A Study of Mechanical Systems in Canadian High-rise Multi-Unit Residential Buildings

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Mechanical systems providing indoor environmental control and domestic hot water functions generally represent the largest consumer of energy in Canadian high-rise multi-unit residential buildings. Many different systems exist, but limited literature is available to guide the selection process. This thesis seeks to identify current available technologies, define the driving factors behind system selection, and to determine if there are specific systems or technologies which are advantageous with respect to economic, environmental, and practical characteristics.

Research was divided into four categories. A literature review was conducted to identify both similar high level research projects as well as specific details associated with the design and operation of mechanical systems. A model of an existing high-rise MURB was built and calibrated from extensive real world data. This model was used to construct six reference buildings – 3 code-based, and 3 low-energy – located in Vancouver, Toronto, and Edmonton. Using these reference models, a series of simulations were conducted to evaluate the relative performance of a wide variety of mechanical systems and equipment.

Analysis and discussion of system characteristics revealed no mechanical systems which were advantageous in all scenarios, though there are systems which are clearly advantageous to specific stakeholder groups. Location and climate were found to influence ventilation loads more than any other building load. The carbon intensity of the electric grid was found to be the determining factor of greenhouse gas emissions for systems using electricity as their primary fuel source. Heat pump technology was identified as providing the lowest site energy consumption. Air-to-air heat recovery was found to be the most effective in reducing ventilation energy consumption and emissions.

Recommendations for future work include expansion of scope to low- and mid-rise buildings with different form factors. Targeted studies could also be performed to evaluate the impact of internal distribution losses as well as to help refine the cost-to-performance relationship of heat pump technology in order to identify cost competitive applications.

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List of Abbreviations

ABC	Alberta Building Code
ACH	Air changes per hour
AFUE	Annual Fuel Utilization Efficiency
AHU	Air Handling Unit
ASHP	Air Source Heat Pump
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BCBC	British Columbia Building Code
BSC	Building Science Corporation
CMHC	Canadian Mortgage and Housing Corporation
COP	Coefficient of Performance
DHW	Domestic Hot Water
DOAS	Dedicated Outdoor Air Systems
EER	Energy Efficiency Ratio
EF	Energy Factor
ERV	Enthalpy/Energy Recovery Ventilator
EUI	Energy Use Intensity
FCU	Fan Coil Unit
FDWR	Fenestration and Door Area to Gross Wall Area Ratio
GHG	Greenhouse Gas
HPWH	Heat Pump Water Heater
HRV	Heat Recovery Ventilator
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, Ventilation, and Air Conditioning
HWH	Hot Water Heater
IBC	International Building Code
IECS	Indoor Environmental Control Systems

LEED	Leadership in Energy and Environmental Design
MAU	Make-up Air Unit
MEL	Miscellaneous Electrical Load
MNECB	Model National Energy Code for Buildings
MUA	Make-up Air
MURB	Multi-Unit Residential Building
NECB	National Energy Code for Buildings
NRCan	Natural Resources Canada
OBC	Ontario Building Code
RCC	Reverse Cycle Chiller
RDH	RDH Building Science, Inc.
SEER	Seasonal Energy Efficiency Ratio
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
VRF	Variable Refrigerant Flow
WSHP	Water Source Heat Pump
WWR	Window-to-wall Ratio

Chapter 1 : Introduction

Buildings represent one of the largest consumers of energy by sector in Canada. This energy is used to provide a habitable environment for the occupants complete with lighting, environmental control, and utilities. The primary consumer of energy varies by building type, but for Canadian high-rise multi-unit residential buildings (MURBs) most energy use is typically associated with the mechanical systems that provide indoor environmental control and domestic hot water functions. In general, systems are selected in accordance with codes, standards, common practice, and design guides which strive to ensure all of these functional requirements are met. With respect to high-rise MURBs, however, only a small amount of literature is currently available to assist with initial mechanical design decisions at a system level. Considering the significant implications these systems have with respect to energy consumption, there is a need for a systematic analysis of available technologies to assist with early stage design decisions.

1.1 Background

In Canada, buildings represent one of the largest consumers of energy, with around 30% of secondary energy consumption attributed to the building sector alone (Natural Resources Canada, 2014). Of this energy, the majority can be attributed to ongoing operational energy demand as opposed to the initial energy associated with the construction and production of building materials (Cole & Kernan, 1996). The design phase can play a large role in the life cycle energy consumption of a given building, as design choices dictate how much energy is used once the building is occupied.

The distribution of end-use energy consumption varies from building to building, but it can generally be characterized by building sector. Within the Canadian residential sector, an estimated 84% of annual secondary energy use is devoted to mechanical systems which provide indoor environmental control and domestic hot water functions, with the remainder being comprised of lighting and miscellaneous electrical loads (Natural Resources Canada, 2014).

High-rise multi-unit residential buildings – also known as multifamily buildings in the United States – represent a small but growing percentage of the Canadian building stock. Often referred to as apartment or condo buildings, MURBs of more than 75 feet in height (approximately 6 stories) are classified as high-rises (International Code Council, 2014). As of 2011, high-rise MURBs represented 9% of the Canadian occupied residential building stock based on number of dwelling units. This housing segment showed significant growth between 1991 and 2011 and this growth is expected to continue as cities increase in population density (Canadian Mortgage and Housing Corporation, 2012). MURBs pose unique design challenges, with many recurring problems becoming apparent to the engineering community over the past 30 years – particularly with respect to thermal comfort and indoor air quality, but also in terms of energy consumption.

A small amount of literature is currently available to assist with initial design decisions surrounding mechanical systems in high-rise MURBs. Generally, relevant expertise is held within consulting firms and is developed through years of industry experience with this building type. As such, without direct industry contact it is difficult to ascertain what current practices are, or the relative advantages and disadvantages of different designs at a system level. Most standard practices have developed during a time when energy efficiency was not highly valued, low capital cost was the primary driver, and target demographics for the buildings were different than at present. Furthermore, any change from conventional, proven systems brings with it inherent risk that the new system may not function as intended, as well as additional learning required by all levels of personnel involved with the design and construction process. This risk and learning curve combine to generally increase the budget required to implement unproven systems. Consequently, there are obstacles to innovation and a tendency towards conventional solutions.

1.2 Objectives

This research seeks to answer the following question: with respect to the range of climates in Canada, and given currently available technologies, which mechanical systems are best suited for use in high-rise MURBs? In this context, best refers to a combination of economic, environmental, and physical system characteristics.

The objective of this thesis is to systematically evaluate and compare mechanical systems in Canadian high-rise MURBs with an emphasis on energy consumption, operating costs, and carbon emissions in order to identify the most appropriate system selections under varying conditions. This thesis also aims to contribute to the available literature associated with the early stage design of said systems. Specifically, the goals are as follows: (1) develop a baseline computer model of a typical of current construction practices from measured field data, (2) generalize the model to reflect current practices in three different Canadian locations, (3) simulate a set of different mechanical systems based on currently available technologies, and (4) systematically compare systems based on design choices and stakeholder priorities in order to identify the most appropriate options for new MURBs. Based on the results of these simulations, this work aims to draw conclusions and make recommendations with respect to the design of mechanical systems for new high-rise MURBs in Canada.

1.3 Scope

This research is only concerned with indoor environmental control and domestic hot water systems, and does not address domestic cold water systems, sanitary systems, sprinkler systems, elevators, or any other systems typically designed by the mechanical consultant on a residential building project.

The systems in question are only considered with respect to selected Canadian climates. More specifically, three key cities with varying climate types are analyzed but the results may be extrapolated to other parts of North America with similar climates. The three cities chosen, Vancouver, Edmonton, and Toronto, cover a range of different Canadian climate zones.

The analysis is limited to high-rise non-combustible multi-unit residential buildings greater than 6 stories in height. In this case, non-combustible construction is defined as steel and concrete structural assemblies. Furthermore, only new construction projects are considered, although deep energy retrofit projects which result in significant enclosure enhancements and total replacement of mechanical systems can often be considered similar to new construction.

Mechanical system design discussions are limited to an early stage context, and do not address detailed designs or specifications.

Energy consumption is analyzed on a detailed quantitative basis, but all practical characteristics including economic and comfort characteristics are analyzed on a qualitative basis.

Further limitations are imposed by simplifying assumptions associated with the modelling inputs, often informed by building standards such as ASHRAE Standard 90.1 or energy modelling guidelines such as the Model National Energy Code of Canafda for Buildings (MNECB).

1.4 Methodology

Comparing mechanical system energy consumption would ideally be conducted experimentally with monitoring and utility data from a set of existing buildings located across Canada. However, this kind of an experimental setup would be costly, time consuming, and would generate a very large amount of data which would be difficult to collect and analyze. Building energy simulation software provides a lower cost, faster, and more flexible means of performing this analysis.

Modern energy simulation or energy modelling software calculates an energy balance at sequential time steps – often hourly increments over a typical year – on a computer model of a given building in order to determine both space and system loads. Many different software packages are available with different calculation engines and modelling capabilities.

DesignBuilder is the energy modelling software selected for this project. DesignBuilder consists of a third-party user interface built on top of the open source platform of EnergyPlus (DesignBuilder Software, 2008). EnergyPlus was developed by the US Department of Energy

(DOE), and is the most recent in the line of DOE energy modelling software packages. EnergyPlus uses the heat balance method at incremental time steps, which is generally accepted as being more accurate than previous calculation methods such as the radiant time series or bin method (Hanam, 2010). EnergyPlus can be difficult to interact with directly, however, which is why third-party interfaces are frequently used. All analyses in this thesis use DesignBuilder version 4.6.0.015 and EnergyPlus version 8.4.001.

The energy modelling analysis is conducted in two phases. The initial phase consists of modelling an existing high-rise MURB about which abundant design and operational data is available. This serves to help identify key design characteristics inherent to high-rise MURBs while also serving as a verified baseline for future simulations. In the second phase, three reference buildings are developed by modifying the baseline model to be consistent with building codes and typical practices in Vancouver, Edmonton, and Toronto. A further three reference buildings are added to represent more expensive and higher performance construction technologies based on literature. All six reference buildings are then used to simulate different mechanical systems and compute the associated energy consumption, operational costs, and greenhouse gas emissions.

Based on the modelled mechanical systems, comparisons and observations can be made within climate zones with respect to energy consumption while also addressing economic, environmental, and physical system characteristics not captured by the energy model. From this assessment, conclusions can be drawn and recommendations formed with respect to mechanical system selections for low-energy high-rise MURBs.

1.5 Literature Review

Currently available literature relevant to mechanical systems in high-rise multi-unit residential buildings falls into three broad categories: discussions of whole building energy consumption, design documentation and analysis reports, and performance issues in existing buildings. A critical review of each category is provided below.

1.5.1 Energy Use in High-rise MURBs

In recent years, awareness of energy consumption has sparked a series of broad initiatives to better understand how energy is currently being used. With respect to buildings, a number of jurisdictions (e.g. New York City, European Union) have begun to require public disclosure of energy consumption, with many academics, research groups, and consultancies producing reports quantifying how the current building stock uses energy and identifying ways in which efficiency can be improved. As comparing energy numbers alone often has limited application, normalized metrics such as energy use intensity (EUI, defined as energy use per unit conditioned floor area) and energy per dwelling unit are often used (Kohta Ueno, 2010a). As high-rise MURBs have been the focus of some studies and jurisdictions, there is a considerable amount of available high-level literature discussing the energy use of this building type.

RDH Building Engineering (RDH), a consultancy, released a 2012 report focused on energy benchmarking of high-rise MURBs located in the lower mainland of British Columbia (RDH Building Engineering, 2012). The study was based on utility data from 39 high-rise MURBs. They reported average annual energy use intensity of 213 ekWh/m^2, with 37% of this energy being used for space conditioning. While the purpose of the study was aimed at building enclosure energy efficiency strategies, some evaluation of mechanical systems was also conducted. It was concluded that decoupling the space conditioning and ventilation systems improves efficiency and traditional pressurized corridor ventilation systems do not provide adequate ventilation. The study also concluded that separate in-suite ventilation and space heating strategies could lead to improved energy efficiency and system efficacy, with heat recovery ventilators showing significant energy savings.

A study by the University of Toronto focused on energy benchmarking and characteristics of MURBs in the City of Toronto (Touchie, Binkley, & Pressnail, 2013). Their refined dataset consisted of 40 buildings with an average energy use intensity of 300 ekWh/m^2. The focus of the study was to determine building characteristics which correlate with energy consumption across the dataset, and did not specifically consider mechanical systems. The study did however conclude that MURB energy use correlated with boiler efficiency.

Liu conducted a study with some of the same data as Touchie et al. by using the CMHC HiStar database (Liu, 2007). In total, 81 Canadian MURBs were analyzed with respect to their energy consumption and energy intensity. Across Canada, the average EUI was 0.96 GJ/m^2 (267 ekWh/m^2) with Ontario high-rises at 0.94 GJ/m^2 (261 ekWh/m^2). General trends were found between location and EUI, likely due to varying climates. West Coast MURBs used the least energy, and those in the Prairies used the most, although most of the sample buildings were located in Ontario.

Seattle implemented mandatory energy benchmarking in 2010, and has compiled results of over 3000 buildings – more than half of which were classified as multifamily (Seattle Office of Sustainability & Environment, 2015). The average high-rise multifamily building consumed 155 ekWh/m^2 (49 kbtu/ft^2), which was substantially higher than low- and mid-rise MURBs. This finding was based on 90 high-rise MURBs, which were defined as buildings of 10 or more stories. Additionally, with respect to building age, modern multifamily buildings were found to have the highest energy use intensities since 1950s era construction. Furthermore, both the energy use intensity and energy use per dwelling unit were found to increase with the number of floors. It was suggested that this can be attributed to the higher glazing ratios of most high-rise MURBs, but it could also be associated with additional distribution losses and more complex mechanical systems.

The Canadian Mortgage and Housing Corporation (CMHC) conducted a study of strategies to achieve low-energy MURBs in different Canadian climate regions (Canadian Mortgage and Housing Corporation, 2015). In this context, low-energy was defined as achieving the Canadian Passive House standard which requires very low heating and total primary energy intensities of 15 ekWh/m^2 and 120 ekWh/m^2 respectively, as well as high levels of airtightness. The study found that based on currently available enclosure technologies, it is possible to achieve compliance with this standard in Vancouver and Kelowna with a high performance enclosure, electric baseboards and in-suite heat recovery ventilators. Furthermore, the low-energy model buildings using electric heating were not found to be economically viable in locations where the ratio between the cost of electricity and natural gas was greater than 4, such as Toronto or Edmonton.

1.5.2 Design of Mechanical Systems for High-rise MURBs

Heating, ventilation, air conditioning and domestic hot water equipment is generally well understood and documented within the industry. However, different building types and applications often require different systems and design approaches. For this reason, many common building types such as hospitals, laboratories, or core and shell commercial construction have their own design guides. High-rise multi-unit residential buildings do not have a dedicated publicly available design guide, or even documentation of current practices. As such, only limited relevant literature is currently available to assist with the design and system selection process.

A commonly cited authority on mechanical design of building systems in North America is the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE). ASHRAE maintains a series of four handbooks intended to cover the basics of mechanical building design, with supplemental design guides and research papers available to provide additional insight when needed. Despite the popularity of the building type, no design guide exists for high-rise MURBs. Additionally, the *HVAC Applications* handbook, while intended to cover all common building types, contains only limited information on high-rise MURBs (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2015). This information is spread between three chapters: residences, tall buildings, and hotels, motels, and dormitories.

The 2015 ASHRAE Handbook of HVAC Applications does address high-rise MURBs, but only briefly in a one page subsection of the chapter on residences (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2015). The section does mention some common HVAC systems and equipment including hydronic four-pipe fan coils, water loop heat pumps, packaged terminal heat pumps (PTHP) and air conditioners (PTAC), and unitary forced air furnaces. A small amount of design guidance and system selection criteria is provided, although in some cases further information can be found in the *Systems and Equipment* handbook (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2012). Specific challenges associated with apartment buildings are also identified such as the difficulties related to controlling infiltration and ensuring adequate indoor air quality, and the internal gains associated with distribution losses from domestic hot water piping. The chapter on tall buildings in the *HVAC Applications* handbook includes a discussion of stack effect and wind pressure which is relevant to high-rise MURBs, but the HVAC discussions are all focused on commercial construction and largely are not applicable. The chapter on hotels, motels, and dormitories is somewhat relevant as well in that multiple dwelling units are present within one structure, but the internal gains, operation schedule, and design priorities of these buildings are quite different than those present in high-rise MURBs.

The Canadian Mortgage and Housing Corporation published a guide to mechanical equipment within low-rise MURBs in 2001. While no comparative analysis was conducted, the guide does provide a list of pros, cons, capital costs, operational costs, and general energy performance characteristics associated with an exhaustive list of mechanical equipment typically found in low and high-rise MURBs (Canadian Mortgage and Housing Corporation, 2001). Furthermore, the guide focuses on individual pieces of equipment rather than systems containing combinations of equipment working together, and does not form any design recommendations.

Building Science Corporation (BSC) has published a series of papers on various building science topics – several of which are relevant to the mechanical design of MURBs. Lstiburek assembled a list of recommendations for HVAC systems in multi-unit residential buildings which puts an emphasis on compartmentalization of the ventilation system along with the heating, cooling, and domestic hot water systems such that each unit is essentially treated as a separate detached house (Lstiburek, 2006). The motivation behind these design decisions is based on practical industry experience with respect to maintenance issues, operational costs, capital costs, and ensuring adequate indoor air quality. Similar arguments are made by Straube in more general discussions of best practices for HVAC systems with respect to balanced ventilation and compartmentalization (J. Straube, 2009).

RDH in conjunction with Walsh Construction Co. (WCC) completed a report in 2005 focusing on practical industry based recommendations for mechanical systems in MURBs located in the Pacific Northwest (RDH Building Sciences, 2005). No quantitative analysis was conducted, but experience-based qualitative guidelines and recommendations were provided – largely aimed at ensuring building durability and delivering reliable indoor air quality. WCC took these recommendations a step further in 2011, adding additional low-energy targets which they quantified with energy modeling and life-cycle costing (Walsh Construction Co., 2010, 2011). WCC did not conduct extensive energy modeling however, and relied on loads generated by a single suite eQuest model of a hypothetical building.

1.5.3 Documented Performance Issues in Existing Buildings

High rise multi-unit residential buildings have been present within the Canadian building stock for quite some time. While each building is different, some recurring performance issues are prevalent, and are consequently well studied by the building design community. The most notable issues are associated with inadequate indoor air quality, and are typically related to mechanical ventilation or infiltration. Many papers provide recommended alternatives, but despite all of this literature, practices have remained unchanged in most Canadian jurisdictions.

The Canadian Mortgage and Housing Corporation published a study in 2003 which evaluated ventilation systems specifically for Canadian MURBs with the purpose of assessing current practices and developing innovative alternatives (Canadian Mortgage and Housing Corporation, 2003). The study identified numerous issues with conventional MURB ventilation systems revolving around their inability to ensure adequate indoor air quality. The study went on to evaluate alternatives to conventional systems with a focus on heat recovery for energy efficiency and balanced air flow control for indoor air quality. Both proved to be important design considerations in terms of system efficacy, efficiency, capital cost, and operational cost.

The Consortium for Advanced Residential Buildings (CARB) performed a number of different airflow measurement tests on mechanical ventilation systems in MURBs located largely in the Northeastern US in order to evaluate current ventilation strategies (Maxwell, Berger, & Zuluaga, 2014). While meeting make-up air (MUA) requirements is important, an interesting finding was that many systems do not provide make-up air through controlled means. Make-up air through ducted supply from a central air handling unit was found to provide the most reliable controlled MUA with 71.4% through controlled means. All the other systems tested performed much more poorly, including those with pressurized corridor systems, passive trickle vents, and PTAC units. In all cases, the performance of the system varied widely from suite to suite and building to building, often with design flow rates vs. airflow measured ranging from less than 50% to more than 150%. For high-rise MURBs, ducted make-up air from central air handling units was recommended.

Handegord described an alternative approach to corridor pressurization ventilation systems based on experience and observation of current deficiencies (Handegord, 2001). Specifically, pressurized corridor systems were found to violate ASHRAE recommendations, building codes, and provide inadequate smoke, sound, and airflow control. The alternative system proposed would involve compartmentalized suites with in-suite exhaust and passive inlet supply air. With induced passive supply through the enclosure, condensation concerns can be eliminated in heating dominant climates such as Toronto. Additionally, airflow and smoke control could be improved given the elimination of vertical duct runs or door undercuts for supply air.

Ricketts conducted a field monitoring study of a high-rise MURB located in Vancouver, British Columbia, both pre- and post- building enclosure rehabilitation (Ricketts, 2014). The focus of the study was on airflow and ventilation with an emphasis on understanding airflow characteristics rather than on the mechanical systems explicitly. The study did, however, conclude that pressurized corridor ventilation systems fail to consistently provide adequate ventilation air, over ventilating upper floor suites and under ventilating lower floor suites, and consequently do not constitute a viable ventilation strategy regardless of energy consumption.

Chapter 2 : Residential Mechanical Systems and Equipment

A mechanical system is a very broad term which encompasses all systems inherent to building design that move mass or thermal energy. This typically includes heating, ventilating, and air conditioning (HVAC) systems, plumbing and drainage systems, and fire protection systems, but may also include any other system meeting the previous definition. This chapter serves to provide background information surrounding mechanical systems which are responsible for substantial portions of whole building energy use in high-rise MURBs. Specifically, an understanding of mechanical functions and characteristics will be developed and then applied first at an equipment level and then at a system level. Note that background information on energy use in buildings can be found in Appendix A.

2.1 Energy Intensive Mechanical Systems

In residential buildings, annual energy consumption is primarily attributed to mechanical systems, with the remaining energy associated with lighting and miscellaneous electrical loads (MELs). Figure 2-1 shows the flow of energy use in buildings from the raw resources to the building end-uses, and illustrates the concept of source-to-site energy. Within Canadian residential buildings, specific mechanical systems tend to dominate national consumption as shown in Figure 2-2 (Natural Resources Canada, 2014). While many other mechanical systems may present in a typical residential dwelling, space heating and water heating are the major end-uses within the sector.

Space heating and water heating both describe individual energy uses or functions, but do not describe the overarching parent systems of which they are associated. Space heating is one function within the parent grouping of indoor environmental control systems (IECS), and may exist independently or coupled with other IECS (J. F. Straube, 2014). Similarly, water heating is one function within plumbing and drainage systems, and may exist as an independent domestic hot water (DHW) system, or coupled with other systems. Both complete space heating and water heating systems involve some combination of equipment and materials which all contribute to the total energy use. Note that other specific mechanical systems may also be present in a given building such as elevators or snow melting systems, but these do not consume the same scale of operational energy, and are therefore not considered energy intensive. Figure 2-3 displays the typical mechanical systems found in residential buildings, and identifies energy intensive mechanical systems in red.

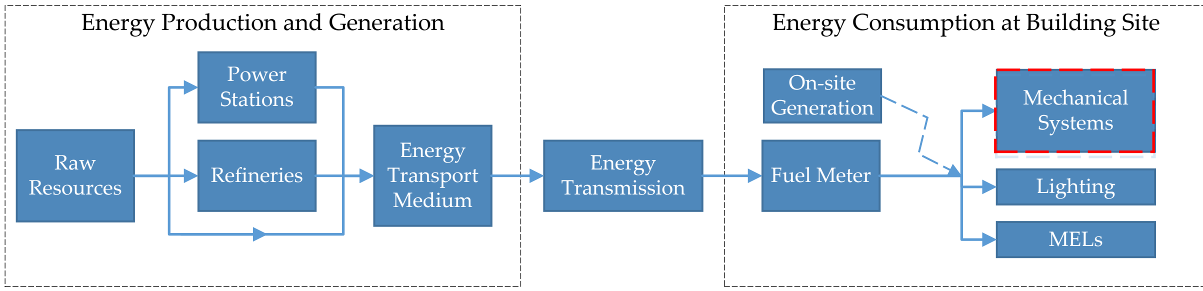


Figure 2-1: Flow of energy in residential buildings, with raw resources on the left and building end-uses on the right. Mechanical systems are highlighted in red.

