion of Natural Gas to Electric Heating Model
The efficiency of natural gas heating is dependent upon several factors including the efficiency of the combustion equipment. Therefore, the total energy input to the building in terms of equivalent kilowatt-hours would be different between the models with natural gas versus electricity. In other words, a greater number of equivalent kilowatt-hours of natural gas must be delivered to the building to meet a particular heating load than would be required by electricity because of inefficiencies in the on-site combustion. Therefore, rather than judging model equivalency based on kilowatt-hours of space heating energy required, the hydronic and electric baseboard whole-building models had to be compared using other parameters. To ensure the whole-building electric baseboard model was equivalent to the original hydronic model, envelope and infiltration losses, solar and internal gains and zone temperatures were checked. In the end, two equivalent models were generated. One model included electric baseboards in the suites and hydronic baseboards in the common areas. A second model included electric baseboards throughout the building. The annual energy intensities of these whole-building models are shown in Figure 111.

The natural gas consumption in the original model is attributed to space heating and DHW while the electricity consumption consists of energy-use components including fans, pumps and plug, lighting and cooling loads. While the overall heating load of the building did not change...
between the original model and the two electric models, the overall reduction in energy intensity is due to the difference in efficiency associated with the shift from natural gas to electric heating, discussed above.

Once the original whole-building model with hydronic heating had been converted to equivalent models with electric baseboard heating, the factors from the suite-based models could be applied.
Appendix S: Derivation of the Factor Influencing COP_{eff}
In the case where the ASHP<sub>Hybrid</sub> draws the TBZ temperature down below the apartment temperature, the apartment heating load increases. Thus, this draw-down case is not directly comparable to the electric heating case because the apartment heating load has changed. To ensure a like-to-like comparison between the cases, the additional heat load in the apartment must be taken into account. This can be accomplished by reducing the heat available to the ASHP<sub>Hybrid</sub> (q<sub>avail</sub>) by an amount equal to the increased apartment heating load (q'<sub>TBZ',TBZ</sub>). After accounting for this heat returned to the apartment, a new term, the effective COP (COP<sub>eff</sub>), was used to describe the COP of the ASHP<sub>Hybrid</sub>. The algebraic expression describing the derivation of the COP<sub>eff</sub> is set out here.

To begin, the definition of the COP described by Equation 14, can be combined with Equation 15 to form a modified definition of the coefficient of performance. The numerator in Equation 14a has two components: the heat extracted by the ASHP (q<sub>p</sub>), and the electrical power required by the ASHP (q<sub>Power</sub>).

**Equation 14**

\[
COP = \frac{q_d}{q_{Power}}
\]

**Equation 15**

\[
q_d = q_p + q_{Power}
\]

**Equation 14a**

\[
COP = \frac{q_p + q_{Power}}{q_{Power}}
\]

where:

\[
COP = \text{coefficient of performance of the ASHP}
\]

\[
q_d = \text{heat delivered by ASHP [W]}
\]

\[
q_{Power} = \text{electrical power required by ASHP [W]}
\]

\[
q_p = \text{heat energy extracted or pumped by ASHP [W]}
\]
Using Equation 14a, the effective COP ($\text{COP}_{\text{eff}}$) can now be defined as set out in Equation 14b using the net heat pumped as defined by Equation 18.

**Equation 14b**

$$\text{COP}_{\text{eff}} = \frac{q_{p,TBZ,Total} + q_{\text{power}}}{q_{\text{power}}}$$

**Equation 18**

$$q_{p,TBZ,Total} = q_{\text{avail}} - q'_{TBZ,TBZ}$$

where:

$q_{p,TBZ,Total} =$ net heat pumped by ASHP from TBZ [W]

$q_{\text{avail}} =$ heat available to be pumped by ASHP from TBZ [W]

$q'_{TBZ,TBZ} =$ additional heat flow from Apartment to TBZ when TBZ is cooled [W]

The heat available to be pumped, as defined by Equation 17, can now be used to modify Equation 18, thereby creating Equation 18b.