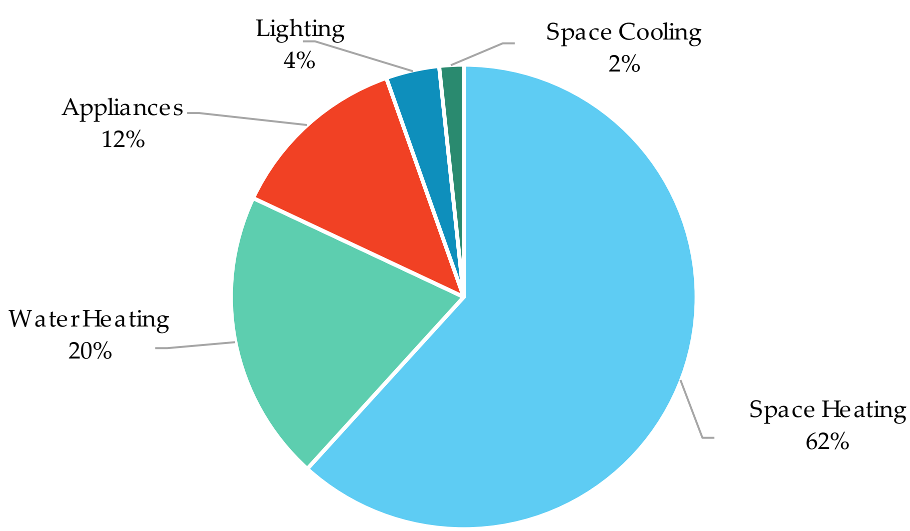


Figure 2-2: 2011 Canadian site (secondary) energy consumption within the residential building sector (Natural Resources Canada, 2014)

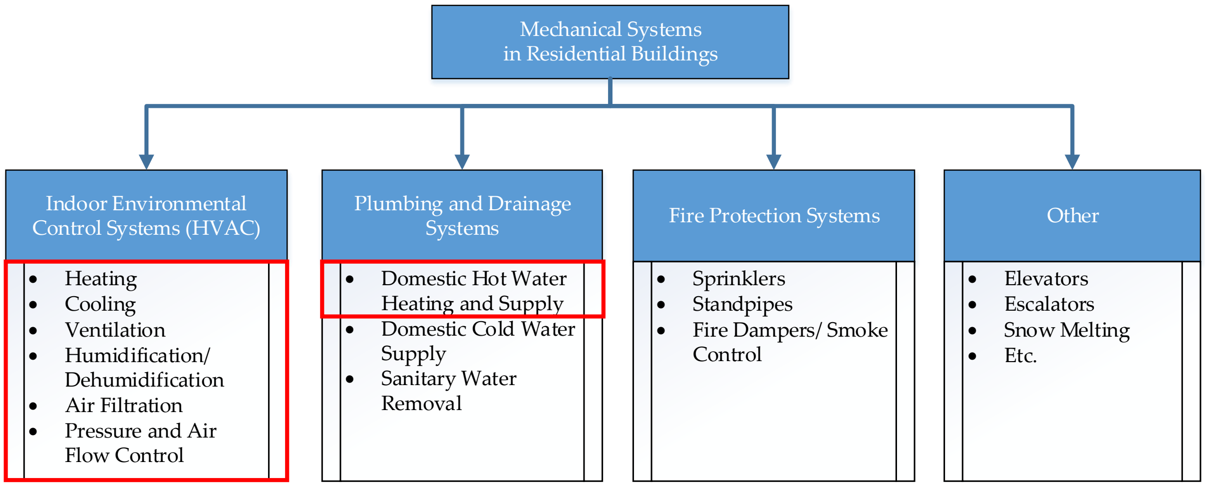


Figure 2-3: Mechanical systems in residential buildings with energy intensive mechanical systems highlighted in red

Indoor environmental control systems is a term used to describe systems which provide a comfortable and healthy environment for occupants residing within a building (J. F. Straube, 2014). This includes heating, cooling, ventilation, humidification, dehumidification, air filtration, and air flow control. The areas within the building which are serviced by the IECS are collectively referred to as conditioned space, and are often broken down into individual zones within the building. In this context, a zone is a location with uniform IECS loads, as defined by a physical area or volume. The term "HVAC" is a common industry acronym and colloquially refers to the same systems as IECS. The acronym itself, however, refers specifically to heating, ventilation, and air conditioning which is somewhat limiting, and therefore will not be used much within this discussion.

Plumbing and Drainage systems encompass all of the systems and equipment associated with the conditioning and supply of hot and cold water for cleaning and general purpose use, along with the piping required to capture and dispose of the wastewater to the municipal infrastructure. Domestic hot water systems are commonly abbreviated to DHW and comprise the equipment required to heat and store the hot water along with the pipes and pumps required to deliver it to the required locations throughout the building. DHW systems use considerably more energy than domestic cold water or wastewater systems as they must heat the water in addition to transporting it.

Fire protection systems, as the name implies, are associated with the control and prevention of fires which occur within buildings. These systems are strictly defined in fire safety and building codes as they deal directly with the protection of human life – the primary responsibility of all engineered systems. Sprinkler systems contain pressurized water at all times with temperature sensitive sprinkler heads which release water in the event of a fire in an attempt to prevent the spread of fire. Fire dampers are temperature sensitive louvers which can close off a duct to airflow in the event of a fire. Standpipes act like fire hydrants and are located near the entrances of buildings so that firefighters can attach their fire hoses to them for supply.

Other mechanical systems, such as elevators, are designed, built, and installed by specific consultants which deal only with one given system. A general mechanical consultant will often not have any involvement with the design of these systems.

Energy intensive mechanical systems comprise the majority of mechanical energy use in residential buildings, along with significant associated operational and maintenance costs. In addition, unlike fire protection systems which are tightly prescribed by fire safety codes, energy intensive mechanical systems are highly variable as many system options and equipment types exist and are permitted by building codes. As such, the capital and operational costs as well as the energy consumption of these mechanical systems is largely impacted by the mechanical design process.

2.2 Functions of Energy Intensive Mechanical Systems

Energy intensive mechanical systems have been identified as those which address indoor environmental control and domestic hot water functions. However, the design process always starts by identifying the problem to be addressed which can be referred to as the design intent. For domestic hot water systems, the goal is clearly to provide potable hot water to designated spaces within each dwelling unit. In the context of indoor environmental control systems, the problem consists of maintaining an indoor environment which may be different than the local outdoor environment. Specifically, the goal is to maintain acceptable thermal comfort and indoor air quality within the interior space.

Thermal comfort is a broad term which refers to a handful of different criteria. It identifies conditions which satisfy a statistically acceptable portion of the population with respect to the air temperature, mean radiant temperature, humidity, and air velocity. It is a heavily studied research area, and consequently is addressed by dedicated standards such as ASHRAE Standard 55 (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2013).

Indoor air quality (IAQ) refers to the concentrations of particles and gaseous contaminants found in interior air. As such, acceptable indoor air quality implies these particles and contaminants are within established safe ranges for human occupancy. In building applications, the practical solution to provide acceptable IAQ involves reducing or eliminating pollutant sources, direct exhaust of pollutants, and dilution of remaining pollutants with clean air often from outdoors. These general strategies can include filtration, air cleaning, humidity control, and airflow control. ASHRAE Standard 62.1 is frequently referenced by North American building codes, and establishes minimum acceptable ventilation rates and contaminant ranges (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2016).

Design functions describe the tasks which must be accomplished by the design in order to solve the problem and thus meet the design intent. Unlike thermal comfort and indoor air quality, which are broad terms, design functions are specific and tangible requirements. Mechanical systems may be required to address up to seven functions in order to meet the design intent:

1. Heating
2. Cooling
3. Ventilation
4. Filtration and air cleaning
5. Humidification and dehumidification

6. Air pressure and airflow control
7. Domestic hot water

Heating, or space heating, refers to the addition of heat to conditioned interior space in order to maintain an interior temperature setpoint. The temperature setpoint typically is based on occupant thermal comfort, but in special circumstances can also serve to satisfy thermal energy storage requirements for objects or building materials within conditioned space. In Canada, some form of heating is required in all occupied residential buildings.

Cooling refers to the removal of heat from conditioned interior space in order to maintain an interior temperature setpoint. As with heating, the temperature setpoint is based on occupant thermal comfort and material requirements. In Canada, cooling in high-rise MURBs is only common in certain locations such as Toronto, but its use is becoming more common.

Ventilation refers to the supply of clean air, and the exhaust of indoor air in order to remove or dilute contaminants generated within conditioned space. Typical contaminants include carbon dioxide and water vapour from human respiration and perspiration, cooking and waste odours, and off gassing of objects and building materials within the space. Ventilation can be provided passively, but often requires an active mechanical solution.

Filtration and air cleaning refers to the removal of particulates and gaseous contaminants from air within conditioned space in order to keep concentrations within acceptable levels. Some level of filtration is always required for equipment maintenance and the removal of dust and allergens, but more substantial filtration and air cleaning may be required by individuals suffering from respiratory illnesses, or if the outdoor air itself does not meet IAQ requirements.

Humidification and dehumidification may be required in order to maintain the interior relative humidity within an acceptable range for thermal comfort – typically 20-70% depending on activity levels and the time of year (McQuiston, Parker, & Spitler, 2005). As with heating and cooling, the need for humidity control is dependant on the climate, and thus is of varying importance across Canada. In a marine climate such as Vancouver, humidity control is not often required in summer whereas in a climate such as Toronto, both humidification and dehumidification are often desirable.

Air pressure and airflow control refers to the manipulation of relative pressure differentials across interior and exterior partitions to influence the passive flow of air. Some level of air pressure control is necessary to reliably provide ventilation, but often additional requirements are imposed in order to meet other practical needs such as acoustic requirements, odour isolation, fire and smoke control, and thermal comfort.

Domestic hot water refers to hot water which is provided for sanitary or cooking purposes within designated spaces such as bathrooms and kitchens. While viewed as an amenity, Canadian building codes require the provision of domestic hot water within dwelling units when available. In the context of high-rise MURBs in major Canadian cities, DHW will always be required.

2.3 System Characteristics

Every system can be evaluated based on a set of quantitative and qualitative criteria herein referred to as system characteristics. The emphasis of this analysis is on the energy consumption of each system, but this cannot be evaluated independently as many other factors are important when comparing system design choices. System characteristics can be broken down into three broad categories: economic, environmental, and physical, as summarized by Figure 2-4.

Economic system characteristics are associated with the capital and operational costs of each system. Capital costs include the initial procurement costs for each piece of equipment, along with the initial installation and commissioning costs. Operational costs represent the ongoing expenses associated with running the system, and include energy costs, maintenance and repair costs. Energy costs are a function both of energy consumption as well as fuel type and energy source. Maintenance costs are related to the relative ease at which maintenance can be performed, as well as the frequency at which it is required.

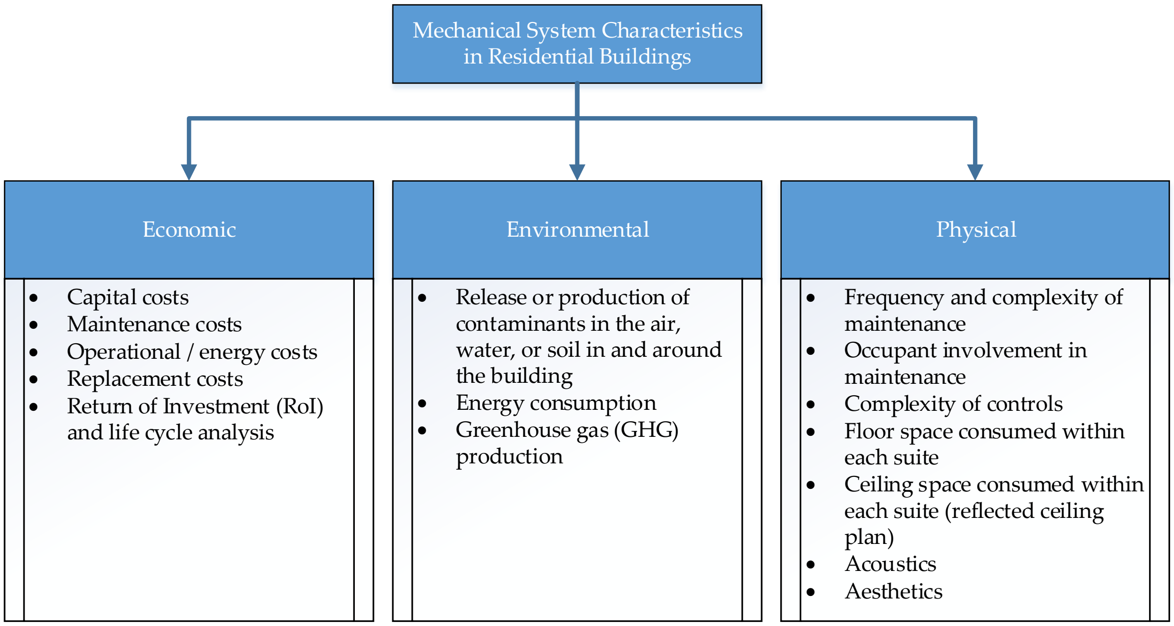


Figure 2-4: Mechanical system characteristics in residential buildings (Bhatia, 2012; RDH Building Sciences, 2005)

Environmental system characteristics are associated with a given system's interaction with the local and global environment. The local environment includes areas within the building, as well as areas directly surrounding the building. Factors affecting the local environment could include the release or production of contaminants which are introduced into the air, soil, or water at the building location. The global environment is more concerned with larger implications such as energy consumption – and by extension, greenhouse gas emissions.

Physical system characteristics represent the implications of each system with respect to the space within the building, and the interaction each system has with the occupants. This includes the frequency at which maintenance is required, the skill level required to perform said maintenance, and the involvement necessary on the part of the occupants in conducting this maintenance. Physical characteristics also include the means through which the occupants control the system, as the well as the space consumed within each suite and the noise produced by the operation each system.

2.4 Mechanical Equipment and Components

Every mechanical system is comprised of one or more distinct components. Some components are very complicated and contain many pre-manufactured systems and controls, while other components are very simple and contain no moving parts. Every component in a mechanical system can be classified into one of the following four categories: energy production/rejection components, distribution components, terminal units, or packaged units (Bhatia, 2012). Figure 2-5 displays some typical components which can be found in each category.

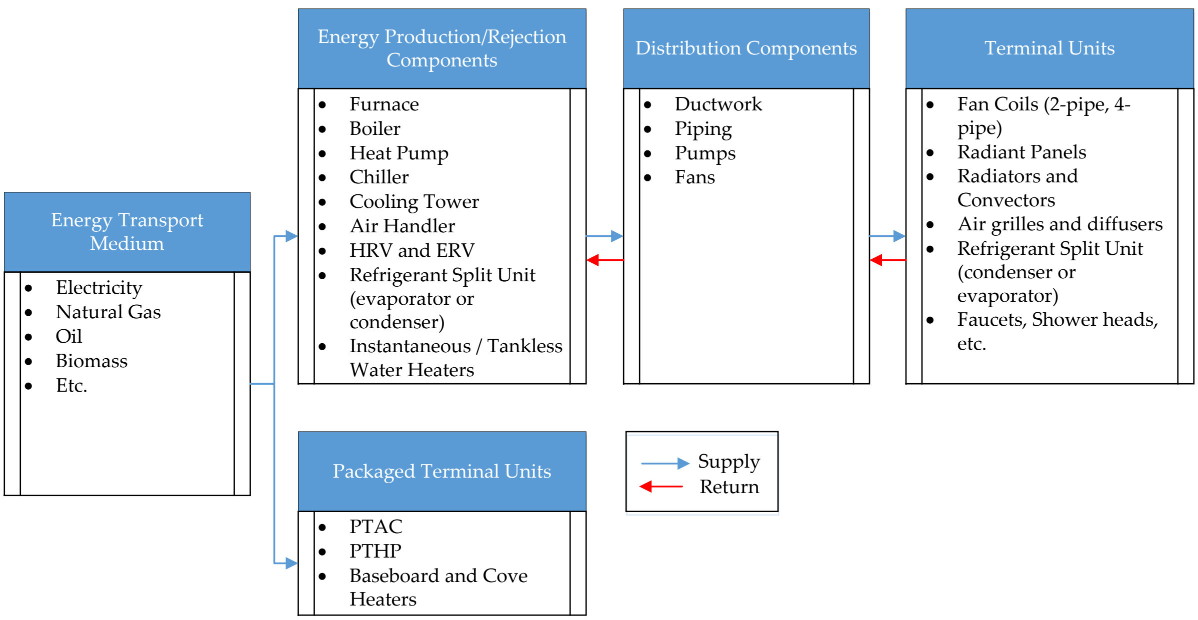


Figure 2-5: Classification of common equipment and components found in residential mechanical systems in Canadian high-rise MURBs

Energy production/rejection components are pieces of equipment which perform an energy conversion in order to produce or reject heat. Typically, these components are not located in the zone which they serve, or they serve multiple zones. In either case, distribution components are required to transport the given service from the energy production/rejection component to the zone in which it is required. Once there, terminal units are required in each zone in order to control the delivery of the service to the zone.

Although not always required, both supply and return distribution components are often included as part of balancing and controlling the given service within the zone. Additionally, in some cases there are multiple energy production/rejection components connected to each other via distribution components in order to provide a given system function or set of functions.

Packaged terminal units often contain some combination of energy production/rejection components and distribution components, and must contain a terminal unit. By virtue of their terminal unit inclusion, they are located within the zone they serve and are purchased as self-contained prefabricated units.

Together, some combination of energy production/refection components, distribution components, terminal units and packaged units can be assembled into systems which provide the necessary functions described in Section 2.2 in each zone which they are required.

2.5 Mechanical Systems

Residential mechanical systems are typically named based on the primary function they perform, and fall into three categories: heating and cooling systems, ventilation systems, and domestic hot water systems. Like the acronym HVAC, this traditionally naming scheme can be a bit misleading as the first two system categories could provide one or more additional functions such as filtration or humidity control which are otherwise not mentioned. Therefore, the names used to discuss said systems in this thesis will be thermal comfort systems, indoor air quality systems, and domestic hot water systems. Figure 2-6 depicts these three systems, and demonstrates how they are not necessarily independent but can in fact be combined into more complex systems. The numbering of the different areas will be important for defining systems in Section 4.2 (Test Set of Mechanical Systems) and Appendix E.

Thermal comfort systems, indoor air quality systems, and domestic hot water systems are all very common and often exist independently of one another. Within each system category, there are several subcategories based on the specific functions provided, which are summarized in Table 2-1. Note that each subcategory is named simply after the primary function or functions that are provided. Combination systems can straddle multiple subcategories, but typically constitute some combination of type 1 and type 2 or type 1 and type 3 systems.

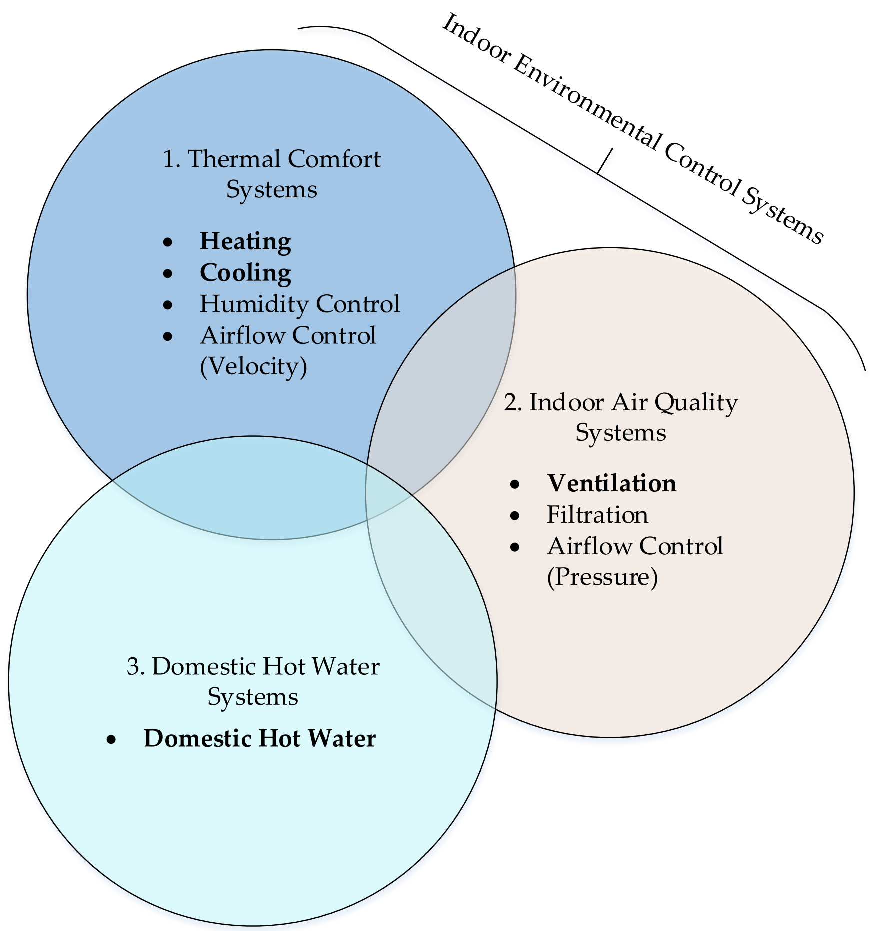


Figure 2-6: Residential mechanical system types 1-3 as defined for the purposes of this body of work

Table 2-1: Residential mechanical system subcategories as defined for the purposes of this body of work

System Number	Subcategory
1a	Heating
1b	Cooling
1c	Heating and Cooling
2a	Suite Ventilation
2b	Corridor Ventilation
2c	Suite and Corridor Ventilation
3	Domestic Hot Water

Mechanical design requires the designer to consider both the functions and system characteristics previously discussed in order to select equipment and components which together constitute the overall system with its associated advantages and disadvantages. In addition to these considerations, however, there are several system level design choices which can dictate system selection:

1. Layout
2. Controls
3. Fuel type
4. Thermal transport fluid

The system layout refers to the relative location of energy production/rejection components, and the scale on which the system functions. Typically, systems are either centralized or distributed. Centralized systems involve large centrally located energy production/rejection components, with extensive distribution networks which deliver the service throughout the entire building to every conditioned zone. Distributed systems involve multiple equivalent components, each of which serves a portion of the conditioned zones in the building. Floor-by-floor, suite-by-suite, and room-by-room systems are all types of distributed systems, and are characterized by the size and location of the energy production/rejection components.

Centralized systems serve more suites and hence are larger in capacity and benefit from economy of scale with respect to equipment cost, and may in some cases have higher efficiency, but must overcome significant distribution energy costs and physical losses. Additionally, centralized systems provide much easier access for maintenance, however any system downtime corresponds with a service outage for the entire building. Lstiburek, RDH and others have argued for suite-by-suite and room-by-room systems as they often involve simpler equipment which can be serviced by less skilled technicians, incorporate simpler control schemes, and can ensure that the functional requirements are met for every suite (Lstiburek, 2006; RDH Building Sciences, 2005). Table 2-2 summarizes some of the common advantages and disadvantages of centralized and distributed mechanical systems.

Table 2-2: Advantages and disadvantages of centralized and distributed mechanical systems

System Type	Advantages	Disadvantages
Centralized	• Economy of scale in energy production/rejection equipment capital cost • Easy access for maintenance • Familiarity of system designs • Less in-suite equipment helps ensure aesthetics meet architectural design intent	• Extensive distribution system resulting in higher distribution losses • Any system downtime constitutes a service outage for entire building • Control systems tend to be more complex
Distributed	• Simpler equipment and control schemes • Equipment can be service by less skilled technicians • Suites can be compartmentalized, ventilation can be more easily balanced • Equipment failure only results in a service outage for the individual suite	• Gaining access to each suite required for any maintenance • Often more maintenance is required on the part of the tenants • In-suite equipment consumes valuable floor and/or ceiling space

Mechanical system controls range from very simple to very complex depending on the size of the system, the number of functions being provided by the given system, the type and quantity of sensors being used, and the number of independent zones being served. Generally speaking, with increasing system complexity, the more difficult it becomes to ensure energy efficiency. Additionally, systems which serve multiple zones and provide multiple functions may struggle to ensure all requirements are met at all times. Simultaneous heating and cooling at a system level can completely overshadow high equipment efficiencies when it comes to total energy consumption (Ihnen, Weitner, & Donnell, 2012). As the industry moves in favour of building automation systems (BAS) driven by direct digital controls and complex algorithms, many industry experts recommend simplified controls to ensure functional requirements are met (RDH Building Sciences, 2005; J. Straube, 2009).

The availability and implications of different fuel types can also play a factor on system level choices. Electricity is always wired to every suite, but the decision to plumb natural gas to each suite with separate sub-metering represents a significant incremental cost if not already part of the construction budget (Mather, 2015). Additionally, the pricing and availability of fuels can vary greatly by location which can impact economic factors such as energy costs and return on investment while also impacting environmental factors such as greenhouse gas emissions based on source-to-site ratio.

The thermal transport fluid is the fluid used to convey thermal energy between the energy production/rejection component(s) and terminal units via the distribution components in any system providing heating and or cooling. This fluid can be water, air, or refrigerant depending on the system in question. Unlike other functions which have a predefined medium, such as air for ventilation or water for domestic hot water, the choice of thermal transport fluid for heating and cooling must be made carefully. Each fluid has its associated advantages and disadvantages as highlighted in Table 2-3.

Table 2-3: Advantages and disadvantages of air, water, and refrigerant for use as the thermal transport fluid in thermal comfort systems

Fluid	Advantages	Disadvantages
Air	• As ventilation is required, some form of mechanical ventilation system likely already exists as part of the building design which can be additionally purposed to provide heating and cooling • Easier to achieve well-mixed air temperatures within conditioned space • Less skill and effort required to produce ductwork	• Ducts take up large amounts of floor and ceiling area if sized appropriately to minimize noise and fluid velocity • Complete fluid flow control is much more difficult to achieve than with other fluids as air loops are open • The heat capacity of air is relatively low • Moving air at higher pressure differentials through smaller ducts is energy intensive
Water	• Piping takes up substantially less area than ductwork • Pumps tend to be more efficient than fans as water is considered to be incompressible • Water has one of the highest heat capacities of any liquid	• A separate air conveying system is still required to meet ventilation requirements • Terminal units – with the exception of radiant panels – take up more suite area than air terminal units • Leaks are costlier to repair than in air based systems
Refrigerant	• Piping takes up substantially less area than ductwork • Refrigerant acts both as the transport medium and the working fluid in the vapour compression refrigeration cycle	• Can only be used in split systems, with specific mini/multi-split terminal units • Scale of system is often limited to a maximum of suite-by-suite, requiring an outdoor compressor unit for every suite • High level of skill and effort required for piping • Leaks are costlier to repair than in air based systems, and many common refrigerants have significant global warming potential

Once the mechanical system functions have been identified, the choices of layout, control scheme, fuel type, and thermal transport fluid all represent high level mechanical design decisions which form the structure of subsequent system and equipment selections.

2.5.1 Type 1: Thermal Comfort Systems

Thermal comfort systems provide heating, cooling, or heating and cooling, along with potentially providing a combination of other functions. While fuel types and distribution layouts varied throughout the simulations, the heating and cooling systems chosen to be modelled generally fell into one of the following categories: electric resistance heating, in-suite Air Handling Units (AHUs), Fan-coil Units (FCUs) and convectors, radiant panels, Packaged Terminal Air Conditioners (PTACs) and Packaged Terminal Heat Pumps (PTHPs), and Variable Refrigerant Flow (VRF) heat pumps.

2.5.1.1 Electric Resistance Heating

Electric resistance heating is very common in only a few areas of North America (e.g. the Pacific Northwest), and can take on many physical forms. These include cove heating, radiant panels, and electric furnaces (see Section 2.5.1.2), but the focus of this section will be electric baseboard convectors as these are the most common type of residential electric resistance heating (RDH Building Engineering, 2012). From a thermodynamic perspective, all of these technologies are more or less equivalent in that heat is generated by passing an electric current through a resistive medium, a process which has a thermal efficiency of 100%.

Electric baseboards offer low capital and maintenance costs due to their lack of moving parts, combustion equipment, or distribution components. Operational costs, however, vary by location, as do energy consumption and GHG emissions.

Electric baseboards are only capable of providing space heating and no other functions. Units are typically located along exterior walls, under fenestrations to prevent condensation and make up perimeter losses, with separate units for each zone served. The zonal nature of the simple controls can allow for heating to operate only in occupied areas of a suite, which can result in energy savings of up to 20% as compared to conditioning all interior space (US Department of Energy, 2016).

Physically, electric baseboards do require space within the zones they serve, which can negatively impact interior aesthetics and requires suite access for maintenance in the rare occasion that it is required. The footprint of each baseboard is relatively modest, and due to the lack of moving parts, baseboards have little impact on acoustics.

2.5.1.2 In-suite Air Handling Units

In-suite air handling units (AHUs) take the concept of forced air heating and cooling common single-family low-rise housing, and implement it on a suite-by-suite basis in multi-unit residential buildings. The heating technology may be a natural gas or electric furnace, or an air or water source heat pump. In all cases, conditioned air is transported from a central unit – typically located in a perimeter mechanical closet directly vented to the exterior – to each zone of the suite via ductwork. While cooling is not necessarily required in these systems, the ability to easily add cooling and other functions is one of the major advantages these systems offer over electric baseboards or radiant floors (see Section 2.5.1.4). As such, in-suite AHUs can provide heating, cooling, and filtration, with dehumidification occurring only during cooling operation, and provision for humidification possible but often not included.

In practice, packaged units containing the heating and cooling equipment along with distribution fans and filters are produced by many manufacturers. Those implementing warm air furnaces with direct expansion cooling or air source heat pumps are completely self-contained, and do not rely on any other plant equipment.

All in-suite AHUs require distribution ductwork to be installed throughout each suite, although ductwork tends to be limited and simple given that most suites are compact. Even so, ductwork can add distribution energy, duct losses, and acoustic concerns if not sized properly (John, 2014; Zimmerman, 2013). Additionally, the throw of air terminal units must be carefully specified to not negatively impact thermal comfort, and the placement of ducts must be coordinated with the reflected ceiling plan of each suite.

The requirement for in-suite ductwork can lead to moderate installation costs as compared to electric baseboards, but the total capital and maintenance costs are somewhat dependant on the type of energy production/rejection equipment (US Department of Energy, 2016). Furthermore, if not already part of the budget, plumbing natural gas to each suite represents a substantial incremental cost (Mather, 2015). Electric resistance heating, as previously discussed, will have lower installation and maintenance costs than combustion equipment. With added complexity, the skill level required and cost of maintenance tends to increase, and this is even more relevant to heat pump based systems (Lstiburek, 2006).

As these units are located in conditioned space, furnaces are classified as non-weatherised and can achieve higher efficiencies than weatherized units as jacket losses usually provide useful heat gain to the spaces they are located in (Lutz, Dunham-Whitehead, Lekov, & McMahon, 2004). This does however mean that proper air supply and exhaust is required for combustion equipment, and access to outdoor air is required for heat rejection and collection when implementing vapor compression refrigeration equipment. Properly designing the combustion gas venting is very important to ensure proper system performance without compromising indoor air quality (Dale, Wilson, Ackerman, & Fleming, 2000). These added penetrations through the building enclosure are often quite large, and can create difficulties with respect to detailing the continuity of enclosure control layers.

The overall heating and cooling efficiency of the system (based on site energy use, not always source energy) is largely dependent on the type of energy production/rejection equipment selected, with heat pumps offering the highest efficiencies, followed by electric resistance heating and lastly condensing natural gas furnaces. Air source heat pumps can only operate to a set minimum outdoor air temperature below which system performance drops off. In the past, this temperature was high enough that most heat pump systems in cold climates required backup electrical heating, but a growing number of systems have sufficient capacity and efficiency to obviate the need for backup heating (Natural Resources Canada, 2015). While the heating fuel source may be natural gas or electricity, all systems require electricity for cooling as well as fan energy for circulation – something which can account for a non-trivial amount of annual energy consumption (Pigg, 2003).

Control strategies for in-suite AHUs tend to be fairly rudimentary, with one thermostat located in a central location, and balanced delivery of air to all zones in the suite. This limits the ability to provide zone level control, but such control is rarely required in modestly sized suites, and the single thermostat greatly simplifies installation, commissioning, operation, and maintenance.

2.5.1.3 Hydronic Fan Coil Units and Convectors

Hydronic systems typically involve boilers and chillers which transport energy using water to hydronic terminal units located within conditioned spaces. Fan coil units (FCUs) and convectors are both examples of hydronic terminal units, and both are available in a few different forms. Hydronic convectors can only provide heating, but fan coil units can provide heating and cooling if energy rejection components such as chillers are incorporated into the system design.

Fan coil units are typically 2-pipe or 4-pipe, which denotes the number of supply and return pipes connected to each terminal unit. 2-pipe FCUs have a single supply and return, and thus can only provide heating or cooling at one time, and require seasonal transitions between energy production and rejection equipment if cooling is desired (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2012). It is common to have electric resistance backup coils in 2-pipe configurations to assist in shoulder season conditions when the plant has been transitioned to cooling but heating is required to satisfy setpoint temperatures. Four (4)-pipe FCUs have independent supply and return piping for heating and cooling water. This arrangement – while more capital cost intensive – is generally preferable due to eliminating the need for seasonal transitions between plant equipment, and added ability to provide heating and cooling to different zones at the same time during shoulder seasons. In either case, each unit consists of a water-to-air heat exchanger and a fan, and utilizes forced convection to condition space air.

Convectors utilize natural convection to deliver heat to a given space. As natural convection is less effective at driving heat transfer than the forced convection achieved by the fans in FCUs, convectors rely more heavily on high temperature differences between heating water and space air, along with larger heat exchangers. As high temperate differences are more easily achieved when heating than when cooling, and due to the requirement for condensate drains for cooling coils, convectors are typically only used for heating.

Convectors can take the form of baseboard heaters, induction units (which require forced air from a remote source), or radiators. Note, however, that baseboards and radiators are the most common forms of convectors, and as convective heat transfer comprises the majority of total heat transfer from radiators, both are essentially thermodynamically equivalent.

Hydronic systems offer many advantages over air-based systems in that they can deliver the same amount of heat while requiring significantly less space for distribution equipment, and while consuming substantially less distribution energy than air-based systems due to the higher heat capacity and density of water (Boldt & Keen, 2015). The terminal units still require space within each conditioned zone however, which can have a negative impact on aesthetics and acoustics in the case of FCUs.

Condensing natural gas boilers can be extremely efficient, with peak thermal efficiencies reaching 97% and beyond (Charbonneau, 2011). However, boiler efficiency is highly dependent on entering water temperature, that is, the temperature of the water returning to the boiler from the supply loop. With FCUs and convectors, it is common to supply water at temperatures of 70-80°C, with a loop delta T of 10-15°C. At these temperatures, regardless of the peak rated efficiency of the boiler, condensing efficiencies will not be achieved, and the system will operate in a non-condensing fashion with peak thermal efficiencies around 80-85%. Modern engineering that favours energy efficiency would design systems to ensure low return water temperatures. Reducing the water temperatures would improve boiler efficiency, and may either require an increase in pumping energy or larger plumbing. Furthermore, lower temperature differences between water and space air will require larger terminal units and/or larger fans. Outdoor reset control systems for boilers account for the much lower heat demand at warmer-than-design outdoor temperatures by lowering supply water temperatures. Such controls can allow condensing efficiencies during the vast majority of operating hours per year with no change in distribution or terminal equipment (The Viessmann Group, 2004). Condensing efficiencies are therefore possible with FCUs and convectors if carefully designed, but may be more expensive to achieve if larger sizes are required. Electric boilers alleviate the boiler efficiency limitations. However, higher distribution losses will always be expected with higher supply water temperatures.

Chillers are required if cooling is to be provided by fan coil units. There are many types of chillers, but a common approach is to have a central water-to-water chiller which removes heat from the closed building loop, and transfers it to an open loop connected to a cooling tower. Chiller efficiencies vary by type, but not all chillers are applicable for use in high-rise MURBs as each type has a limited capacity range. Centrifugal chillers offer the highest efficiencies, but require a higher minimum load than rotary chillers which are more common in residential settings (Natural Resources Canada, 2002).

Capital costs tend to be comparable to other centralized systems requiring distribution pipe installation, along with plant equipment and terminal units. Maintenance costs depend on the type of energy production/rejection components selected, but natural gas boilers and evaporative cooled chillers typically require moderate maintenance costs due to the inherent degradation of combustion equipment, and the water treatment required in order to prevent scale buildup in open loops.

Controls are moderately complex, as water temperature, flow rate, and air flow rate can be modified in order to achieve the desired amount of space conditioning. Thermostats can control temperatures at a suite level or at a zone level depending on the system implementation, and often work by varying the amount of water circulated through the terminal units from a central closed loop. FCUs can also vary the fan speed, which is often controlled manually on the unit itself.

2.5.1.4 Water Source Heat Pumps and Ducted Fan Coil Units

Water source heat pumps and ducted fan coils represent a combination of hydronic fan coil units and in-suite AHUs; both involve a single unit, located in each suite, which distributes conditioned air to zones through ductwork as with all in-suite AHUs. However, rather than having a furnace or air source heat pump, each AHU contains a hydronic fan coil or water source heat pump which is connected to a central plant loop. In this way, water source heat pumps have unique characteristics.

Both systems require a central boiler plant to create hot water, however only ducted fan coils require a chiller as water source heat pumps can transfer heat from space air into the closed recirculation loop as long as it is maintained within a fairly flexible temperature range – a task which can be accomplished with a cooling tower and heat exchanger (Mather, 2015). Loop temperatures do have an impact on plant efficiencies, but both of these systems are capable of operating at lower heating water temperatures.

Ducted fan coils require fewer units than having traditional FCUs located in every zone served which does reduce capital costs, however the addition of supply ductwork and duct losses must also be accounted for. Increased pressure drop from the ductwork will also increase fan energy consumption. Water source heat pumps represent a cost premium over ducted fan coils or traditional in-suite AHUs, but the lack of central chiller does reduce plant equipment costs.

From an efficiency standpoint, water source heat pumps operate more like fan coil units than air source pumps when heating because the boiler must still provide enough heat to the hot water loop to meet the heating load. However, the ability to have more modest water loop temperatures for heating and cooling will reduce distribution losses.

2.5.1.5 Radiant Panel Heating and Cooling

Radiant panel heating and cooling involves using very large terminal units, often concealed in the building's fabric, to provide space conditioning predominantly by means of radiant heat transfer and natural convection between objects and occupants within the space. Because of the nature of these systems, operative temperature becomes the dominant control variable as opposed to air temperature. Furthermore, the radiant panels themselves can operate at relatively low temperature differences with respect to the zone operative temperatures due to the presence of large effective heat exchange areas.

Radiant panels can take many forms, depending on the energy source. Generally, electric resistance heating elements or hydronic piping are imbedded into a cement screed or topping which is set on top of a floor, wall, or ceiling structure. Metal panels suspended from, or embedded in, the ceiling with hydronic tubing bonded to their backs, is another common terminal unit. In all cases, insulation is required between the energy source and structure in order to ensure heat only flows in one direction. Additionally, a low resistance, high emissivity outer surface is necessary in order to ensure adequate radiative transfer between objects in the space and the surface of the panel.

Radiant floors are commonly used for heating in order to take advantage of natural convective currents. For these reasons, walls and ceilings do not function as effectively for heating, and are mostly seen in cooling applications. Conversely, radiant floors are less common in residential cooling applications, and are mostly reserved for large open rooms or atriums with large glazing areas in order to directly control solar gains (Nall, 2013). The effectiveness of radiant floors is commonly compromised by the presence of furniture and floor coverings. Cooling slabs have the added complication that surface temperatures cannot drop below the interior dew point in order to prevent condensation issues.

In locations where the practice of radiant heating is very established, such as Germany, it is claimed that radiant floor heating is no more expensive than other hydronic systems such as baseboard convectors (Olesen, 2002).

When heating, hydronic panels require relatively low supply water temperatures, which enables high plant efficiencies when coupled with condensing natural gas boilers. Additionally, as space mean radiant temperatures are higher, equivalent operative temperatures can be achieved at lower air temperatures – a factor which can result in energy savings, provided that the enclosure does not exert highly variable solar loads. However, the surface temperature of radiant panels cannot exceed 30°C if occupant thermal comfort is considered, and therefore radiant panel heating cannot provide more than approximately 100 W/m^2 of space heating (Olesen, 2002). For this reason, radiant panel systems require high performance enclosure assemblies to reach their full potential.

Physically, radiant panels do increase the depth of the assemblies which they are incorporated into, which can be difficult given the tight restrictions on floor height typical of high-rise MURBs. However, their concealed nature results in no visible presence within the zones they serve, little or no acoustic impact depending on recirculation pump operation, and generally very low maintenance required at a zone level.

Radiant panels can be controlled a number of different ways depending on whether electric resistance or hydronic systems are implemented. Hydronic systems can implement recirculation pumps within each zone with a constant flow central loop, or a variable flow central loop with suite control valves to regulate temperatures. In either event, radiant panels must accommodate the thermal storage of the mass in structure-integrated panels, which can increase perceived thermal comfort but renders the system slow to respond to sudden changes in space loads.

2.5.1.6 Packaged Terminal Heat Pumps and Air Conditioners

Packaged terminal units incorporate energy production/rejection, distribution and delivery equipment into one component. Packaged terminal air conditioners (PTACs) utilize direct expansion cooling either independently or coupled with electric resistance heating, which is delivered to the zone via a distribution fan which may also serve as the evaporator fan. Packaged terminal heat pumps (PTHPs) are similar, except that the vapour compression refrigeration cycle can be reversed to provide heating. In either event, the units are typically mounted on exterior walls of perimeter zones, and are most popular in applications where individual zone level control is required such as hotels or residences.

PTACs provide cooling, and PTHPs also provide heating. Dehumidification can also be provided indirectly when the space is being actively cooled. Filtration of space air is achieved as well, but the level of filtration is often only sufficient to protect heat exchange surfaces, not ensure air quality. Some systems include the supply of outdoor air as well.

Packaged terminal units require an independent unit for every zone served, which may mean 2 or more units per suite, depending on the layout and perimeter exposure. The performance and capacity of air source heat pumps is diminished at lower outdoor air temperatures, and may require electric resistance backup heating in cold climates.

Capital costs are dependent on the number of units required per suite. If only one unit is necessary, PTACs and PTHPs can be a relatively low cost solution, however as the number of units per suite increases, the cost will become less competitive. Maintenance is fairly simple, but does require suite access.

2.5.1.7 Variable Refrigerant Flow Air Source Heat Pumps

Variable Refrigerant Flow (VRF) heat pumps employ fan coil units sometimes combined with an outdoor ventilation air system, connected to a central outdoor unit by means of refrigerant piping. In small scale residential applications, VRF systems are often referred to as ductless split systems, mini-splits, or multi-splits (Roth, Westphalen, & Brodrick, 2006). The fundamental concept is to use refrigerant directly as the thermal transport medium, thus turning the indoor fan coil units into evaporator or condenser coils, which can improve system efficiency. Furthermore, if heating and cooling is required simultaneously in different zones within the same system, heat can be transferred between spaces with very little energy input, resulting in very high system COPs.

VRF systems can be implemented with one outdoor unit per suite, or with upwards of 20 indoor units connected to one outdoor unit – resulting in one outdoor unit for every few floors (Goetzler, 2007).The indoor units typically are fan coils with no air supply, but air can be provided through ducted units provided a secondary dedicated outdoor air system (DOAS) is present. A suite-by-suite approach would offer the application of currently available residential multi-split systems, which could simplify installation and maintenance (Lstiburek, 2006). However, centralized systems offer better system level efficiency as the aforementioned part load case where heating and cooling are required simultaneously in different zones will most likely occur on opposite elevations of a given MURB.

VRF systems often claim better part load performance than traditional direct expansion heat pumps due to multistage, variable speed compression and fan performance. Furthermore, many outdoor units are better suited to low temperature operation, with some still capable of delivering 100% of the heating capacity available at 16°C at temperatures as low as -20°C, and operation down to -25°C (Afify, 2008). Beyond those limitations, electric resistance heating or a supplemental natural gas heating system is required.

Capital costs for VRF systems largely depend on industry familiarity, but in North America a cost premium of 5-20% over traditional hydronic systems can be expected (Goetzler, 2007). Maintenance costs would likely also be higher than conventional systems due to the added complexity, and lack of widespread familiarity within the industry.

VRF systems boast very low electrical energy consumption compared to other system options, which will have variable GHG implications depending on the electrical grid infrastructure for the buildings location. However, there are hidden GHG implications which must also be considered; while packaged heat pumps and chillers typically exhibit minimal refrigerant leakage over the course of their service life, limited data is available for VRF systems. The most comparable application utilizing large scale site-built refrigeration is grocery stores, for which it is estimated 10-15% of the system refrigerant charge is lost annually (Baxter, Fischer, & Sand, 1998). At these rates, even the recommended sustainable refrigerant R-410a still poses significant GHG concerns as it has a global warming potential 1725 times that of carbon dioxide (Afify, 2008). Other refrigerants with lower global warming potentials are available for the same applications as R-410a such as propane (R-290) and R-123, but their adoption is not currently widespread (Critchley, 2011; Lampugnani & Zgliczynski, 1996)

Functionally, several different forms of indoor units exist which can all be connected to the same outdoor unit. These include exposed and concealed units, which can be wall mounted, ceiling mounted, or suspended. Each indoor unit offers consistent zone level temperature control, with some limited filtration of suite air. Due to the improved part load performance, more consistent thermal comfort can also be achieved.

When installing VRF systems, vertical refrigerant pipe runs are limited (e.g. less than 60-150 feet for many models) which can pose difficulties for taller buildings (Afify, 2008). A potential solution involves routing upper floor piping to roof mounted units with lower floors routed to ground level units in the parkade or adjacent space, but this can only be applied to a maximum of around 30 stories (Lstiburek, 2006). Outdoor units can also be hung on the side of buildings, but this requires the architectural design to coordinate with the mechanical design. Often for taller buildings, interstitial mechanical rooms are required, with enclosure area for the air source condensing equipment.

2.5.1.8 Ground Source Heat Pumps

Ground source systems utilize a hydronic earth heat exchange loop coupled with some combination of previously discussed systems to provide space conditioning. The building systems will likely take one of the following three forms:

1. A central water-to-water heat pump connected to the ground loop providing heating or cooling water to in-suite hydronic terminal units such as radiant panels or FCUs
2. In-suite water source heat pumps which transfer heat directly to or from the central ground water loop to suite air
3. A central water source VRF system coupled to the ground water loop

Earth heat exchange loops can either involve vertical bore holes or horizontal trenches. Vertical bore holes are much more expensive, but require substantially less space and are therefore often the only practical option for high density sites. As high-rise MURBs often are situated in high density downtown areas, vertical bore holes are the only broadly applicable configuration, often with the bore hole field located beneath the underground parking garage.

Ground source heat pumps offer the distinct advantage over air source heat pumps in that the ground temperature does not undergo significant annual variations. Furthermore, the earth can act as a form of thermal storage, being charged during the cooling season and drained during the heating season. Most climate zones of Canada and the northern United States have much larger heating loads than cooling loads, so a truly seasonally balanced system is unlikely. However, as buildings strive for higher performance, the heating loads often drop more quickly than the cooling loads, which means that ground loops can become more closely balanced.

Capital costs vary depending on the building systems implemented, but the drilling fees associated with creating the ground loop are fairly significant – particularly with vertical bore holes located beneath taller high-rise MURBs. Drilling costs vary from 5-15 US Dollars/foot depending on the type of earth, but higher costs can be expected for harder rock – such as that found beneath downtown Toronto (S. Kavanaugh, 1998). In some cases, the ground loop can be treated as a district energy system, paid for by utility companies and billed monthly to condo owners at an amortized rate over the service life of the building (S. P. Kavanaugh, 2016). Investigations into implementation of ground loops in Toronto have demonstrated reasonable payback periods provided cooling is functionally required (Canadian Mortgage and Housing Corporation, 2002).

Ground loops offer higher efficiencies than air loops – particularly at lower outdoor air temperatures – and can potentially provide energy savings of 20-50% over conventional air source heat pumps (Cooperman, Dieckmann, & Brodrick, 2012). However, GSHPs do not benefit from the economy of scale with respect to central plant efficiency, and tend to favour smaller water source heat pumps (S. Kavanaugh, 1998). The project-specific and often complex design of GSHPs requires more care than pre-packaged air source systems and hence performance is highly dependant on the design choices made (especially with regard to pump power, ground loop size, etc.).

2.5.2 Type 2: Indoor Air Quality Systems

Indoor air quality systems provide outdoor air in order to help address indoor air quality requirements. The primary function served is ventilation, but some form of filtration, humidity control, or air pressure control may also be addressed by these systems. All occupied spaces, including the suites and corridors in high-rise MURBs require ventilation air, and as such ventilation systems can address these locations with separate, independent systems or with central combined systems. In either case, the fresh air requirements are usually based on ASHRAE Standard 62.1. The delivery effectiveness (i.e. how well the system delivers design airflow in normal operational conditions) varies depending on the system configuration and has been shown to vary widely (Maxwell et al., 2014).

2.5.2.1 In-suite Heat Recovery and Enthalpy Recovery Ventilators

Heat recovery ventilators (HRVs) and enthalpy recovery ventilators (ERVs) are packaged residential units which serve to provide balanced flow of ventilation air similar to a commercial dedicated outdoor air system (DOAS). Both types of units employ heat recovery to precondition incoming outdoor air with exhaust space air, while enthalpy recovery units also provide latent moisture transfer between air streams.

HRVs and ERVs can be implemented in a number of ways, but when operated independently of other mechanical systems, they are often simply located near the building enclosure and connected to a large conditioned space such as the living room. In-suite distribution ductwork adds additional cost, and is often only installed if also required for heating and cooling functions. Without ductwork, the distribution effectiveness (the ratio of ventilation air supplied to the breathing zone as compared to the total supply airflow rate) throughout the suite is considered to be 0.5, while if connected to distribution ductwork through ceiling bulkheads the value would increase to 0.8 (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2016). The value of 0.5 is to accommodate re-entrainment supply air in the exhaust air stream, whereas 0.8 is used for supply of warm air at a high level.

Heat can be recovered from bathroom exhaust streams, but kitchen exhaust must always be directly vented to the exterior to prevent buildup of organic contaminants on heat exchange surfaces, which can block flow and pose fire safety concerns. Label efficiencies for the exchange of heat or energy can reach 80% for high performance units. Sensible pre-heating effectiveness extends the range of use by considering the heat addition to the air stream from the fan energy.

In-suite HRVs and ERVs impose a cost premium over more traditional MURB ventilation systems, but the low operational costs help mitigate some of these concerns. Maintenance typically involves filter replacement, but more significant repairs surrounding heat exchanger fouling is also possible. Regardless of the cause for maintenance, suite level access is required, and even then the units themselves are often located in difficult to reach areas.

Many studies have identified in-suite HRVs and ERVs as the best option for providing ventilation air in high-rise MURBs, due to the direct connection to each suite, suite level controls, and balanced air flows (Canadian Mortgage and Housing Corporation, 2003; RDH Building Sciences, 2005; Walsh Construction Co., 2011).

2.5.2.2 Floor-by-Floor or Central AHUs Providing Dedicated Outdoor Air

Floor-by-floor or central air handling units (AHUs) can be configured as dedicated outdoor air systems (DOAS), and serve either just the corridors, or the corridors and suites. If multiple suites are served by the same system, it is common practice to sub-duct the suites in order to limit noise transfer and manage fire and smoke spread.

Central systems, with rooftop supply-only AHUs, are typically only used in corridor only applications due to the difficulty and cost associated with installing supply and return ductwork to and from every suite in a high-rise MURB to one central location.

Floor-by-floor based systems can be implemented in high-rise MURBs, with one AHU serving one or more floors. Such systems can either just serve the corridors, or serve suites and corridors, although the latter requires sub-ducting as previously described. Note that the floor on which the unit is located often requires extra ceiling space in order to accommodate the ductwork (Canadian Mortgage and Housing Corporation, 2003). As high-rise MURBs are often carefully sized to maximize zone height restrictions, adding additional building height purely for mechanical systems is undesirable.