**Equation 17**

$$q_{\text{solar,eff}} + q'_{TBZ,APT} + q'_{TBZ,EXT} = q_{\text{avail}}$$

**Equation 18b**

$$q_{p,TBZ,Total} = q_{\text{solar,eff}} + q'_{TBZ,APT} + q'_{TBZ,EXT} - q'_{TBZ,TBZ}$$

where:

$q_{\text{solar,eff}} =$ effective solar gains [W]

$q'_{TBZ,EXT} =$ heat flow from Exterior to TBZ when TBZ is cooled [W]
Equations 18b can now be expanded by substituting the general form, steady state, one dimensional heat flow equation shown here as Equation 19, to form Equation 18c, the heat available for pumping.

**Equation 19**

\[ q = \frac{A}{R} \Delta T \]

**Equation 18c**

\[ q_{p, TBZ_{\text{Total}}} = q_{\text{solar,eff}} + \frac{A_{\text{APT}}}{R_{\text{APT}}} (T_{\text{APT}} - T_{\text{TBZ}}) - \frac{A_{\text{TBZ}}}{R_{\text{TBZ}}} (T'_{\text{TBZ}} - T_{\text{EXT}}) \]

*where:*

\[ Q = \text{heat flow [W]} \]

\[ A = \text{area [m}^2\text{]} \]

\[ R = \text{thermal resistance } \left[ \frac{m^2K}{W} \right] \]

\[ \Delta T = \text{temperature differential across the area [K]} \]

\[ A_{\text{APT}} = \text{wall area between TBZ and Apartment [m}^2\text{]} \]

\[ A_{\text{TBZ}} = \text{wall area of balcony enclosure [m}^2\text{]} \]

\[ R_{\text{APT}} = \text{thermal resistance of wall between TBZ and Apartment } \left[ \frac{m^2K}{W} \right] \]

\[ R_{\text{TBZ}} = \text{thermal resistance of wall between TBZ and Exterior } \left[ \frac{m^2K}{W} \right] \]

\[ T_{\text{APT}} = \text{Apartment temperature [K]} \]

\[ T_{\text{TBZ}} = \text{TBZ floating temperature [K]} \]
Equation 18c can now be substituted into Equation 14b. The COP determined in the laboratory study described here as Equation 13, can next be substituted into Equation 14. The modified Equation 14 can now be rearranged to solve for $q_{\text{power}}$, as described by Equation 21.

**Equation 13**

$$COP = 0.069T_{\text{amb}} + 2.24$$

**Equation 21**

$$q_{\text{power}} = \frac{q_{\text{solar,eff}} - \frac{A_{\text{APT}}}{R_{\text{APT}}} (T'_{\text{APT}} - T'_{\text{TBZ}}) - \frac{A_{\text{TBZ}}}{R_{\text{TBZ}}} (T'_{\text{TBZ}} - T_{\text{EXT}})}{0.069T'_{\text{TBZ}} + 1.24}$$

where:

$COP = \text{coefficient of performance of ASHP}$

$T_{\text{amb}} = \text{ambient temperature surrounding outdoor unit [°C]}$

Equation 16a, (Equation 16 rearranged), can now be substituted into Equations 18c and 21. These modified Equations can now be substituted into Equation 14b. Then rearranging and simplifying the modified Equation 14b, Equation 22 results.

**Equation 16a**

$$q_{\text{solar,eff}} = -q_{\text{TBZ,APT}} - q_{\text{TBZ,EXT}}$$

**Equation 22**

$$COP_{\text{eff}} = (0.069T'_{\text{TBZ}} + 1.24) \left( \frac{1}{1 + \frac{A_{\text{APT}}}{R_{\text{APT}}} \frac{R_{\text{TBZ}}}{A_{\text{TBZ}}}} \right) + 1$$