Both floor-by-floor and centralized systems offer easier maintenance than in-suite systems and often can be built at a reduced capital cost (the central units are always cheaper per unit of flow, but the cost of ductwork and fire/smoke dampers can become very significant). Controls are no longer at a suite level, however, which can make it difficult to ensure proper ventilation is provided to each suite as these systems are effected by wind pressures and can be difficult to balance.

While both of these systems in theory can provide the same amount of ventilation air, centralized systems do not typically allow for compartmentalization of suites, which can lead to contaminant transfer due to complex 3-dimensional airflow networks between ducts, hollow building spaces, and occupied spaces.

Supplemental heating and/or cooling capacity can be easily built into the central or floor-by-floor AHUs to handle conditions where heat recovery alone is insufficient in providing air at acceptable temperatures for occupant thermal comfort.

2.5.2.3 Pressurized Corridor Ventilation

Pressurized corridor ventilation systems are historically the most common way to ventilate high-rise MURBs, and are still typical of modern construction despite the many documented performance issues and underlying conceptual design flaws associated with them (Canadian Mortgage and Housing Corporation, 2003; Handegord, 2001; Ricketts, 2014). The basic concept involves supplying air from central rooftop MAUs through vertical supply air ducts to every corridor. It is assumed that the ventilation air provided to the corridors will enter the suites through door undercuts or cross-over ducts. Unlike the previously discussed ventilation systems, pressurized corridor systems are incapable of incorporating heat recovery due to the lack of return ductwork, and instead must condition all outdoor air directly.

Functionally, pressurized corridor systems provide the correct amount of outdoor air to the building, but studies have shown that delivery of ventilation air to the suites is very unreliable, and highly affected by wind and stack pressures (Ricketts, 2014). The lack of compartmentalization can allow for air transfer between building areas, including between underground parking and suites, or corridors and garbage rooms.

Due in part to industry familiarity, and the minimal ductwork required, pressurized corridor systems boast low capital and maintenance costs when compared to other ventilation systems while serving both the suites and corridors. Operational costs will inherently be much higher, however, as no form of heat recovery can be implemented, and controls typically require 24/7 operation at a constant volume. However, it is difficult to compare costs to other systems since pressurized corridor systems rarely reliably ventilate each suite in a building.

The National Energy Code of Canada for Buildings (NECB) states that heat recovery ventilation is optional in Vancouver or Toronto, but in Edmonton pressurized corridor systems without heat recovery do not meet the energy code requirements.

The pressure created across suite doors can make opening and closing of any doors connected to the corridor difficult. Additionally, noise and odour transfer from corridors to suites can be significant due to the necessity of door undercuts.

2.5.3 Type 3: Domestic Hot Water Systems

Domestic hot water systems provide hot water to water outlets within occupied space. These systems often are one of the largest consumers of energy, regardless of Canadian location, due to the relatively consistent demand for hot water within residential settings.

2.5.3.1 Storage Tank Hot Water Heaters

Storage tank hot water heaters are the most common residential technology associated with domestic water heating. Designed for single dwelling application such as Part 9 housing, storage tank hot water heaters consist of a tank with an integrated electric resistance or natural gas heating element.

Storage tank hot water heaters offer flexibility with respect to loads, easily transitioning from no use to multiple simultaneous load scenarios such as having a dish washer and shower operating at the same time. This flexibility is due to maintaining a large volume of water at 55±5°C at all times. This temperature is high enough to cause burns, and thus must be mixed with cold water to a temperature of 50°C before it can be delivered to water outlets. This high storage temperature is however necessary in order to prevent biological contaminant growth within the water tank.

Energy performance is denoted in the form of an energy factor for natural gas units, and a standby loss coefficient for electric resistance units. The energy factor is measured under specific test conditions, but is a weighted measurement of the efficiency of the unit over a specific time period, with multiple draws of specified duration and/or volume. Standard natural gas units have fairly poor energy performance, with a high performance unit achieving an energy factor of approximately 0.7 (Natural Resources Canada, 2012). This poor performance is due to the high burner entering water temperature, but also due to standby losses which are experienced by both natural gas and electric resistance units. Modern condensing tanked water heaters are also now becoming available, with thermal efficiencies of 92% to 96%.

In the context of a high-rise MURB, storage tank water heaters would likely be implemented on a suite-by-suite basis. This would require space within each suite. But would also offer reduced standby losses as the unit would be located within conditioned space rather than a semi-conditioned or unconditioned mechanical room.

Capital costs would be higher than centralized systems due to the depreciated economy of scale, however the savings in distribution piping and associated reduction in heat losses can often balance this. The relatively simple equipment requires minimal maintenance. Suite level access would however be required to perform the maintenance.

2.5.3.2 Instantaneous Hot Water Heaters

Instantaneous or tankless hot water heaters have only a small tank – often only 1 US gallon – and instead heat water only as it is needed. In this way, standby losses can be minimized, resulting in higher energy performance.

Instantaneous water heater performance can vary, as high return water temperatures can cause condensing units to operate with non-condensing efficiencies. Consistency of supply water temperature can also be an issue during low load conditions.

It is common to either have a dedicated unit for each zone containing water outlets, or to situate all water outlets closely together such that a single unit can serve all locations. In the context of high-rise MURBs, the latter is much easier to achieve than in conventional detached housing.

The main drawback to tankless operation is that equipment sizing for varying loads becomes difficult. While part load performance is often still excellent, determining maximum capacity is crucial to ensure peak loads can be achieved.

From an efficiency standpoint, tankless hot water heaters offer significant improvements over conventional storage tank units. Natural gas units boast higher condensing efficiencies due to the very low inlet water mains temperatures, and both natural gas and electric units benefit from the minimal standby losses. As such, tankless natural gas units can achieve energy factors of up to 0.98 (Natural Resources Canada, 2012).

Tankless hot water heaters have higher capital costs than storage tank hot water heaters, and their use is not as established in the North American market. Furthermore, as individual units are required for every suite, the capital costs are much higher than traditional centralized systems. Maintenance are also higher due to added concerns surrounding scale buildup within the unit heat exchange surfaces, and the need for suite level access to perform said maintenance.

2.5.3.3 Central Boiler with Storage Tanks

The most common approach to domestic water heating in high-rise MURBs involves a central boiler plant with supplemental storage tanks which may in turn include internal heaters. This approach is best suited to natural gas boilers, where the low inlet temperature can generate very high efficiencies when paired with a condensing boiler, and by centralizing the heating plant economy of scale can contribute to low capital costs. Additional benefits include easy access for maintenance, and relatively few pieces of equipment to maintain.

Central domestic water systems can be easily sized to meet capacity requirements, but in order to minimize delays associated with delivery to water outlets, circulation pumping is required. Furthermore, with longer pipe runs, thermal losses through pipe insulation become more significant.

2.5.3.4 Heat Pump Water Heating

Heat pump water heating can take on a number of different forms depending on the application. Residential heat pump water heaters (HPWHs) often are attached to storage tank units in place of or in addition to electric resistance heaters, and use space air as the heat source (Zogg, Dieckmann, Roth, & Brodrick, 2005). Commercial heat pump water heating is typically performed by reverse cycle chillers (RCCs) which use outdoor air as the heat source. In the context of high-rise MURBs, only the latter is broadly applicable as in-suite HPWHs would simply put an additional heating load on the space heating equipment.

Reverse cycle chillers are not commonly used for water heating in Canadian MURBs, predominantly due to the poor performance exhibited by all air source heat pump technologies at low air temperatures. However, a study by Ecotope, Inc. suggests that the use of RCCs fed by parkade exhaust air can mitigate this performance limitation for use in the Pacific Northwest (Heller & Cejudo, 2009). This logic is likely also applicable to high-rise MURBs in colder climates as ground temperatures are fairly consistent. Furthermore, the study also argues that the increased capital cost over electric water heating is justified by a short payback period based on Washington utility rates. This argument is likely not as applicable to other locations in Canada, where natural gas water heating is more traditional.

As with all heat pumps, reverse cycle chillers boast much higher efficiencies than achievable with natural gas or electric resistance heating, although this performance is relative to inlet air temperature.

2.5.3.5 Solar Thermal Water Heating

Solar thermal hot water heating utilizes flat plate or evacuated tube collectors to transfer solar energy in the form of heat directly into water for domestic use. While widely used in Part 9 construction, use of solar thermal systems in high-rise MURBs is not very common in North America, and can be found more commonly in South Korea.

Solar thermal collectors, when properly sized, can provide a significant portion of domestic water heating – although the specific amount varies by location, installation, collector properties, and sizing. Furthermore, as storage is diurnal, supplemental heating is required even in sunny, warm climates in order to deal with successive days featuring overcast cloud cover and limited beam radiation. Systems are often designed to handle 100% of the DHW load during the summer, although the realized performance can very. A study of an apartment complex in South Korea found that the solar thermal system was only able to provide 26% of the annual DHW load, despite being designed to provide 46% of the load (Yoo, 2015).

Solar collectors require regular maintenance, and the system requires secondary storage tanks for integration with building domestic hot water systems. The additional tanks, pumps, and piping increases the system complexity, as well as the cost, over traditional central boiler systems. Furthermore, a backup boiler is still required to meet the heating loads when insufficient solar heating is available.

Solar thermal DHW does not scale well with respect to high-rise MURBs as increasing the number of floors corresponds to increased DHW load with no increase in usable roof area to mount collectors.

2.5.4 Combination Systems

Combinations could take the form of any combination of the three previously discussed system types. In practice, however, combination systems typically involve thermal comfort systems combined with ventilation or domestic hot water.

2.5.4.1 In-suite Hot Water Heaters with Hydronic Terminal Units

In-suite combination systems providing heat and hot water are among the most common combination systems, with a developed marked share in Europe and a growing market in Canada. These systems usually take on one of four forms: a boiler with an internal tankless coil, a boiler with an indirect storage tank, a separate boiler and storage tank combined into one unit, and a storage tank hot water heater which provides hot water for domestic use and space heat (Butcher, 2011).

Combination space and domestic hot water systems provide heating and domestic hot water, but filtration is only possible if FCUs are used for the terminal units. Cooling is typically only possible if the FCUs employ a direct expansion cooling coil or connection to a chilled water supply.

In the context of Part 9 housing, combination units offer capital cost savings as only one piece of equipment is required rather than two. In the context of high-rise MURBs, however, this is less of a cohesive argument as in-suite water heating is less common.

Performance seems to vary depending on the type of combination unit. Some boilers with internal tankless coils are configured to stay hot all year, which results in high standby losses when only DHW heating is required (Butcher, 2011). In contrast, boilers with indirect DHW storage tanks offer efficiency improvements over storage tank hot water heaters. High performance tankless water heaters can offer high efficiencies and cost savings over separate systems (Rudd, 2012).

Traditional storage tank water heaters can be used in combination systems by connecting the terminal units for space heating through a secondary heat exchanger loop. While storage tank water heaters do have relatively low energy factors, these values are low due to flue losses during standby operation. Actual efficiency can improve by 8-10% when used for heating applications because the burner fires more frequently (Clinton, 1999). The use of condensing storage tank systems offers significant efficiency gains.

Many benefits are associated with in-suite combination systems, including added perceived occupant control, and improved water conservation driven by sub-metering of water heating (Canadian Mortgage and Housing Corporation, 2004). Combination systems do, however, require additional space within suites as compared to central systems, and can be difficult to size due to misleading or inadequate performance specifications (Butcher, 2011).

2.5.4.2 Central Boiler with Indirect DHW Storage Tanks

Applying the same principals as found in the in-suite DHW and space heat systems, boilers with indirect DHW storage tanks can also be constructed as a centralized system. In comparison to having separate boilers for DHW and hydronic systems, one boiler plant can serve both functions, saving capital costs.

Combining space and hot water hydronic heating can only be applied to serve heating and DHW functions. Filtration and cooling could only be achieved if the hydronic terminal units were FCUs, which also include a direct expansion cooling coil, or connection to a chilled water supply.

Domestic hot water and space heating water temperatures may vary depending on terminal units or outdoor air reset, which can add complexity to boiler controls when attempting to meet both requirements.

2.5.4.3 In-suite AHUs Providing Space Heating, Cooling and Ventilation

All of the in-suite AHUs, water source heat pumps, and ducted FCUs discussed in Sections 2.5.1.2 and 2.5.1.4 do not typically provide ventilation. However, ventilation can be integrated into any of these systems with relative ease, often through the use of a HRV or ERV (see Section 2.5.2.1).

Providing ventilation through these systems is quite effective, as distribution ductwork is already in place to distribute the air throughout the suite. This offers an improvement in delivery effectiveness from 0.5 to 0.8 over simply supply and exhausting from a central location such as the living room (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2016).

Incorporating HRVs or ERVs into in-suite AHU based systems is advantageous in colder climates, as this mitigates thermal comfort issues associated with cool supply air temperatures during periods of very low outdoor air temperatures.

In-suite AHUs are typically located in a mechanical closet or recess, and as such it can be difficult to fit the ventilation recovery unit and ductwork into the same space.

2.5.4.4 Wall Mounted Terminal Units Providing Space Heating, Cooling and Ventilation

Wall mounted terminal units include fan coil units (see Section 2.5.1.3), packaged terminal heat pumps and packaged terminal air conditioners (see Section 2.5.1.6). These units can all be designed to allow some intake of outdoor air as they are already located on exterior perimeter walls. In the case of PTHPs and PTACs, the unit already penetrates the exterior wall, meaning no additional openings are necessary.

Outdoor air intake through terminal units can be a functional preference to pressurized corridor ventilation given that air is added directly to the suite. However, limited control is available with respect to the outdoor airflow rate, which would additionally be impacted by building pressures and wind (Maxwell et al., 2014).

From a capital cost perspective, there is no significant cost premium associated with this practice over traditional wall mounted terminal units. However, as heat recovery cannot be incorporated, the operational costs will be much higher in comparison to any system which utilized that technology.

Chapter 3 : Existing Building Modelling Results and Discussion

Developing an energy model of an existing high-rise MURB serves as a baseline for future analyses while also helping to identify important building characteristics with respect to energy use. Furthermore, an understanding of how this particular building consumes energy can be discussed and extrapolated to other buildings within this building type. This analysis is structured in four phases:

1. Discussion of the existing building characteristics
2. Analysis of building energy consumption based on available utility and monitoring data
3. Construction of a calibrated energy model based on building data, modelling standards, and assumptions
4. Discussion of the energy model results

Note that the calibrated model energy consumption is building-specific. However, the relative impact of different building design characteristics has broader implications.

3.1 Description of Existing Building

The Belmont is a 13 story, 37-unit high-rise multi-unit residential building located in Vancouver, British Columbia. Originally built in 1986, The Belmont underwent an extensive enclosure rehabilitation in 2012 carried out by RDH Building Engineering in which the walls, windows, doors, and roofs were all replaced or retrofitted with new high performance assemblies. Figure 3-1 shows The Belmont post-rehabilitation in 2013.

Figure 3-1: The Belmont as viewed from the north-east corner in February 2013. Provided by RDH.

3.1.1 Building Geometry

The typical floor plan of the Belmont can be seen in Figure 3-2. Note that complete post-retrofit architectural drawings, along with the original mechanical drawings can be found in Appendix B. A typical unit consists of around 118 m^2 (1275 ft^2) of conditioned and semi-conditioned floor area, with a typical floor consisting of around 418 m^2 (4500 ft^2) and the entire building consisting of approximately 5000 m^2 (54,000 ft^2). The semi-conditioned space consists of enclosed balconies, highlighted in blue in Figure 3-2. While these balconies are located inside the thermal control layer of the exterior wall, they do not contain any heating equipment and therefore the space is semi-conditioned.

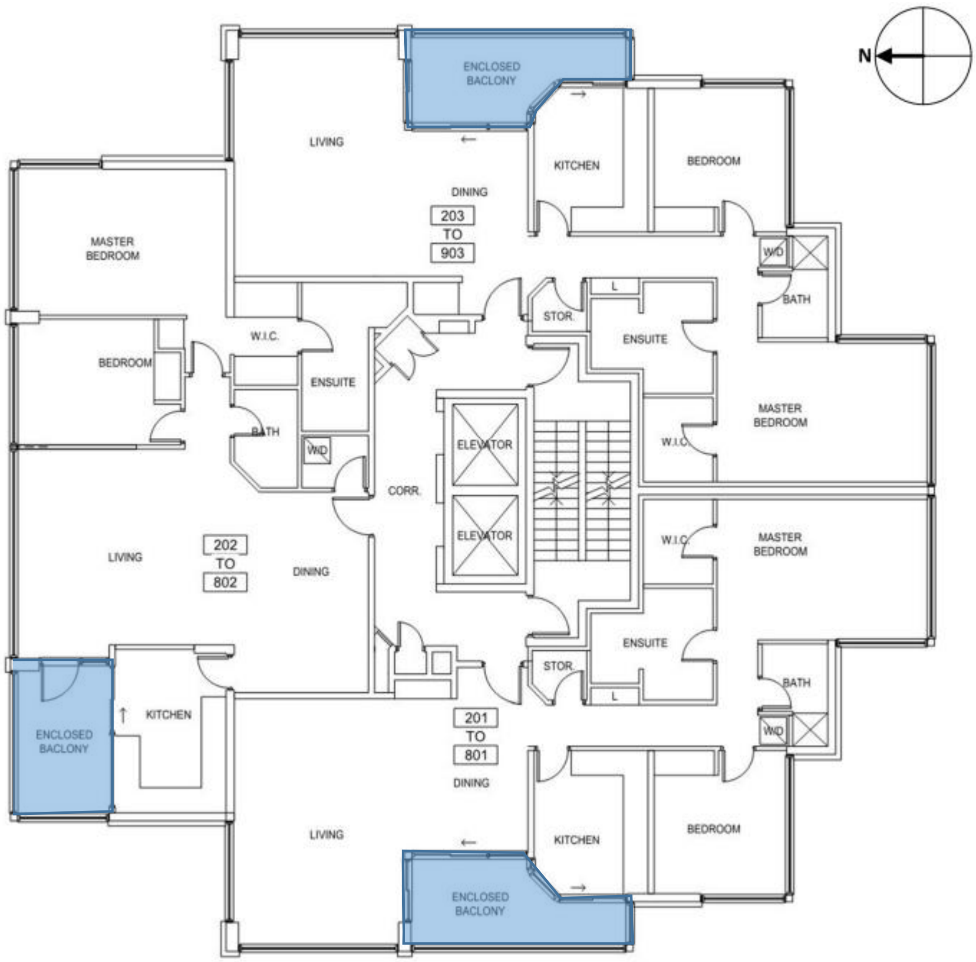


Figure 3-2: The Belmont typical floor plan for floors 2 through 11, provided by RDH. Light blue areas denote semi-conditioned enclosed balconies

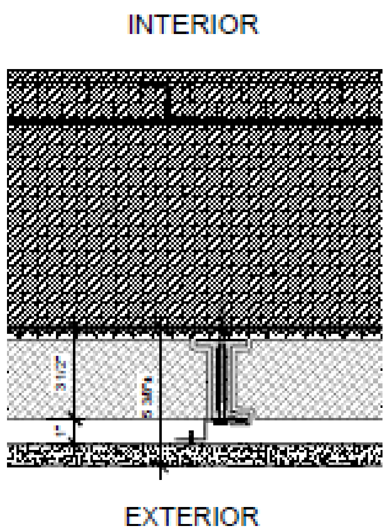
Unique areas of the building include the first floor, the thirteenth floor, and the basement. The first floor only has 2 units – both of which contain exterior terraces in place of enclosed balconies – and includes a larger lobby area. The thirteenth floor is the penthouse, and also includes two units which are larger than those on the typical floors. The basement includes an isolated elevator lobby, some mechanical and electrical rooms, and a large parkade which extends far beyond the footprint of the building.

3.1.2 Constructions and Openings

The enclosure of The Belmont is relatively high performance as compared to the 2012 BC Building Code, which is due to its involvement in a research project carried out by RDH.

The intent of this project was to rehabilitate the enclosure, but also to improve energy performance and building airtightness.

The typical exterior wall assembly is shown in Figure 3-3. All layers outboard of the concrete wall were added during the rehabilitation process, and everything else was previously existing from the original construction. The exterior walls have a nominal RSI-value of 3.9 m^2·K/W (R-value of 22 ft2·°F·hr/Btu), but RDH determined the effective RSI-value to be 2.8 m^2·K/W (R-value of 15.9 ft2·°F·hr/Btu) after accounting for thermal bridging and other three-dimensional heat transfer phenomena.



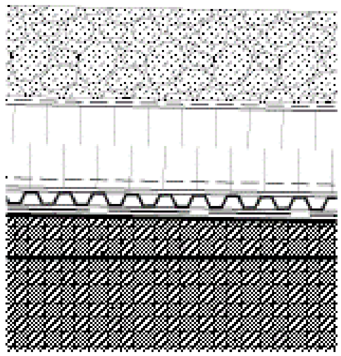
Interior

- Interior gypsum wallboard
- 13 mm (1/2″) rigid insulation, bridged by framing
- Concrete wall (thickness varies) with acrylic coating
- 89mm (3 1/2″) Mineral fibre insulation, bridged by intermittant fiberglass spacers
- Continuous 25mm (1″) vertical galvinized metal z-girt
- 25mm (1″) Air space
- Metal cladding or 22mm (7/8″) stucco

Exterior

Figure 3-3: The Belmont – post-retrofit typical exterior wall assembly. Taken from drawings provided by RDH.

The typical roof assembly is shown in Figure 3-4. This inverted roof has minimal thermal bridging, and as such the nominal and effective insulating values are equivalent with an RSI-value of 3.5 m^2·K/W (R-value of 19.9 ft2·°F·hr/Btu). Note that all layers outboard of the concrete topping were added during the enclosure rehabilitation.



Exterior

- Gravel Ballast
- Filter Cloth
- 100mm (4”) Extruded polystyrene (XPS) insulation
- Drainage mat
- Roof membrane
- Sloped concrete topping
- 190mm (7 ½”) Structural concrete slab

Interior

Figure 3-4: The Belmont – post-retrofit typical roof assembly. Taken from drawings provided by RDH

The windows and doors are triple glazed with fiberglass frames, low-emissivity coatings, and argon fill giving them a USI-value of 0.97 W/m^2 K (U-value of 0.171 Btu/ft2·°F·hr) as determined by RDH. In addition, the windows have a solar heat gain coefficient (SHGC) of 0.2 and a visible spectral transmittance of 0.7. The overall window-to-wall ratio is approximately 65%.

Figure 3-5 shows the exterior wall and windows during their installation. On the right the new windows are visible, but note that the frames appear blue due to a protective adhesive which remained on the frames until the completion of construction. On the left, the typical exterior wall assembly is partially completed with the orange fiberglass spacers visible intermittently between the layers of mineral fibre insulation.

Interior partition walls fall into two categories. Some walls consist of cast-in-place concrete, finished with gypsum wallboard. Others consist of steel framing with fiberglass batt cavity insulation and gypsum wallboard on both sides. The thickness of the stud cavity, as well as the thickness and number of layers of gypsum vary by location throughout each typical floor.

Internal floors consist of an 190 mm (7 1/2”) structural concrete slab, finished on the walking surface with carpet and carpet underlay, and finished on the underside with gypsum wallboard.

Figure 3-5: Typical exterior wall and new windows during construction in 2012. Photo curtesy of RDH.

Below grade walls consist of exposed concrete, and are uninsulated as the parkade is unconditioned space.

Additional drawings for the remaining assemblies can be found in Appendix B.

3.1.3 Mechanical Systems

The Belmont's mechanical systems are representative of its vintage and geographic location. As with any high-rise MURB, the mechanical systems include thermal comfort, indoor environmental control, and plumbing and drainage systems.

The thermal comfort system is fairly simple – baseboard electric resistance heaters provide space heating to all conditioned spaces, with no space cooling equipment installed. A pressurized corridor based ventilation system provides fresh ventilation air by means of a roof mounted make-up air unit (MAU), a single vertical supply duct connected to each corridor, and door undercuts of varying height to each suite. Point exhaust is provided to each kitchen and bathroom with on-demand fans ducted either through ceiling plenums or in-slab ducts. No humidification control is provided, and filtration is only provided at the MAU intake.

Figure 3-6 shows a typical suite floor plan taken from the original mechanical drawings. Each conditioned space is sized with an appropriate capacity electric baseboard. Suites -01 and -03 have a capacity of 10.5 kW, and suites -02 have a capacity of 7 kW. The total installed capacity in all suites is 360 kW, giving an average of 9.74 kW/suite.

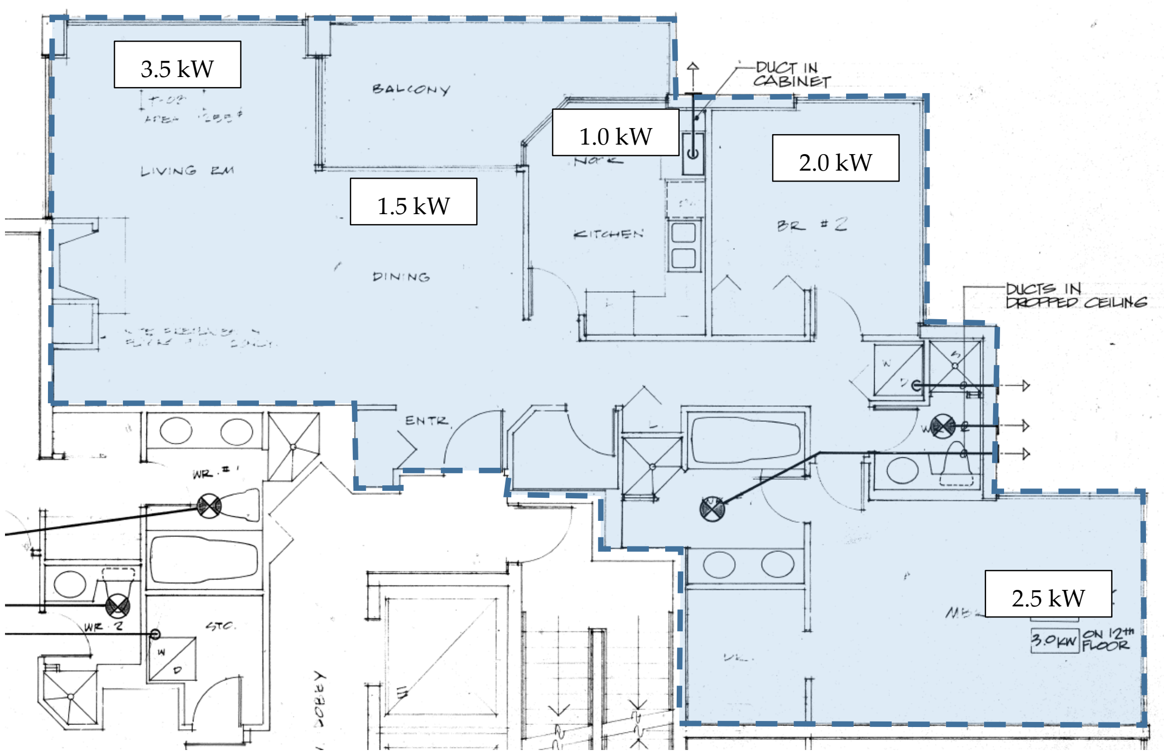


Figure 3-6: The Belmont – typical suite installed electric baseboard capacity. From original issued for construction mechanical drawings by Sterling, Cooper & Associates, 1985. Courtesy of RDH.

Figure 3-7 shows the rooftop MAU. It is an Engineered Air 250S, rated for 1560 l/s (3300 cfm) at 250 Pa (1″ water gauge) of external static pressure. It contains a natural gas heating coil which has an output capacity of 59 kW (200 MBH) at a thermal efficiency of 80%.

Figure 3-7: The Belmont – Engineered Air rooftop make-up air unit (MAU). Photo curtesy of RDH

The DHW system consists of a central indirectly fired natural gas boiler located in the rooftop mechanical room which provides hot water to the entire building through distribution piping.

Figure 3-8 shows the A.O. Smith natural gas boiler used for DHW, which has a maximum output of 147 kW (502,640 Btu/h) at an efficiency of 82.4%. Note that this boiler is attached to two additional Allied Engineering Company domestic hot water heaters which are largely used for storage of hot water.

On floors 9 through 13, a natural gas fireplace is located in each suite living room. Aside from a few units which have been replaced, the majority of fireplaces are the original Fire-song 220n, rated for 8.8 kW (30,000 Btu/h) input. Each unit is vented horizontally outward through the adjacent exterior wall.

Additional miscellaneous equipment includes a single elevator and associated motors, fire pumps, and parking garage exhaust fans.

Figure 3-8: The Belmont – A.O. Smith boiler on the left, Allied Engineering Company DHW heater on the right. Photo courtesy of RDH.

3.1.4 Lighting, Gains, and Occupancy

Limited lighting and internal gains information is available from the original drawings, largely due to the fact that suite loads are somewhat dependent on the task lighting and plug loads installed by each individual suite owner. Additionally, while the original hard-wired lighting may have involved incandescent lamps, it is unclear how many are still incandescent and how many have been replaced with newer more efficient technologies such as LED or compact fluorescent (CFL). However, it can be generally observed that the parkade and corridors have permanently installed lighting which remains on at all times.

The majority of the occupants of The Belmont are retirement age due to a building bylaw requiring a minimum resident age of 55. Typical units contain 2 bedrooms, and are occupied by one or two people.

3.2 Measured Energy Consumption

The Belmont's energy consumption has been monitored and metered in a number of different ways since the completion of the enclosure retrofit in December 2012. Electricity and natural gas data has been provided by the respective utilities, BC Hydro and Fortis BC, as part of their involvement with the rehabilitation project. Additionally, monitoring equipment was installed throughout the building as part of a research study on airflow patterns (Ricketts, 2014). Much of this monitoring data is not explicitly relevant to building energy consumption, but three specific datasets relate directly to energy: natural gas consumption by the make-up air unit, natural gas consumption by the domestic hot water boiler, and temperature readings from thermistors soldered on the fireplace baseplates adjacent to the pilot lights.

3.2.1 Metered Energy Consumption from Utilities

Figure 3-9 displays the monthly total site energy consumption of The Belmont throughout the first two post-rehabilitation years as registered by the utilities. Note that BC Hydro sub-metered the electricity, and provided both suite and common (strata) consumption.

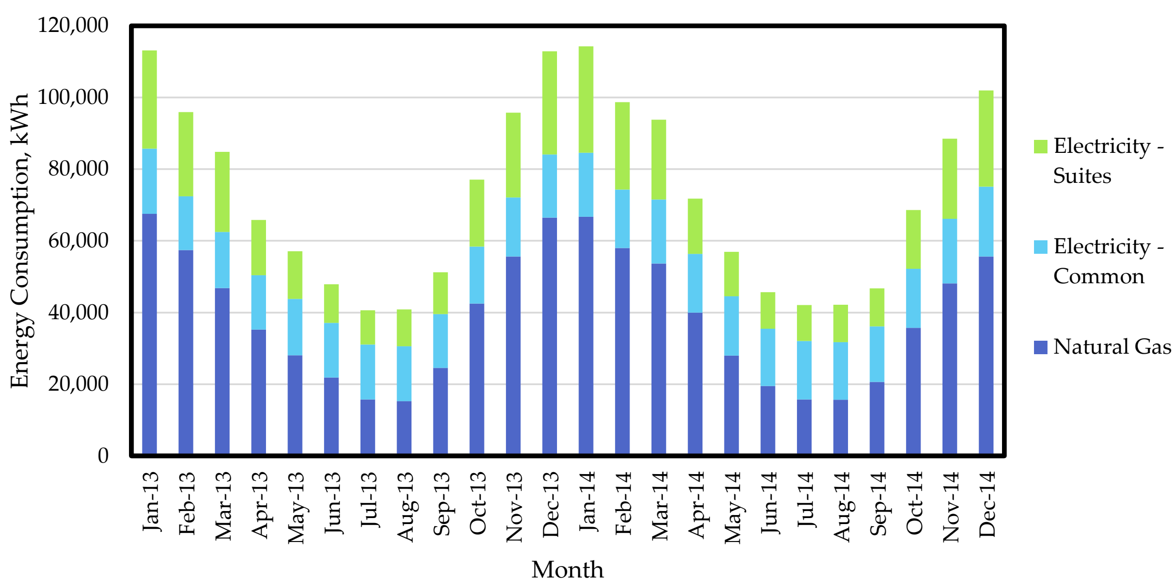


Figure 3-9: Monthly total site energy consumption of The Belmont for 2013 and 2014, as metered by BC Hydro and Fortis BC

By normalizing the consumption by suite, more tangible information can be gleaned from Figure 3-9. On average, the normalized suite consumption is 23,700 kWh/suite/year, or 1980 kWh/suite/month. Of this energy, an average of 5760 kWh/year or 480 kWh/month is suite electricity. Similarly, the common electricity, when normalized by number of suites, is consistently around 5320 kWh/suite/year or 443 kWh/suite/month. The natural gas however, when normalized by suite, averages 12,630 kWh/suite/year, with monthly consumption ranging from 410 to 1830 kWh/suite/month. The moderate seasonal fluctuation in suite electricity indicates that a decent portion of the consumption is connected to seasonal factors such as ambient daylight and average outdoor temperature. The huge seasonal fluctuation in natural gas consumption indicates that the consumption is largely dependent on seasonal factors, but given the natural gas end-uses, the most relevant seasonal factor is outdoor temperature.

Normalizing annual total site consumption by conditioned floor area to generate energy usage intensities (EUIs) allows for comparison to other buildings, given this is the most commonly used building energy performance metric (Kohta Ueno, 2010a). The 2013 and 2014 Belmont EUIs are 177 kWh/m^2 and 174 kWh/m^2 respectively. While the Belmont EUI's would need to be weather normalized for proper comparison to literature, it can be generally observed that the Belmont performs above average but not exceptionally with respect to energy consumption.

3.2.2 Electricity Consumption

From Figure 3-9, it is evident that the natural gas and suite electricity fluctuate considerably throughout the year, but the common electricity remains more or less constant. Figure 3-10 displays the common electricity, which averages 16,390 kWh/month as indicated by the dashed blue line. Note that the minor fluctuation present is likely due to a small amount of baseboard electric heating in the first floor lobby, but the majority of the consumption is likely due to a combination of the parkade lighting, the corridor lighting, stairwell lighting, and the elevator motors.

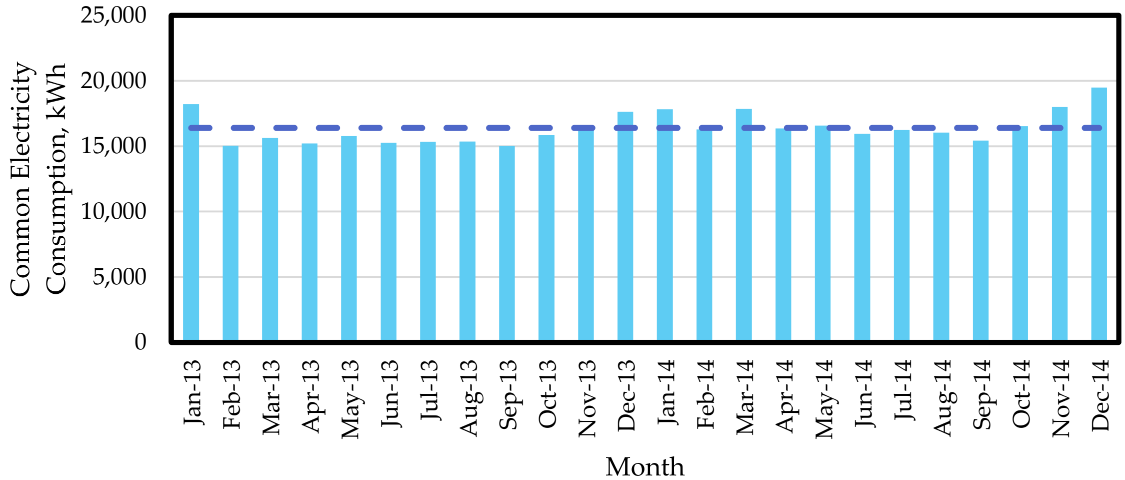


Figure 3-10: The Belmont – monthly common electricity consumption for 2013 and 2014 as metered by BC Hydro. The dashed blue line indicates the monthly average consumption

The suite electricity undergoes a visible fluctuation between the summer and winter. This pattern is visible more clearly in Figure 3-11. The suite consumption includes plug loads, lighting, exhaust fans, and heating, but the seasonal variation is largely due to heating demand. Some seasonal variation can be attributed to increased lighting requirements in the winter, but to a much lesser degree than heating energy.

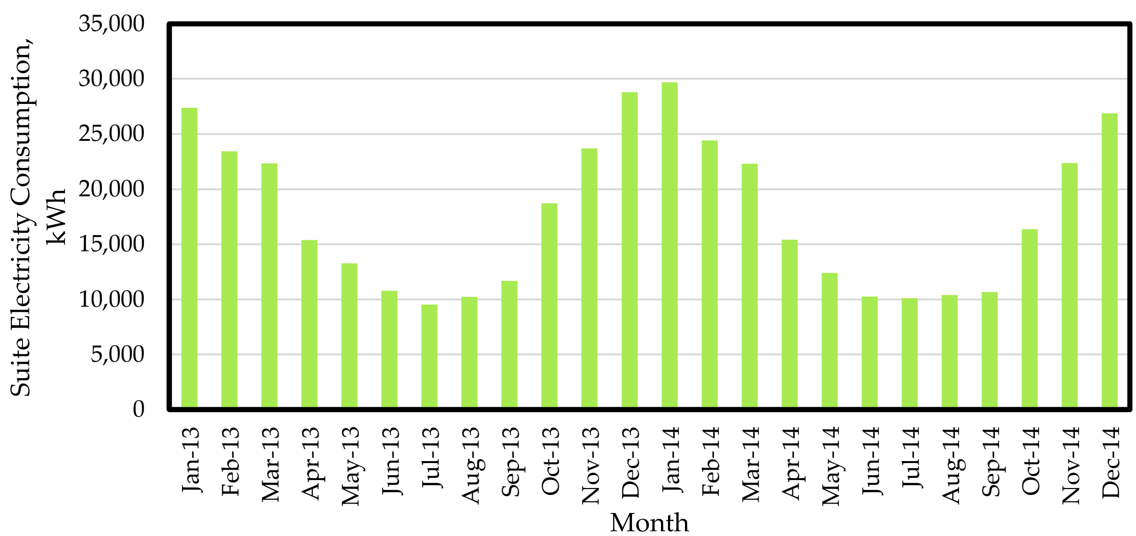


Figure 3-11: The Belmont – monthly suite electricity consumption for 2013 and 2014 as metered by BC Hydro

In order to generate a rough estimate of the baseboard heating energy consumption in the suites, one can weather-normalize the data to isolate baseline consumption from heating consumption. This consists of performing a linear regression on the correlation between suite electricity consumption and Vancouver heating degree days (HDDs). For the purpose of this analysis, a balance temperature of 18.3°C (65°F) was selected as this is the value used by CWEC and EnergyPlus, and HDDs were generated from the Vancouver YVR climate dataset (Government of Canada, 2015). Figure 3-12 displays the regression, which found an intercept of 8315 kWh/month. This intercept constitutes a rough estimate of the electrical base loads in the suites, which encompasses all plug loads, exhaust fans, and lighting. Given the range of variability associated with the baseline, a value of 9000 kWh/month was taken to reflect the level of precision inherent in the value.

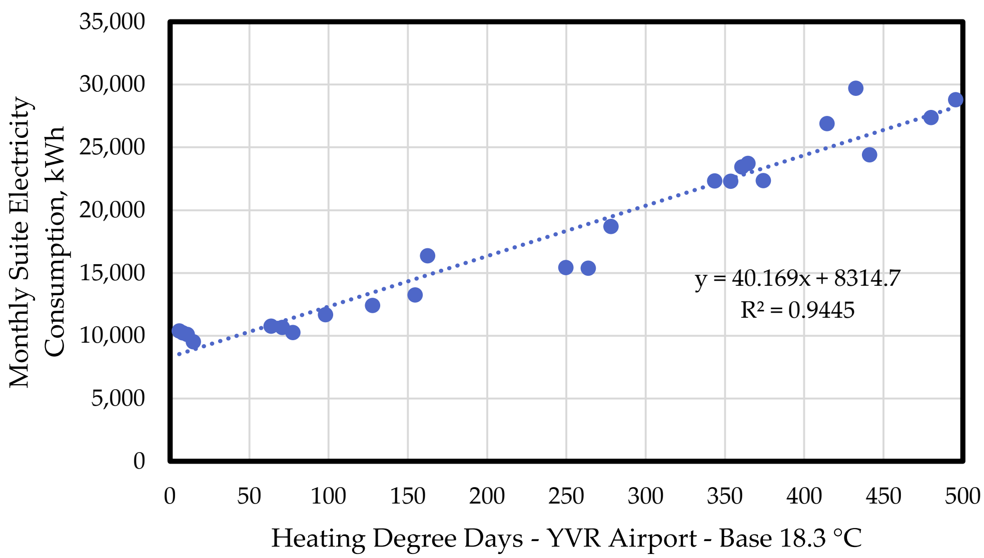


Figure 3-12: The Belmont – monthly suite electricity consumption vs. Vancouver heating degree days for 2013-2014

By subtracting the baseline suite electrical consumption established in Figure 3-12 of approximately 9000 kWh/month from the monthly suite electrical consumption shown in Figure 3-11, one can estimate the monthly consumption of the electric baseboards as shown in Figure 3-13. Note that this is only an estimate due to other considerations previously mentioned.

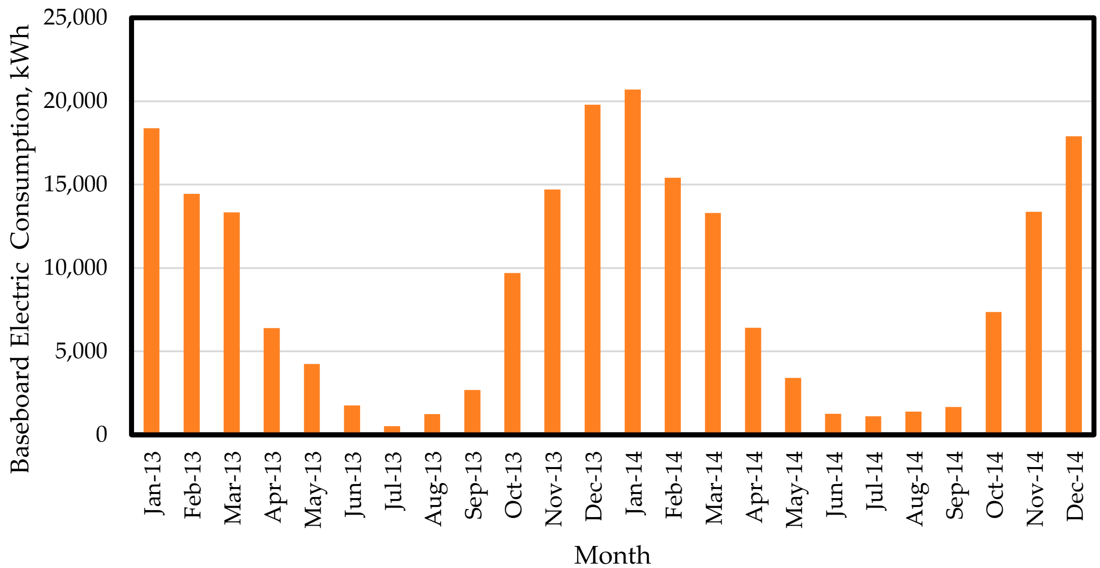


Figure 3-13: The Belmont – monthly estimated electric baseboard consumption throughout 2013-2014

Further breakdowns of electrical end use with respect to plug loads and lighting would be beneficial, but are not possible explicitly without further sub-metering within each suite.

3.2.3 Natural Gas Consumption

No sub-metering is available to provide further resolution on the natural gas end-uses. However, monitoring data is available for the make-up air unit, the domestic hot water boiler, and the fireplaces which together constitute all of the natural gas end-uses in the building. While some more recent data is available, the bulk of the data was recorded during the 2013 calendar year with intermittent data loss due to wireless equipment battery failures. Because of the condition of the data, a specific approach was required to analyze each of the end-use datasets.

For the domestic hot water boiler and the rooftop make-up air unit, a flow meter was attached to each natural gas supply line which provided pulses for every 0.1 m^3 of gas consumption on an hourly basis. The heating value of natural gas varies by utility provider, but for Fortis BC the average value is roughly 0.039 GJ/m3 which was taken for this analysis (Fortis

BC, 2015). The data capture rate was fairly high, but for months with some missing data it was assumed that the captured data was representative of the gap periods.

For the make-up air unit specifically, no data was logged at all for January or December 2013. Because of this it was necessary to weather normalize only the MAU consumption using a similar linear regression analysis used for the baseboard electric heating consumption. This allowed for estimation of the MAU natural gas consumption in these months based on the trend established during the rest of the year. Some error will be associated with this process, but as the regression had an r-squared value of 0.97 based on the other 10 months of data, the estimated consumption should be representative.

For the fireplaces, a different approach entirely was taken as fuel consumption was not measured, but rather the temperature of the baseplate adjacent to the pilot light on each unit. Ideally these temperatures would be hourly averages, but due to battery limitations instantaneous temperatures were taken once an hour and assumed to be representative of the previous hour. The following steps were taken to convert the temperatures to energy consumption:

1. An "adjusted average" was established for each fireplace by taking the average of temperature values below 30°C. The purpose of this was to establish a baseline temperature indicating when the unit was off. Typically, this value was slightly warmer than the average room temperature due to the proximity of the pilot light – around 25°C.
2. For every hour where the registered temperature was 10°C or more above the adjusted average, it was assumed that the unit was on for that previous hour. It is assumed that statistically the partial hours will even out as some will register an "on" temperature and others won't. Note that the maximum temperature varied by fireplace, but was typically around 60°C
3. With the number of "on" hours established, the recorded fireplace capacities were used to estimate the fuel consumption. Recall that typical fireplaces have a rated input of 8.8 kW (30,000 Btu/h).

4. As with the DHW and MAU, if data was missing it was assumed that the recorded data was representative of the gap periods.

Figure 3-14 displays the estimated natural gas end-use consumption based on monitoring data throughout 2013, along with the actual metered total from Fortis BC (the utility supplier). Most month estimates are within 10% of the metered total, and the overall trend is correct.

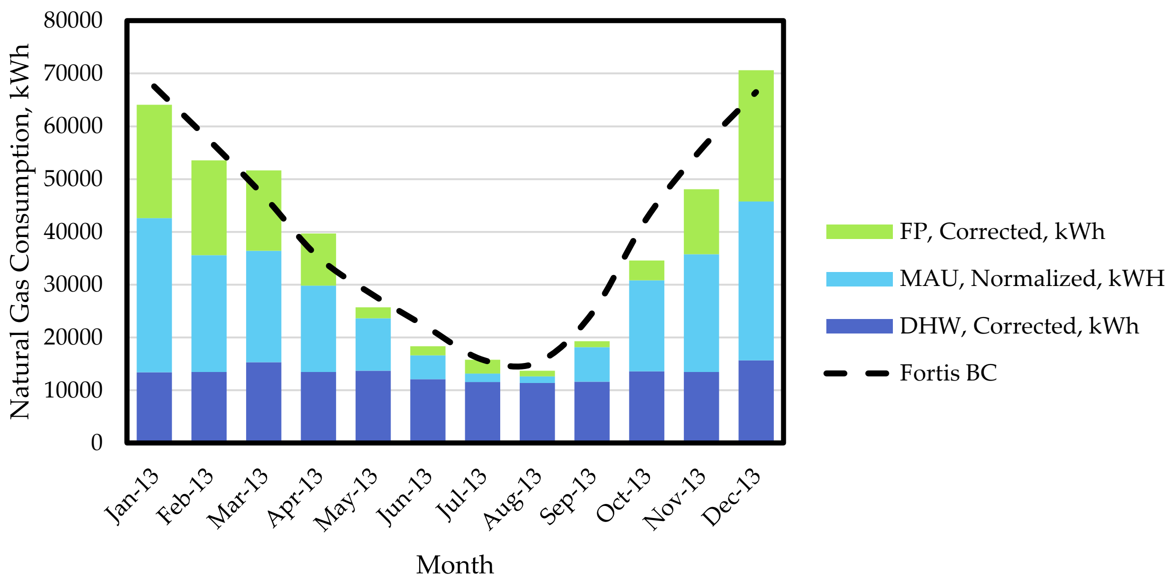


Figure 3-14: The Belmont – natural gas end-use estimates from monitoring data along with the metered total form Fortis BC for 2013

On an annual basis, one can use 2013 to analyze the percentage breakdown of natural gas by end-use as seen in Figure 3-15. Note that the fireplaces constitute a significant portion of annual energy use despite only being installed on 5 of the 13 floors.

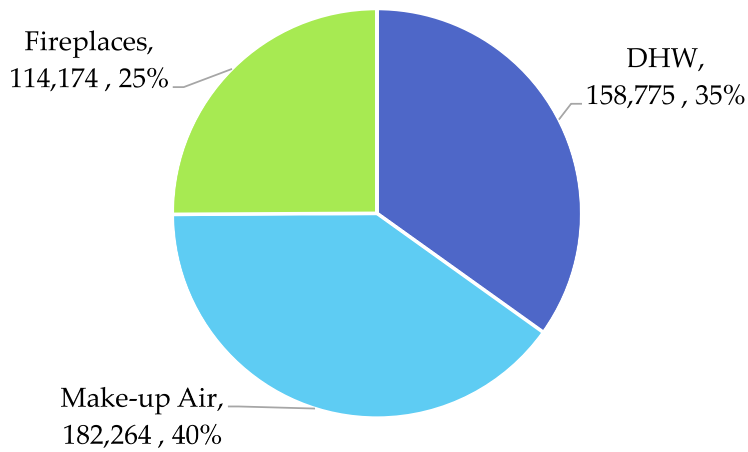


Figure 3-15: The Belmont – natural gas consumption by end-use for the 2013 calendar year

3.2.4 End-use Estimates from Measured Consumption

From Figure 3-14, it's apparent that the monitoring data for 2013 typically falls around 10% below the actual metered fuel consumption as reported by Fortis BC. Assuming that the percentage of energy use by each of the three end-uses is correct, one can apply these percentages to the actual consumption in order to generate estimated natural gas end-use consumptions. Figure 3-16 combines these end-use estimates with the previously discussed electrical end-use estimates to form a monthly analysis of 2013 energy use.

Figure 3-17 displays the 2013 end-use consumption estimates as aggregated throughout the year. Note that while the consumption by specific end uses are estimated using previously described methodologies, the total consumption is as metered by utilities.

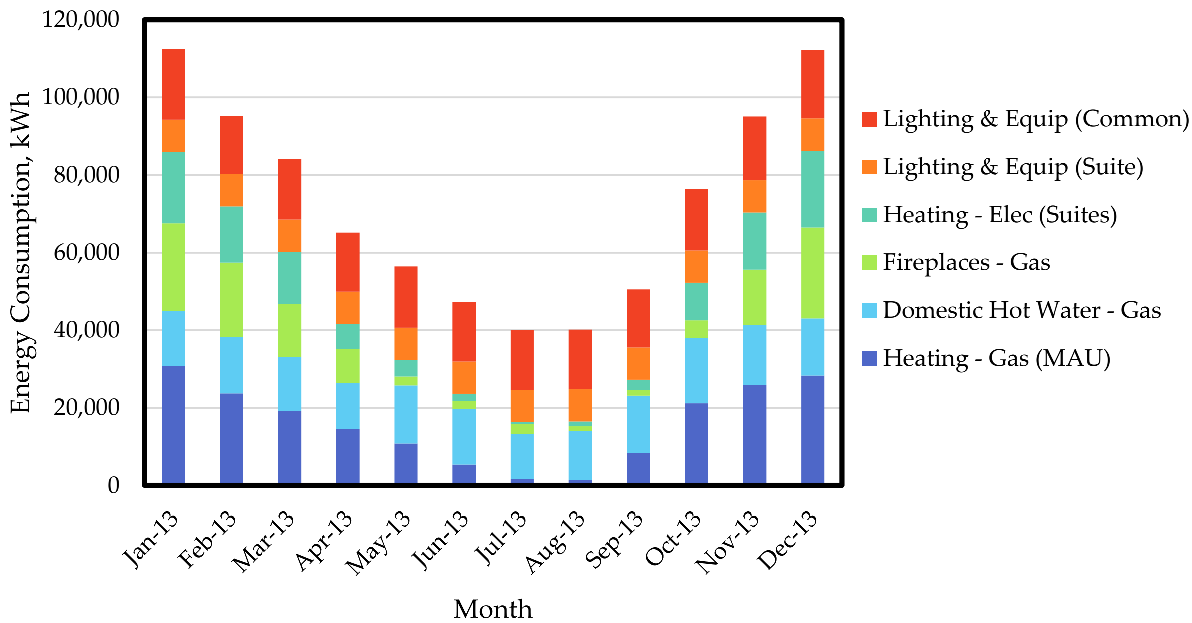


Figure 3-16: The Belmont – estimated 2013 monthly end-use energy consumption from utility and monitoring data

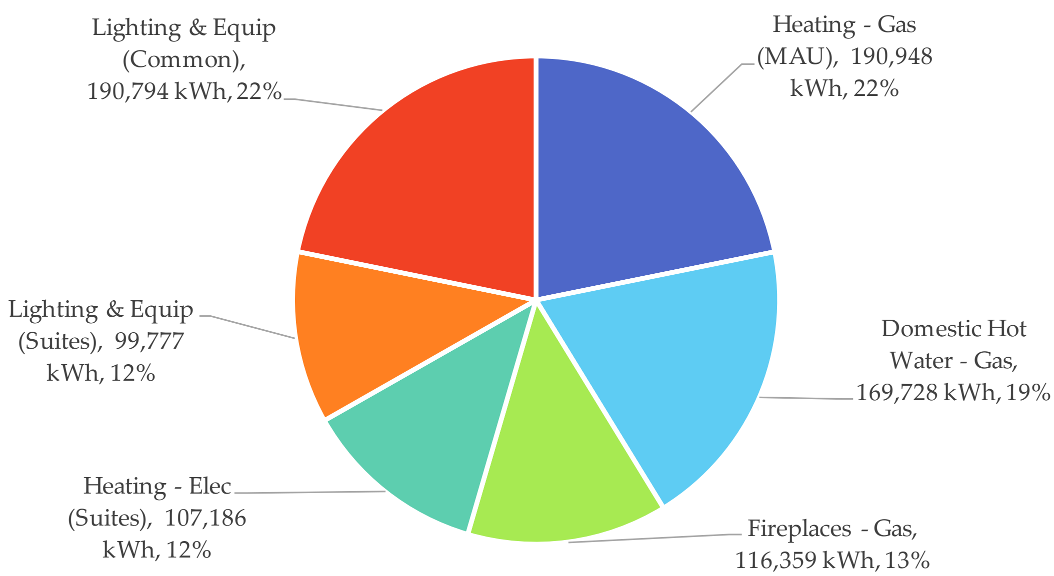


Figure 3-17: The Belmont – 2013 estimated annual end-use consumption

3.2.5 Estimated Domestic Hot Water Consumption

While the domestic hot water demand was not measured explicitly in terms of water consumption, the volumetric natural gas flow meter data can be interpreted to generate estimated hot water volumes.

The estimated 2013 domestic hot water natural gas consumption, as stated in Figure 3-17, is 169, 728 kWh. This number represents the boiler input. The boiler efficiency, as stated in section 3.1.3, is 82.4% resulting in a boiler output of 139, 856 kWh.

Water properties are quite well documented and understood. At atmospheric pressure and 25°C, the specific heat of water is known to be 4.18 kJ/kg·K and the density is known to be 997 kg/m³ (Borgnakke & Sonntag, 2009).

While the temperatures of the domestic hot water system are unknown, the DesignBuilder default water heating setpoint of 55°C and an estimated mains temperature of 10°C can be used, resulting in an estimated 45 K delta T which must be met by the boiler.

By treating the domestic hot water loop as a steady flow open system, one can perform a first law energy balance to find the volume of hot water consumed throughout 2013. Note that changes in kinetic and gravitational potential energy can be neglected.

$$E_{in} - E_{out} + E_{gen} = \frac{dE_{st}}{dt} \qquad \text{Eq. 3-1}$$

$$Q_{in} + m_{in}(c_p T_{in}) - m_{out}(c_p T_{out}) = 0 \qquad \text{Eq. 3-2}$$

$$\dot{Q}_{in} = \dot{V}_{system} \cdot \rho \cdot c_p (T_{out} - T_{in}) \qquad \text{Eq. 3-3}$$

where: E_{in}, E_{out} = rate of energy flow into and out of system, [W]

Q_{in} = rate of heat transfer into system, [W]

m_{in}, m_{out} = rate of mass flow into and out of system, [W]

T_{in}, T_{out} = Temperature of entering and exiting water, [°C]

ρ = Density of water, [kg/m^3]

c_p = specific heat of water, [kJ/kg]

V_{system} = volumetric flow rate of water, [m^3/s]

All of the terms in Equation 3-3 are rate dependant, but as no rate information is available, it must be assumed that rates do not vary significantly over the course of the year. This allows one to integrate with respect to time, resulting in finite terms.

$$Q_{in} = V_{system} \cdot \rho \cdot c_p (T_{in} - T_{out}) \qquad \text{Eq. 3-4}$$

$$V_{system} = \frac{Q_{in}}{\rho \cdot c_p (T_{in} - T_{out})} \qquad \text{Eq. 3-5}$$

where: Q_{in} = heat transfer into system, [kJ]

V_{system} = volume of water, [m^3]

Subbing the aforementioned values into Equation 3-5 yields an annual domestic hot water consumption of 2,680 m^3 (709,200 US Gallons) in 2013. Normalizing by suite, this corresponds to 73 m^3/suite (19,200 US Gallons/suite) during 2013. Further normalization for daily demand yields 0.20 m^3/suite/day (53 US Gallons/suite/day), which is higher than the ASHRAE 90.1 user's manual value of 0.15 m^3/suite/day (40 US Gallons/suite/day) (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2004).

3.3 Calibrated Energy Model

By taking the available information from the original and updated drawings, consumption data, site visits, pictures, and correspondence with condo owners, an energy model was built using the DesignBuilder software package. Where insufficient information was available, assumptions were made based on energy standards and modelling guidelines.

3.3.1 Building Geometry

The building geometry was input based on the 2012 rehabilitation issued for tender drawings. Note that as the parkade was not within the scope of the rehabilitation, basement dimensions were obtained from the original 1985 issued for construction drawings. Outside wall dimensions were taken, and the program was configured to calculate the wall thickness and offset it inwards when calculating the interior floor area. Figure 3-18 shows a visualization of the input geometry. Figure 3-19 shows the typical floor geometry. Note that the drawings indicate a total conditioned floor area of 5000 m2 (54,000 ft2), and the modeled floor area is essentially the same: 5043 m2 (54280 ft2). The difference is likely the result of rounding error and undervaluing the wall thickness, which will be discussed in section 3.3.2.

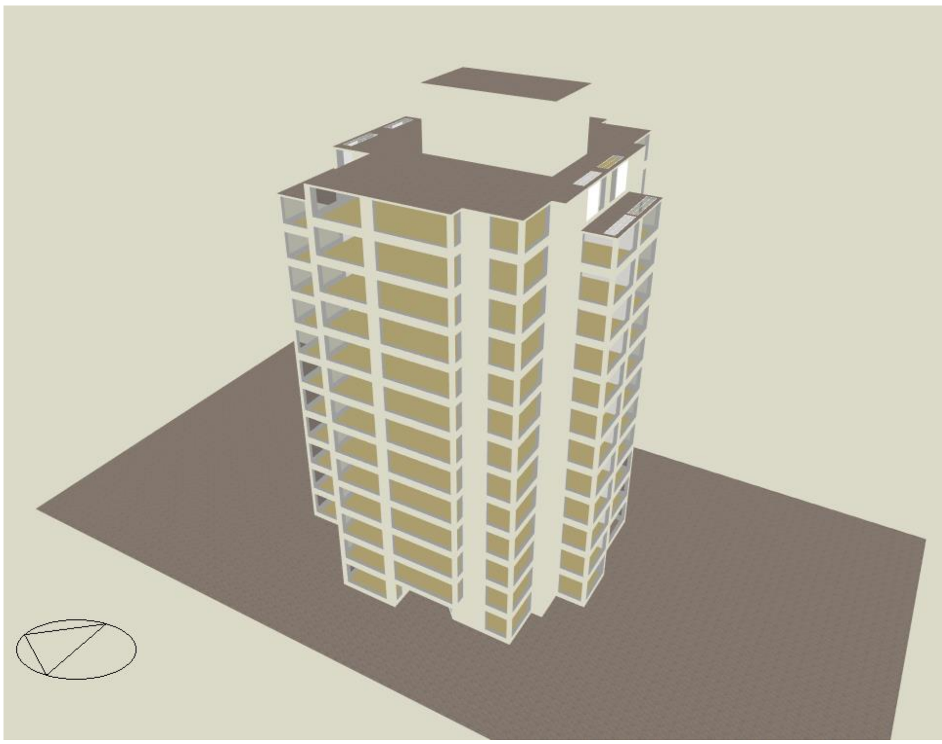


Figure 3-18: Belmont model geometry visualization in DesignBuilder

For the location, Vancouver BC was selected. The weather file was the 2013 actual meteorological year (AMY) weather data recorded at the Vancouver International Airport (YVR).

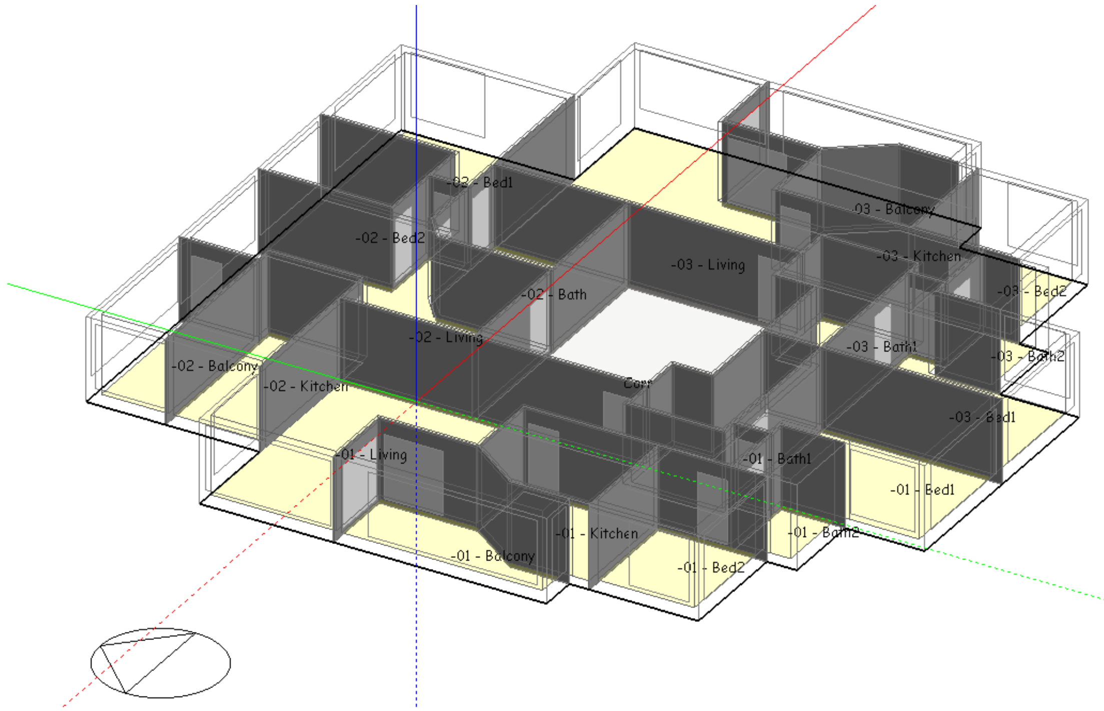


Figure 3-19: Belmont model typical floorplan showing internal partitions in DesignBuilder

3.3.2 Constructions and Openings

One of the challenges associated with defining constructions in DesignBuilder is that the user must input the assemblies as layers of predefined materials, and the insulation value is then calculated based on one-dimensional heat flow. The problem with this approach is that often the effective three-dimensional heat flow differs considerably from the one-dimensional analysis due to thermal bridging, thermal flanking, and other three-dimensional phenomena. In order to input the correct R-value for each assembly, it was therefore necessary to modify the thicknesses of certain layers to decrease the nominal value. For thermal purposes this practice is effective, but due to the method through which geometry is calculated in DesignBuilder, decreasing wall thickness results in an increase in indoor conditioned floor area. As the model only differed from the actual floor area by 43 m2 (280 ft2), this effect was considered to have negligible impact on the hourly calculations.

Table 3-1 below lists the assemblies used in Belmont model. Note that the modifications column describes changes made to the actual assembly in order to decrease the nominal R-value to match the effective R-value calculated by RDH.

Table 3-1: Belmont model assembly constructions, including both the actual and modified assemblies input into DesignBuilder

Assembly	Description	Modifications	RSI-value $m^2 \cdot K/W$	R-value $ft^2 \cdot °F \cdot hr/Btu$
Typical Exterior Wall	• 22mm (7/8") Stucco • 89mm (3.5") Mineral Fibre Insulation • 152mm (6") Concrete • 38mm (1.5") XPS • 16mm (5/8") Gypsum Wallboard	Modified to 70mm (2.75") MF, 13mm (0.5") XPS	2.82	16.0
Typical Roof	• 4" Gravel • 4" XPS • 6" Concrete	N/A	3.47	19.7
Typical Below Grade Wall	• 6" Concrete • 38mm (1.5") XPS • 16mm (5/8") Gypsum Wallboard	Modified to 13mm (0.5") XPS	0.78	4.4
Typical Internal Partition Wall	• 16mm (5/8") Gypsum Wallboard • 100mm (4") Air Gap • 16mm (5/8") Gypsum Wallboard	Modified from 100mm (4”) Fiberglass	0.42	2.4
Typical Internal Floor	• 13mm (0.5") Carpet • 13mm (0.5") Underlay • 152mm (6") Concrete	N/A	0.74	4.2
Ground Floor	• 2" Flooring Screed • 4" Concrete • 1" Brick Slips • 30" Clay Underfloor	N/A	0.93	5.3

To define the fenestrations, the window dimensions and locations were taken from the elevations in the 2012 issued for tender drawings found in Appendix B. The window properties were defined based on the manufacturer shop drawings with an overall USI-value of

0.97 W/m^2 K (U-value of 0.171 Btu/ft^2·°F·hr), a solar heat gain coefficient of 0.2, and a visible light transmittance of 0.7.

Infiltration is an important consideration in energy modelling as the air leakage can result in a significant amount of energy consumption. Some energy codes and modelling standards require constant air leakage rates to be incorporated in the model, while other times it is left to the modeller to set an input value. For example, the Canadian Model National Energy Code for Buildings (MNECB) requires a constant infiltration rate of 0.25 l/s/m^2 wall area (National Research Council of Canada, 1999). In DesignBuilder, the user can input an airtightness value which is converted to an air leakage rate in accordance with BS EN12831 (European committee for Standardization, 2003). For The Belmont, this approach was taken as the enclosure was measured by RDH to have a whole building air tightness of 1.4 ACH at 50 Pa. During the calibration process, however, this value was changed to 3.5 ACH @ 50 Pa in order to achieve the estimated heating load from measured data.

Natural ventilation also plays a large role in high-rise MURBs due to the abundance of operable windows and doors. It was assumed that when the indoor temperature was above 22°C (72°F), the occupants would open the windows resulting in 3 ACH of outdoor ventilation air. While the 3 ACH was a DesignBuilder default value, the indoor temperature setpoint was taken from the NREL house simulation protocols (Wilson, Engebrecht Metzger, Horowitz, & Hendron, 2014).

3.3.3 Mechanical Systems

The mechanical systems consist of three independently defined services: the air loop serving the corridors, the domestic hot water loop serving the suites, and the electric baseboards serving the suites. In addition to these, all suites include bathroom and kitchen exhaust fans, and suites on floors 9-13 also include natural gas fireplaces.

Defining an air loop in DesignBuilder involves starting from a stock template with a customizable air handler which can then be connected to a group of zones. In this case, the zones are the corridors on every floor. Note that The Belmont has no return ductwork to the

MAU, but due to the limitations of the air loop definition, a return connection was required in the model. Table 3-2 lists some of the key properties defining the air loop.

Table 3-2: Belmont model – pressurized corridor ventilation system input properties

Property	Value	Notes
Design Flow Rate	1557 l/s (3300 cfm)	From drawings, verified by field testing performed by RDH
Supply Fan External Static Pressure	250 Pa (1″ H_2O)	From drawings
Supply Fan Efficiency	70%	Assumption
Corridor Mechanical Ventilation	3.136 Ac/h	Based on design flow rate divided by volume of corridors
Heating Coil Capacity	73.2 kW (250 MBH)	Coil rated input from drawings
Coil Part Load Curve	Standard Gas Coil PLC	DesignBuilder default
Heating Fuel Source	Natural Gas	Known
Heating Burner Efficiency	80%	From drawings
Air Loop Setpoint Schedule	DOAS Schedule – Always 18°C	From monitoring and calibrations
Corridor Heating Setpoint	18°C (64.4°F)	Known from monitoring
Unit Availability Schedule	Always On	Known
Corridor Ventilation Schedule	Always On	Known

Defining a domestic hot water loop in DesignBuilder involves starting from an initial template containing a customizable water heater and pump which can then be connected to water outlet zones. Table 3-3 lists some of the key properties defining the domestic hot water loop. Note that the demand is based on the measured value of 53 Gallons/day/apartment. Additionally, the usage schedule was taken from the Model National Energy Code for Buildings (MNECB), and can be found along with all of the other schedules used in Appendix C (National Research Council of Canada, 1999).

Table 3-3: Belmont model – domestic hot water loop properties

Property	Value	Notes
Water Loop Flow	Constant Flow	Assumption
Water Heater Tank Volume	Autosize	Calculated by DesignBuilder
Setpoint Temperature	DHW setpoint schedule – always 55°C	DesignBuilder default
Heating Fuel Source	Natural Gas	Known
Boiler Heating Capacity	178.7 kW (610 MBH)	From equipment boiler plate
Heating Thermal Efficiency	82.4%	From equipment boiler plate
Heater Part Load Factor Curve	Newer Style Moderate Temperature Boiler circa 1983	Selected from DesignBuilder templates based on year of construction
Pump Rated Power Consumption	250 W (1/3 hp)	From drawings
Pump Speed	Constant	Assumption
Rated Pump Head	75 kPa (25 ft H_2O)	From drawings
Pump Performance Curve	Constant Output (no variable speed)	DesignBuilder default
Pump Control Strategy	Continuous	DesignBuilder default
DHW Demand	53 Gal/Day/Apartment	From measurements
DHW Suite Load	0.1794 Gal/ft^2/day	Based on measured consumption, applied to the bathrooms, kitchens
DHW Demand Schedule	MNECB-1999 Multifamily DHW	Assumption See Appendix C
Water Heater Availability Schedule	Always On	Known

Baseboard Convectors were added to each suite as the heating system, powered by electricity using a heating coefficient of performance (COP) of 1.0. Additionally, while the heating setpoints are not known, a setpoint of 22°C (72°F) was taken based on the House Simulation Protocols produced by the US National Renewable Energy Laboratory (Wilson et al., 2014). Table 3-4 list some of the key properties associated with the electric baseboards.

Table 3-4: Belmont model – electric baseboard properties

Property	Value	Notes
Typical Suite Capacity	Autosize	Calculated by DesignBuilder
Heating Fuel	Electricity	Known
Heating COP	1.0	Known
Heating Setpoint Temperature	22°C (72°F)	Assumption from NREL House Simulation Protocols
Heating Setback	None	Assumption from NREL House Simulation Protocols

The typical fireplace unit installed in The Belmont suites has a capacity of 8.8 kW (30,000 Btu/h) as discussed in Section 3.1.3. Based on the average living room area of the suites on the top 5 floors, this results in a space gain of 1.4 W/m^2 (15 W/ft^2) to the living rooms when the fireplaces are operating. As gas fireplaces tend to transmit most of their heat as radiation, and typically only achieve efficiencies of 50-70%, the radiant fraction of the gain was set to 0.6. The fraction lost set to 0.4 in order to account for the energy lost through the flue. Table 3-5 list some of the key properties associated with the natural gas fireplaces.

Table 3-5: Belmont model – natural gas fireplace properties

Property	Value	Notes
Fireplace living room equipment heat gain to space	1.4 W/m^2 (15 W/ft^2)	From mechanical drawings
Fireplace parasitic load	1.8 W/m^2 (0.17 W/ft^2)	From calibration, to simulate pilot light
Heating fuel	Natural Gas	Known
Radiant fraction	0.6	Assumption based on fireplace efficiency
Fraction lost	0.4	Assumption based on fireplace efficiency
Fireplace schedule	Belmont FP Schedule	Custom schedule constructed from monitoring data and calibrations

In each suite, there are two bathroom fans and a kitchen exhaust fan. Each bathroom fan is known to have a rated flowrate of 33 l/s (70 cfm), but this was modelled with a capacity of 24 l/s (50 cfm) at 125 Pa static pressure due to the fact that installed fans typically observe lower than rated airflow due to inadequate rated static pressures to overcome friction losses in ductwork (Canadian Mortgage and Housing Corporation, 2003). For the kitchen fans, the DesignBuilder default value of 100 l/s (211 cfm) at 125 Pa static pressure was retained as this is a reasonable capacity for a kitchen exhaust hood. Both the bathroom and kitchen fan schedules were based on the NREL House Simulation Protocols (Wilson et al., 2014). Table 3-6 summarizes the properties associated with the suite exhaust fans.

Table 3-6: Belmont model – suite exhaust fan properties

Property	Value	Notes
Bathroom Fan Flowrate	24 l/s (50 cfm)	From drawings, (Canadian Mortgage and Housing Corporation, 2003)
Kitchen Fan Flowrate	100 l/s (211 cfm)	DesignBuilder default
Exhaust Fan Static Pressure	125 Pa	DesignBuilder default
Fan Efficiency	45%	(Kohta Ueno, 2010b)
Bathroom Fan Schedule	7-8am daily	NREL House Simulation Protocols
Kitchen Fan Schedule	6-7pm daily	NREL House Simulation Protocols

3.3.4 Lighting, Gains and Occupancy

Internal gains from lighting, occupants, and miscellaneous equipment are crucial in determining the energy use of a building as they both use energy directly as well as offset the heating load which must be met by the thermal comfort system. The difficulty with these gains in the context of the Belmont specifically is that not very much information is available, and so one must rely on default values and generalized inputs from energy codes and modeling standards.

Lighting was broken down into three distinct areas: the parkade, the suites, and the corridors. Lighting intensities were taken from ASHRAE Standard 90.1-2007 using the building area method for multifamily buildings and parking garages, and the suites were calibrated to match consumption data (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2007). The lighting schedules were taken from MNECB-1999, which can be found along with all other schedules used in Appendix C (National Research Council of Canada, 1999).

For MURBs, DesignBuilder defaults to include stepped lighting controls to mimic occupant control with respect to daylighting in the suites. This means that for a given time step, the illuminance of a space due to daylight is calculated and compared to the target illuminance. The discrete steps involved with stepped lighting control simulate turning specific fixtures on or off in order to meet the illuminance target, as opposed to simply turning all of the zone lighting on. In DesignBuilder, the default target illuminance of 300 Lux was used for all spaces.

Table 3-7 displays some key inputs associated with the lighting properties in the three main areas of The Belmont model. Note that all other lighting parameters were left at the DesignBuilder default values, which are listed in Table 3-8.

Table 3-7: Belmont model – lighting properties, assumptions, and schedules

Property	Suites	Corridors	Parkade
Lighting Power Density	2.3 W/m^2 0.21 W/ft^2	6.5 W/m^2 0.6 W/ft^2	2.7 W/m^2 0.25 W/ft^2
Target Illuminance	300 Lux	300 Lux	300 Lux
Schedule	MNECB-1999 Multifamily Lighting	On	On
Lighting Controls	Stepped with 3 steps to mimic occupant behavior	N/A	N/A

Table 3-8: DesignBuilder default lighting properties used in the Belmont model

Property	Value
Luminaire Type	Surface Mount
Radiant Fraction	0.72
Visible Fraction	0.18
Convective Fraction	0.10

Miscellaneous electrical loads exist for the suites, corridors, and the parkade. The elevator electrical equipment load can be concentrated in the mechanical penthouse. Limited information is available with respect to these values, and so the MNECB-1999 value of 5 W/m^2 (0.4645 W/ft^2) was used in suites along with the corresponding MURB miscellaneous electrical load schedule, and calibrations were performed to achieve the final values (National Research Council of Canada, 1999). For the parkade and corridors, values were derived purely through calibration in order to achieve the considerable common miscellaneous loads. Table 3-9 lists some of the key properties associated with the equipment gains.

Table 3-9: Belmont model – miscellaneous equipment properties

Property	Value	Notes
Typical Suite Equipment Gain	5 W/m^2 (0.4645 W/ft^2)	From MNECB-1999
Typical Corridor Equipment Gain	4.75 W/m^2 (0.4413 W/ft^2)	From calibration, on 24/7
Parkade Equipment Gain	2 W/m^2 (0.1858 W/ft^2)	From calibration, on 24/7
Elevator Machine Room Equipment Gain	5 W/m^2 (2 W/ft^2)	(Sachs, 2005)
Equipment Fuel	Electricity	Known
Suite Equipment Schedule	MNECB-1999 Multifamily receptacle	From MNECB-1999
Radiant Fraction	0.2	DesignBuilder default

The Belmont, as previously discussed, is inhabited by individuals of at least 55 years or older. The majority of suites have 2 bedrooms, but are occupied by 1 or 2 individuals. The occupant density and metabolic considerations were based on DesignBuilder defaults for

MURBs, however they are roughly correct based on what limited information is available about the occupants. The occupant schedule was based on MNECB-1999 (National Research Council of Canada, 1999). Table 3-10 displays some key properties associated with the occupancy. Note that these properties only apply to the suites, as the corridors and parkade are considered to be unoccupied.

Table 3-10: Belmont model – occupancy properties

Property	Value	Notes
Typical Suite Occupant Density	0.02 People/m^2 (0.001858 People/ft^2)	DesignBuilder default
Occupancy Schedule	MNECB-1999 Multifamily occupancy	From MNECB-1999
Metabolic Activity Level	Typing	DesignBuilder default
Winter Clothing	1.0 clo	DesignBuilder default
Summer Clothing	0.5 clo	DesignBuilder default

3.3.5 Modelled Energy Consumption

Figure 3-20 displays the model monthly electricity consumption for 2013 as compared to the metered consumption from BC Hydro. Note that the largest discrepancy lies in October with the modelled consumption falling 11% below the metered consumption. All other months were within 7% of the target value.

Figure 3-21 displays the model monthly natural gas consumption for 2013 as compared to the metered data from Fortis BC. Unlike the electrical data, there are several months that fall outside the desired level of agreement, with August reaching 22% above the measured consumption. However, while this is a large percentage, the finite value of the difference is only 3,300 kWh which represents 0.7% of the annual natural gas percentage. Furthermore, the discrepancy is likely due to varying seasonal domestic hot water demands which are not captured in the model given the limited resolution of the DHW schedule.

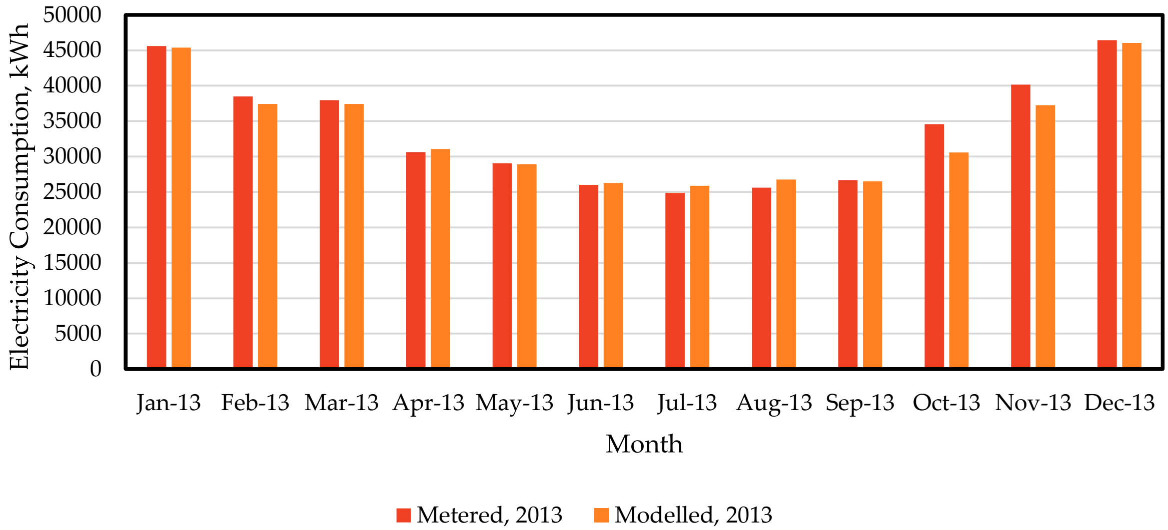


Figure 3-20: Belmont model – comparison of modelled and measured monthly electricity consumption for 2013

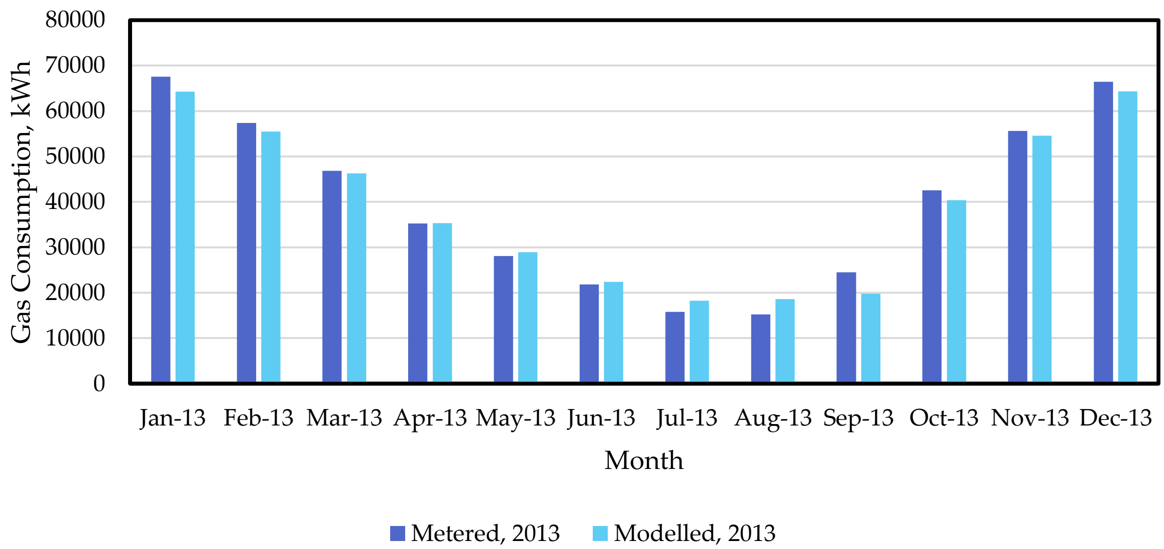


Figure 3-21: Belmont model – comparison of modelled and measured monthly natural gas consumption for 2013

On an annual basis, the end-use splits from both electrical and natural gas demands can be summarized as shown in Figure 3-22.

Figure 3-23 demonstrates the comparison between the third pass modelled end-use consumption and the end-use estimates from monitoring data developed in Section 3.2.4. All modelled end-uses are now within 3% of the estimated consumption, with the common lighting and equipment almost registering an exact match.

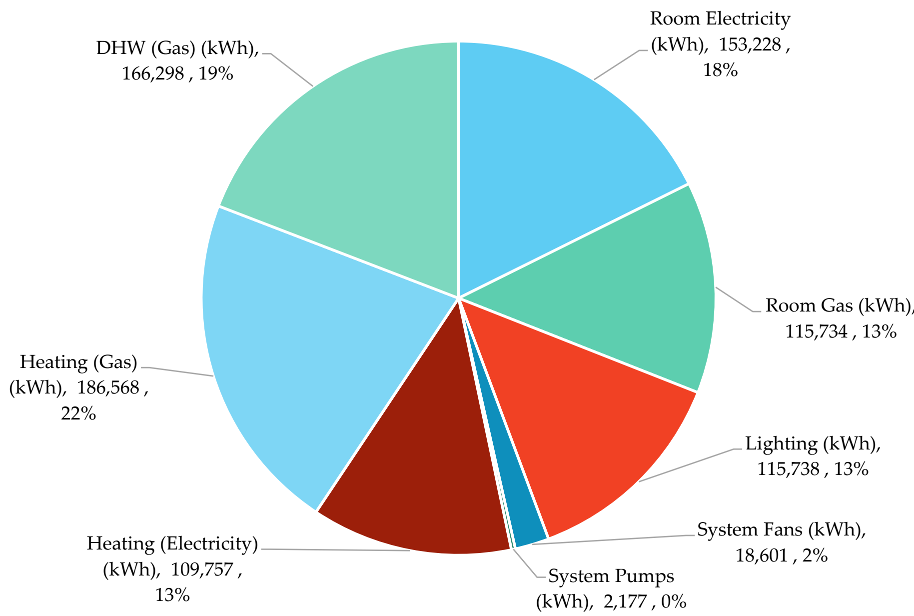


Figure 3-22: Belmont model – 2013 modelled annual end-use splits

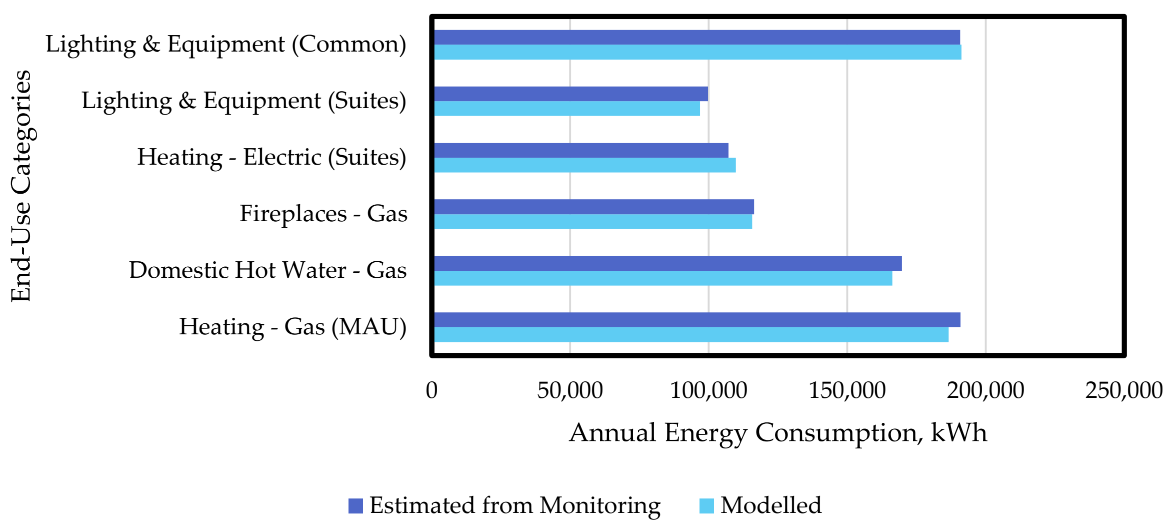


Figure 3-23: Belmont model – comparison of modelled and measured 2013 annual energy consumption by end-use

Figure 3-24 and Figure 3-25 display the monthly simulated end-use consumption throughout the 2013 meteorological year. On the electrical side, it is visible that the room electricity and lighting comprise the majority of the baseload and remain constant throughout the year, while all of the seasonal fluctuations are largely the result of electric baseboard space heating. With respect to the natural gas consumption, it is evident that the fireplace and MAU consumption vary significantly by season while the DHW consumption only varies slightly due to fluctuations in the water mains temperature.

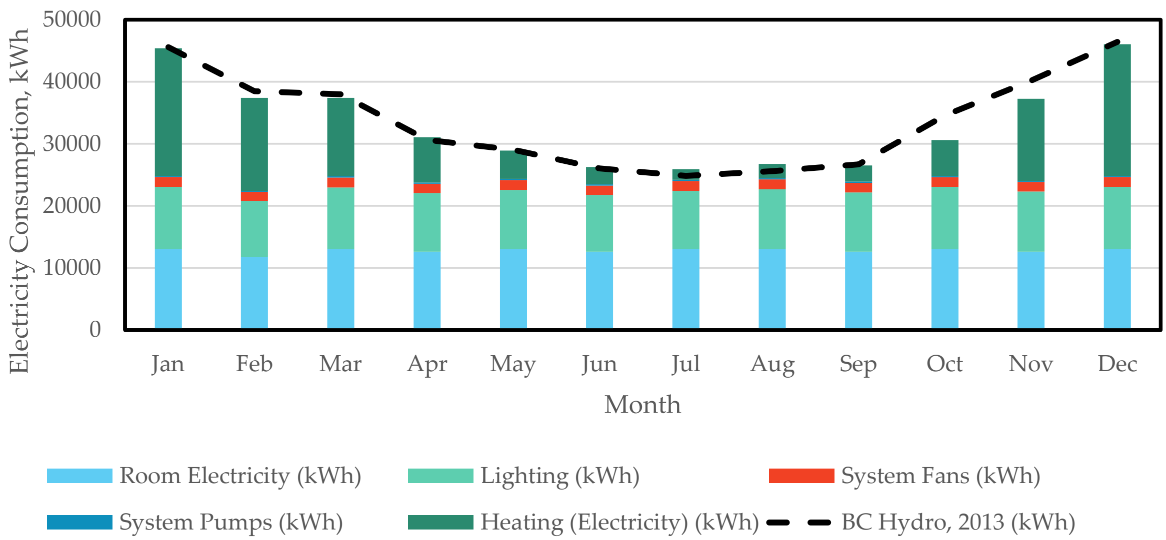


Figure 3-24: Belmont model – 2013 monthly electrical end-use consumption. The black dashed line represents the measured consumption from BC Hydro

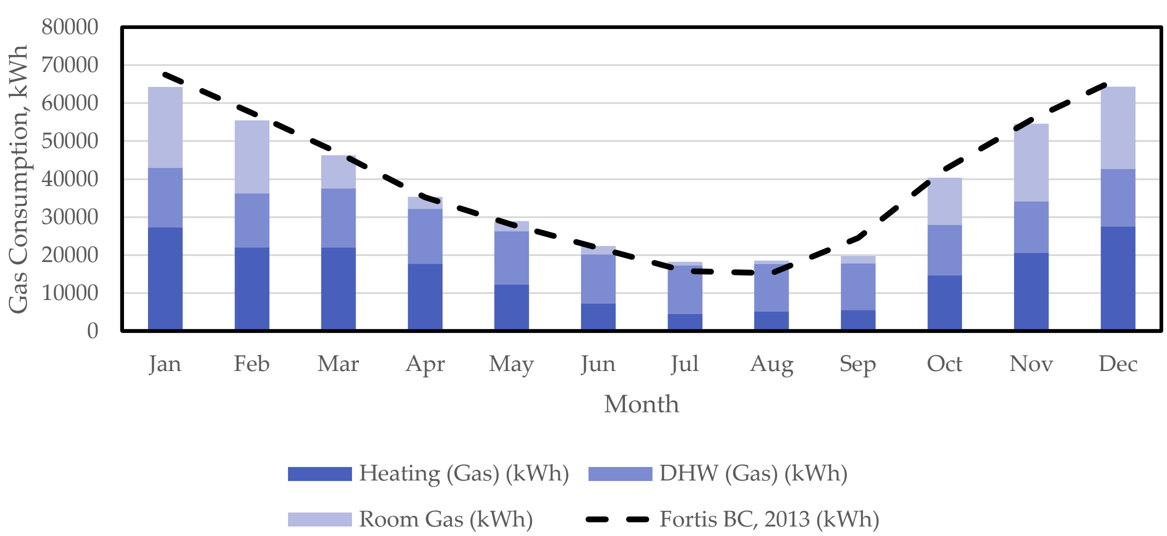


Figure 3-25: Belmont model – 2013 monthly natural gas end-use consumption. The black dashed line represents the measured consumption from Fortis BC

3.4 Modelled Energy Consumption Discussion

The developed model of The Belmont represents a comprehensive attempt to recreate the observed consumption as recorded by the utility companies and the monitoring equipment installed by RDH. However, it is impossible to completely recreate the consumption given the number of unknown variables and assumptions inherent in energy modelling. However, the results can be analyzed to ensure they fall within established statistically acceptable ranges for consumption and demand, and additional information can be learned from the model beyond the energy consumption such as the heat flow balance.

3.4.1 Error Analysis

Measurement and Verification (M&V) is a process through which buildings – either recently constructed or renovated – are analyzed to evaluate the effectiveness of energy conservation measures. Although there are numerous ways to perform this analysis, a common approach involves calibrating an energy model to measured consumption. While this is not an M&V project, the calibration procedures are still relevant. Numerous standards and guidelines have been produced for this type of analysis, including ASHRAE Guideline 14 *Measurement of Energy and Design Savings* and the International Performance Measurement and Verification Protocol (IPMVP) (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2002; IPMVP Comittee, 2002).

An important step in the calibration process, as outlined in M&V documents, involves ensuring that the variation between the measured and modelled energy consumption and demand fall within an acceptable range. Typically, this is assessed by calculating the Normalized Mean Bias Error (NMBE) and the Root Mean Square Error (RMSE), although the acceptable ranges vary between standards and depend on the resolution of the utility data. For monthly data, ASRHAE recommends a NMBE of ±5% and a RMSE of ±15% (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2002).

The NMBE and the RMSE coefficients are defined as follows for calibration based on monthly consumption data:

$$\mathrm{NMBE} = \frac{\sum_{i=1}^{n}(y_{pred,i} - y_{data,i})}{(n-p)/\ y_{data}} \qquad \text{Eq. 3-6}$$

$$\mathrm{RMSE} = \frac{\sqrt{\dfrac{\sum_{i=1}^{n}(y_{pred,i} - y_{data,i})^2}{(n-p)}}}{y_{data}} \qquad \text{Eq. 3-7}$$

where: $n =$ number of months, typically 12 for an annual analysis

$p =$ total number of regression parameters, typically 1

$i =$ month of current iteration

$y_{pred,i} =$ predicted monthly energy consumption, [kWh]

$y_{pred,i} =$ measured monthly energy consumption, [kWh]

$y_{data} =$ average measured monthly energy consumption, [kWh]

Table 3-11 displays the calculated error values based on utility data and the simulation results from the Belmont model. Note that all values fall within the previously discussed acceptable ranges.

Table 3-11: Belmont model – calibration error values based as calculated from ASHRAE Guideline 14-2002

Utility	NMBE	RMSE
Acceptable Range from ASRHAE Guideline 14-2002	±5%	±15%
Electricity	-2%	5%
Natural Gas	-2%	6%

3.4.2 Demand Analysis

Both ASHRAE Guideline 14-2002 and IPMVP require evaluation of both consumption and demand data for full calibration. The demand analysis can be performed on whatever scale is available, but typically monthly demand data is provided.

In the case of the Belmont, no demand data is available, which means that conventional demand assessments using normalized mean bias error and root mean square error cannot be performed. However, hourly electricity and monitoring data is available, which can be used to perform an alternative demand analysis.

Load-duration curves involve plotting demand data vs. time, with the demand sorted from highest to lowest. No demand data is available, but hourly energy consumption can instead be used if one assumes that the energy consumption occurred at a constant rate during the record period. For small time steps, this assumption may be invalid, but on a monthly or annual scale it can be useful.

3.4.2.1 Electrical Demand Analysis

Hourly electrical consumption data for the Belmont is available for 2013, sub-metered between the 37 suites and 2 common utilities. Together, there are 39 independent data sets of hourly consumption data for 2013, most of which are nearly complete. In some cases, a few hours are missing sporadically due to equipment error, while in the case of one of the common data sets half of January is not available. In terms of the whole building consumption, 99.16% of the hourly data is available, with 100% of the data available for the months of September through December.

Figure 3-26 displays the modelled and measured whole building electrical load-duration curves for 2013 from the Belmont simulation and BC Hydro respectively. Note that the majority of the missing data is from one of the common accounts during the first half of January, and therefore likely responsible for some of the missing peak consumption. However, it is still clear that the model slightly under predicts the peak consumption while slightly overestimating the baseload for a small portion of the year. Despite these discrepancies, a good agreement is visible for the majority of the year in question.

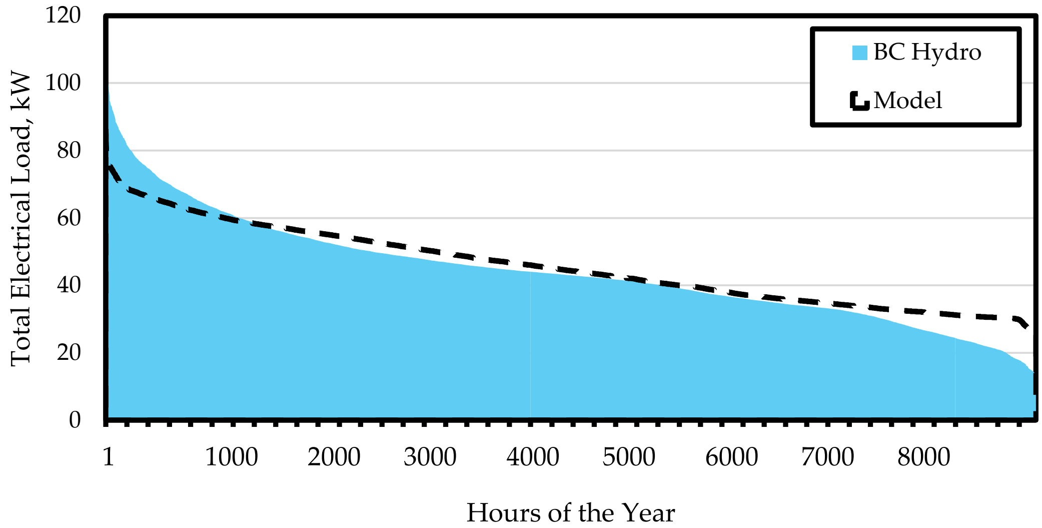


Figure 3-26: Whole building electricity load-duration curves for the measured and modelled data throughout the 2013 calendar year

Figure 3-27 displays the modelled and measured whole building electrical load-duration curves for September through December inclusive. For these 4 months, 100% of the hourly data was available, and so there should be less error associated with the analysis. Despite this, it is clear that the model is under predicting the baseload consistently throughout these months.

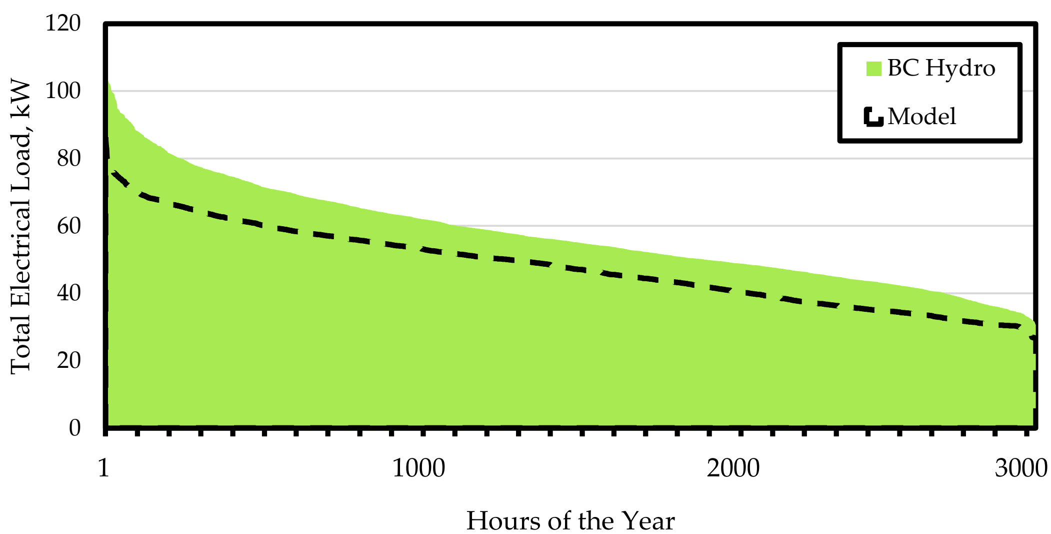


Figure 3-27: Whole building electricity load-duration curves for the measured and modelled data during September – December 2013

3.4.2.2 Natural Gas Demand Analysis

No hourly natural gas data is available, but hourly monitoring data is available for the domestic hot water boiler and the make-up air unit heating coil. Hourly temperature readings are available from the fireplaces, but given the uncertainty and number of assumptions associated with the fireplace analysis discussed in Section 3.2.3, it was determined to be impractical to extend the demand analysis to include this data.

The hourly DHW boiler natural gas flow meter readings were available for the 2013 calendar year, but due to equipment errors and battery failures, the only large string of consecutive complete data was from March to May. Combined with previously discussed assumptions, this provided hourly energy consumption data which could then be compared to the model.

The hourly MAU heating coil natural gas flow meter readings were also available, but contained similar periods of missing data to the DHW readings. As such, complete data was only available for the months of July through October 2013. These flow meter readings were converted to energy consumption values using the same assumptions as the DHW dataset, allowing for comparison to modelled values.

Figure 3-28 displays the load-duration curves for the measured and modelled DHW natural gas consumption during March through May 2013 – a period of 2208 hours. The stepwise nature of the modelled consumption can be attributed to the prescribed increments associated with the DHW demand schedule discussed in section 3.3.3. However, the overall trend is consistent between the two data sets.

Figure 3-29 displays the MAU modelled and metered load-duration curves for July through October 2013 – a period of 2952 hours. Unlike the previous curves, some major discrepancies are apparent, with the model over predicting during certain periods and under predicting in others. It is possible that the MAU heating coil is turned off in the summer months, which could account for the sudden drop in measured consumption as opposed to the steady decline observed in the modelled data, but such information was never gathered from the building owner.

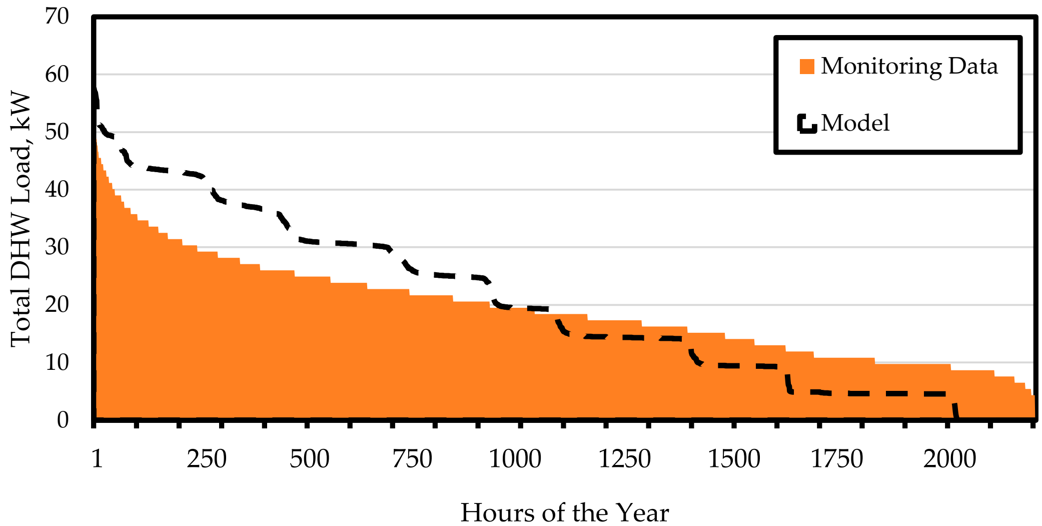


Figure 3-28: DHW load-duration curves for the measured and modelled data during March – May 2013

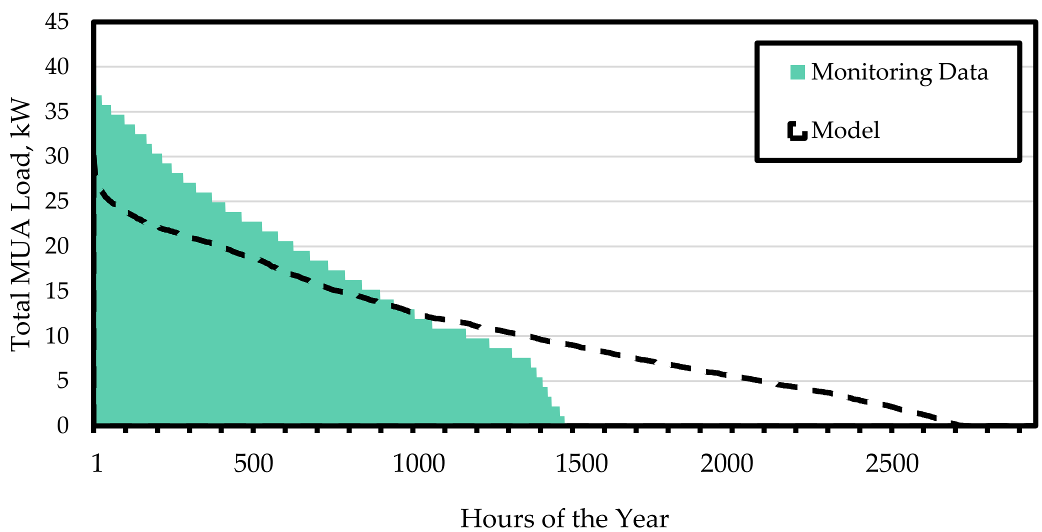


Figure 3-29: MAU load-duration curves for the measured and modelled data during July – October 2013

3.4.3 Lessons Learned from Model Calibration

The development of the calibrated energy model of the Belmont required several iterations which are described in detail in Appendix D. Throughout the calibration process, several input assumptions were identified as being incorrect in the initial model, which resulted in large inaccuracies in modelled energy consumption. These inaccuracies were only fully apparent when compared to measured consumption data. These specific inputs represent potential sources of error when developing models in the absence of consumption data, i.e., during the design of a new building.

The most significant source of error resulted from the incorrect selection of the supply air setpoint temperature for the make up air unit in the pressurized corridor ventilation system. The default heating setpoint schedule in DesignBuilder results in a supply air temperature of 35°C. While this is an appropriate temperature for a furnace providing space heating, it far exceeds the typical supply air temperature for a DOAS of 18°C.

Another major source of error resulted from the use of the airtightness test result input option for air leakage within DesignBuilder. The simple equation used within the software suite is derived from British Standard BS EN12831, and results in an under prediction of air leakage (European committee for Standardization, 2003). Furthermore, this method does not account for additional infiltration due to the opening of operable windows by occupants during the heating season as natural ventilation controls are based on logical temperature setpoints.

Based on default DesignBuidler templates and modelling standard assumptions for MURBs and apartment buildings, minimal miscellaneous electrical load is attributed to common spaces. However, the measured data indicated that a substantial amount of the whole building energy consumption was associated with the common electricity meter.

The default fan and pump pressure ratings are 0.6 kPa and 20 kPa respectively within DesignBuilder. While these values are appropriate in certain situations, in many cases the fan pressure is too high and the pump pressure is too low.

Chapter 4 : Mechanical System Modelling Results

To evaluate the relative performance of residential mechanical systems in high-rise MURBs, the following methodology was followed: a set of reference models were developed, a test set of mechanical systems was selected for each location, and energy simulations combined with post processing energy analyses were conducted in order to determine the energy consumption, GHG emissions, and operating costs of each system for each reference model. This chapter will cover all aforementioned steps of the modelling process and present the simulation results. The discussion of these results can be found in Chapter 5. Figure 4-1 displays the methodology steps visually.

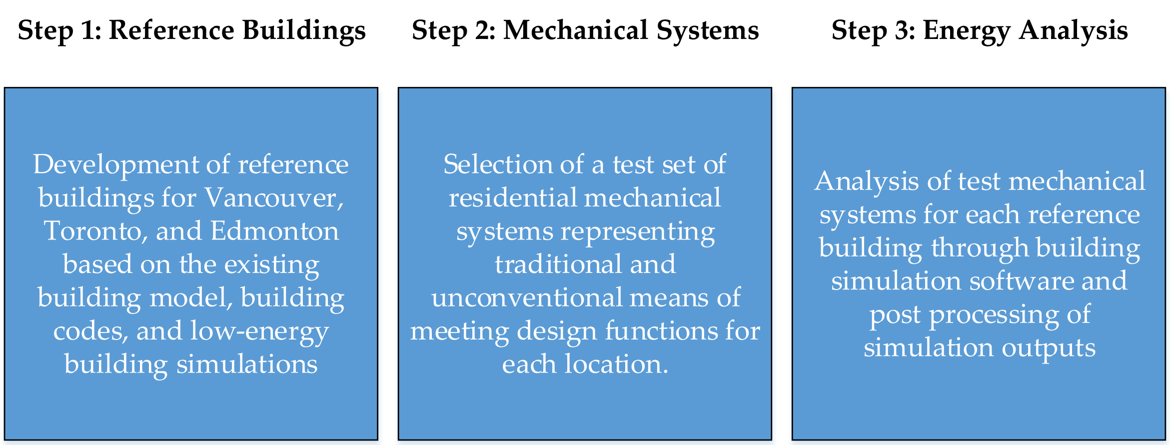


Figure 4-1: Methodology for residential mechanical system modelling

4.1 Development of Reference Models

The existing building model discussed in Chapter 3 serves as a calibrated baseline which can be verified with real world results. However, many of the model inputs are fairly unique to that particular building, and are therefore not representative of typical new construction practices. It is therefore necessary to make the model more generic with the help of building codes and standards, while still maintaining calibrated inputs not directly informed by code such as the occupancy level, domestic hot water demand, effective modelled infiltration, and internal equipment loads. As three different Canadian locations are being considered, the intent is to create new reference buildings for each location – Vancouver, Toronto, and Edmonton. Changes from the existing building model can be classified into three categories: general modifications, model simplifications, and building enclosure modifications.

4.1.1 General Modifications

The Belmont, beyond the specifics of the building envelope and mechanical systems, has two building characteristics which are atypical of current practices. Specifically, these include the in-suite fireplaces, and the enclosed balconies.

In-suite natural gas fireplaces were popular for a time, but are no longer typical in Vancouver or elsewhere within high-rise MURBs. Fireplaces provide ambiance, but are very inefficient and don't effectively heat interior space. In order to fuel fireplaces, every suite must have natural gas plumbed to the unit with separate sub-metering for billing purposes – a significant incremental capital cost if not already part of the building design. Additionally, fireplaces require direct venting out an exterior wall, which results in additional building enclosure penetrations which must be detailed to ensure continuity of critical barriers.

Enclosed balconies can be found in modern high-rise MURBs, but are not as common as having either no balconies or traditional exposed balconies. Enclosed balconies introduce semi-conditioned space into each unit, which requires additional design work with respect to space conditioning and insulation levels. The Belmont has enclosed balconies as it was a design choice made during the rehabilitation project conducted by RDH.

In order to address both of these features in the baseline models, in-suite fireplaces were removed from all three locations, and the enclosed balconies were reallocated into conditioned interior space.

4.1.2 Model Simplifications

While quite detailed, the model of The Belmont developed in Chapter 3 is very time intensive both from a data entry standpoint as well as a simulation standpoint. The large number of repetitive spaces offers opportunities to simplify the model while retaining simulation accuracy within acceptable levels.

The Belmont model contains all 37 suites modelled distinctly, complete with all interior partition walls, resulting in over 250 interior zones for the suites alone. Many of these zones have identical input values, although they experience slightly different simulated loads due to wind exposure and vertical heat flows.

The large number of zones results in significant amounts of time being required both for data entry and simulation. Some input variables cannot be applied in a general fashion, and so if a change of input is desired, it must be changed for every zone manually. Additionally, with many zones and fenestrations, daylighting calculations and radiant heat balances take much longer to complete.

In the interest of modelling many systems within a practical amount of time, the model was simplified geometrically without altering the simulation parameters. Rather than modelling all suites and rooms, only whole suites will be modelled, and only for 5 floors: floor 1, 2, 7, 12, and 13. Floor 7 represents typical floors 3 through 11 with a zone multiplier of 9, while all other typical floors are replaced with adiabatic blocks as shown in Figure 4-2.

As many loads are applied on a per unit floor area basis, some inputs were recalculated as without internal partition walls, the conditioned floor area is slightly larger. In this fashion, the equivalent input energy was retained, and thus the impact of the model simplifications could be analyzed independently.

All end uses fell within approximately ±1% between the Belmont model with the general modifications from Section 4.1.1 and the simplified model. Monthly total energy consumption fell within approximately ±3%, and total annual energy consumption achieved an agreement of 0.02%. The largest outliers were the fan energy, and the lighting energy. The fan energy discrepancy likely is the result of the previous three in-suite exhaust fans being consolidated into a single suite exhaust fan, which in turn had to be resized to account for the nonlinear nature of fan energy consumption as dictated by fan laws. The lighting energy discrepancy likely results from additional daylighting of spaces previously blocked from daylight by interior partition walls. Additionally, while most end-uses scaled properly with zone multiplier, the domestic hot water did not and needed to be corrected in post-processing data analyses. Figure 4-3 displays the monthly comparison between detailed and simplified model geometries.

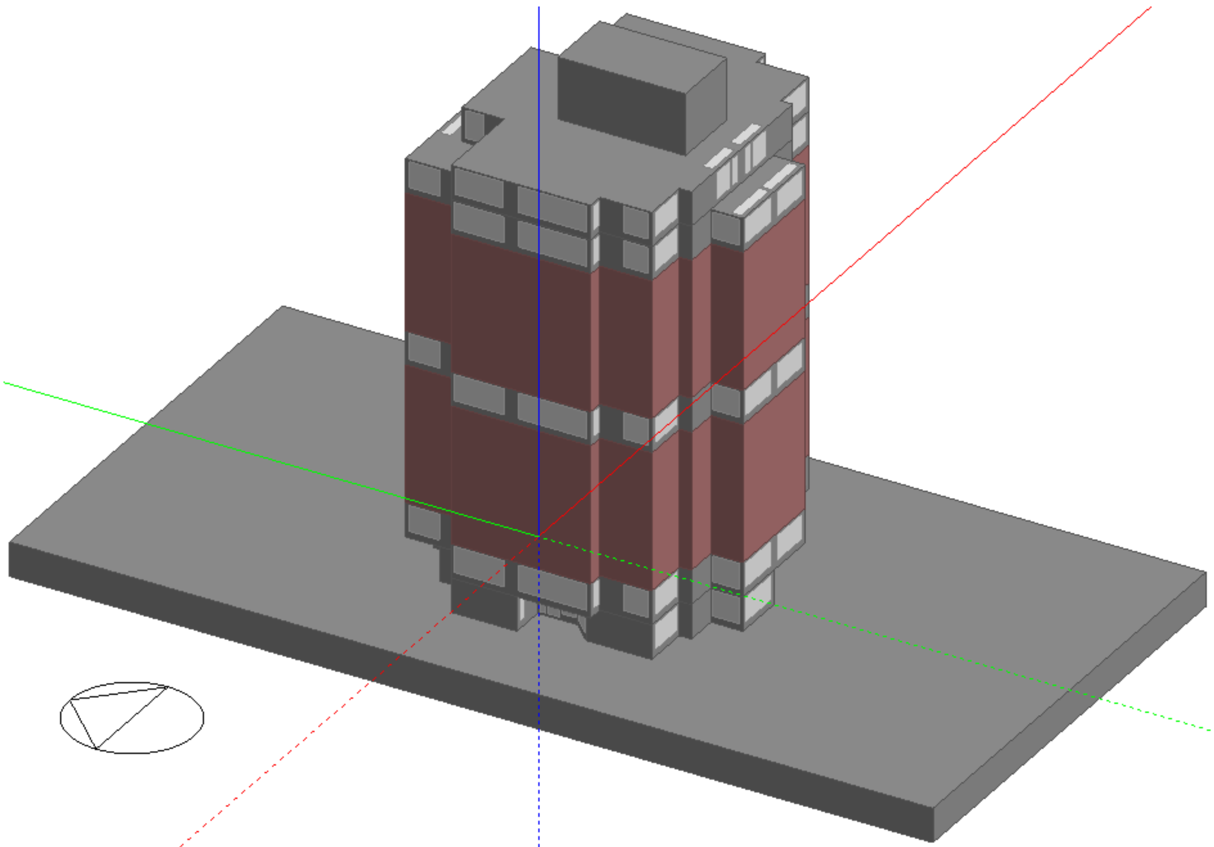


Figure 4-2: The Belmont model simplified by using a typical floor and zone multipliers. Red blocks are adiabatic, while grey blocks represent modelled space

Simplifying the model geometry inherently imposes additional inaccuracies, particularly with respect to the use of adiabatic blocks. However, the added variability of ±1% in annual end-use consumption is more than justified by the 90% decrease in simulation time and ease of data entry gained.

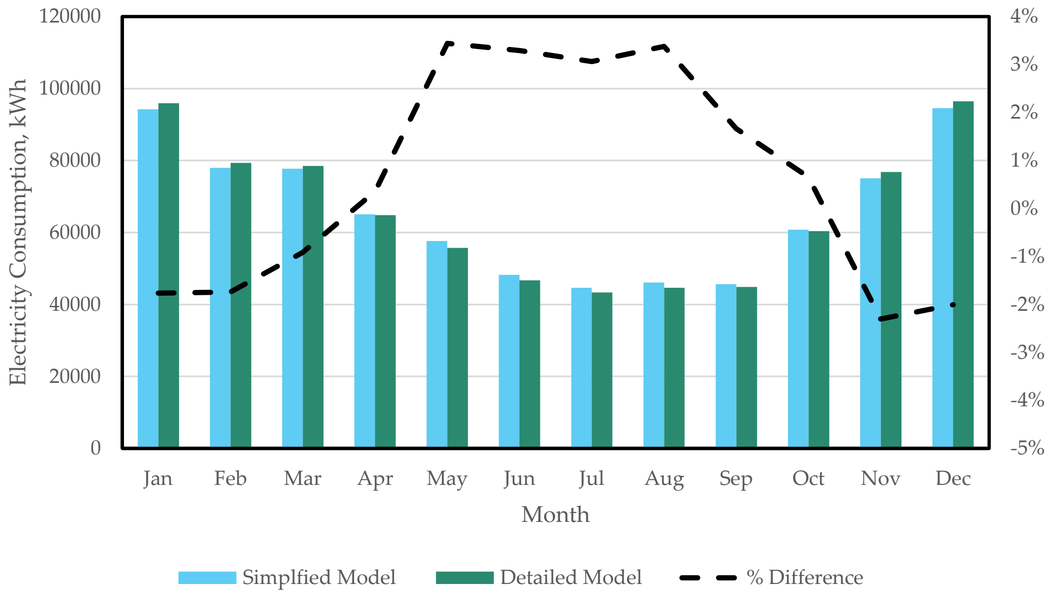


Figure 4-3: Comparison of simplified and detailed model geometries, both incorporating the general modifications discussed in Section 4.1.1

4.1.3 Building Enclosure Modifications

Canadian buildings are all designed in accordance with codes and bylaws which have jurisdiction in the given area. There is a 2015 National Building Code (NBC), but it is a model code that informs the individual provincial building codes. In the context of Vancouver, Toronto, and Edmonton, the applicable building codes at the time of this research are the 2012 British Columbia Building Code (BCBC), the 2012 Ontario Building Code (OBC), and the 2014 Alberta Building Code (ABC). In addition, buildings constructed in Vancouver must also comply with the 2014 Vancouver Building Bylaw (VBBL). All of these codes have a similar hierarchy of divisions and parts which selectively describe aspects of construction, and apply to different building types. For the building enclosure of high-rise MURBs, all codes include sections which address environmental separations and energy consumption. Note that low-rise residential buildings typically fall under Part 9 of the codes, but high-rise MURBs are addressed throughout as they more closely resemble commercial construction.

Typically, the discussion of environmental separation does not provide specific insulation levels or window heat transfer characteristics, but instead the energy section defers to additional energy codes and standards. The 2012 BCBC Division B Part 10 and the 2014 VBBL require compliance with either the 2011 National Energy Code for Buildings (NECB) or ASHRAE Standard 90.1-2010. The 2012 OBC Division B Part 12 requires designs to exceed ASHRAE Standard 90.1-2010 by 5%, or meet the same standard as modified by MMAH Supplementary Standard SB-10 Division 3 Chapter 2. The 2014 ABC requires conformance with the 2011 NECB.

Table 4-1 lists the climate information and the applicable code or standard having jurisdiction in Vancouver, Toronto, and Edmonton. Note that the climate zones are defined in ASHRAE Standard 90.1-2010 based on Canadian Weather for Energy Calculation (CWEC) historical heating degree days (US Department of Energy, 2015). In the case of Vancouver, both ASHRAE Standard 90.1 and NECB are valid options for compliance, but the former was selected as the values appear to be less demanding.

Table 4-1: Climate data and applicable energy codes and standards in Vancouver, Toronto, and Edmonton

Parameter	Vancouver	Toronto	Edmonton
ASHRAE Climate Zone	5C (Marine)	6A (Moist)	7
CWEC Historical Annual Heating Degree Days (HDDs)	3020	4089	5583
Applicable Energy Codes and Standards	**ASHRAE Standard 90.1-2010**, or NECB 2011	ASHRAE Standard 90.1-2010 with MMAH SB-10	NECB 2011

All of the codes allow for a building to demonstrate compliance by one of several paths. The prescriptive path lists enclosure and equipment requirements and limits the window-to-wall ratio to 40%. In many cases, the prescriptive path does not provide sufficient flexibility for many designers and one of the alternate compliance paths is chosen. Alternate paths are intended to allow building designs that consume the same amount of energy as a nominally compliant prescriptive path building but allow trade-offs between different parts of the building enclosure and mechanical and lighting equipment. This allows lower performance enclosure elements to be used, or higher window areas, by deploying more efficient mechanical systems, better controls, etc. The trade-off analysis is generally conducted using an hourly energy simulation.

Table 4-2 and Table 4-3 list the prescriptive path building enclosure overall heat transfer coefficient and assembly insulation levels respectively based on code requirements for the three cities in question. Note that the overall heat transfer coefficient is commonly referred to as the U-value in imperial units, or the USI-value in metric units. Similarly, the assembly insulation level is often discussed in terms of the R-value in imperial units, and the RSI-value in metric units, with these values being equal to the inverse of the overall heat transfer coefficients. Additionally, a conductance or C-value has equivalent units to a U-value.

Table 4-2: Opaque assembly overall heat transfer coefficients for Vancouver, Toronto, and Edmonton based on prescriptive path code compliance in W/m²·K (BTU/hr·ft²·°F)

Parameter	Vancouver	Toronto	Edmonton
Maximum Above Grade Wall U-value	USI-0.45 (U-0.08) For mass walls	USI-0.34 (U-0.06) For mass walls	USI-0.21 (U-0.037)
Maximum Below Grade Wall U-value	CSI-0.67 (C-0.119)	CSI-0.52 (C-0.092)	CSI-0.284 (C-0.05)
Maximum Roof U-value	USI-0.27 (U-0.048) For insulation above deck	USI-0.18 (U-0.032) For insulation above deck	USI-0.162 (U-0.029)
Maximum Floor U-value	USI-0.36 (U-0.064) For mass floors	USI-0.29 (U-0.051) For mass floors	USI-0.162 (U-0.029)

Table 4-3: Opaque assembly insulation requirements for Vancouver, Toronto, and Edmonton based on prescriptive path code compliance in m²·K/W (hr·ft²·°F/BTU)

Parameter	Vancouver	Toronto	Edmonton
Minimum Above Grade Wall R-value	RSI-2.2 (R-12.5) For mass walls	RSI-2.9 (R-16.7) For mass walls	RSI-4.8 (R-27)
Minimum Below Grade Wall R-value	RSI-1.5 (R-8.4)	RSI-1.9 (R-10.9)	RSI-3.5 (R-20)

Parameter	Vancouver	Toronto	Edmonton
Minimum Roof R-value	RSI-3.7 (R-20.8) For insulation above deck	RSI-5.6 (R-31.2) For insulation above deck	RSI-6.2 (R-34.5)
Minimum Floor R-value	RSI-2.8 (R-15.6) For mass floors	RSI-3.4 (R-19.6) For mass floors	RSI-6.2 (R-34.5)

Table 4-4 displays the performance requirements for fenestrations in the three locations in question based on code requirements. Note that the value of NR for the Edmonton SHGC means that there is no code requirement.

Table 4-4: Prescriptive path code fenestration performance requirements for Vancouver, Toronto, and Edmonton

Fenestration Parameter	Vancouver	Toronto	Edmonton
Maximum U-value	USI-2.55 (U-0.45) For metal framing (curtainwall)	USI-1.99 (U-0.35) For metal framing (curtainwall)	USI-2.2 (U-0.39)
Maximum SHGC	0.4	0.4	NR

NECB 2011 and ASHRAE 90.1-2010 require designers to account for thermal bridging, but only with respect to certain aspects of the building enclosure. NECB requires one to account for closely spaced repetitive structural members such as studs, but does not require any accommodation for thermal bridging of floor slabs, columns, or spandrels. ASHRAE 90.1 accounts for thermal bridging by providing assembly effective maximum heat transfer coefficients while also providing the minimal nominal insulation levels. Additionally, ASHRAE 90.1 distinguishes between different types of construction within each assembly such as mass and steel framed walls, whereas NECB simply provides a single value for each type of assembly. All of these factors tend to result in ASHRAE maximum heat transfer values falling higher than NECB values as stated, but the effective insulation levels would likely be equivalent in practice. The Ontario Building Code does require floor slab projections and balconies to be considered if they exceed 2% of the enclosure area.

One key requirement, not stated in Table 4-4, is that the window to wall ratio (WWR) or fenestration and door area to gross wall area (FDWR) is limited in the prescriptive path. ASHRAE-90.1-2010 requires a maximum WWR of 40% for all buildings, which in this context applies to Toronto and Vancouver. NECB 2011 applies equation 4-1 to determine this ratio, which results in a maximum FDWR of 29% in Edmonton assuming an annual average of 5583 HDDs (National Research Council Canada, 2011).

$$\text{Max FDWR } = 0.4 \text{ for HDD} < 4000 \qquad \text{Eq. 4-1}$$

$$\text{Max FDWR } = \frac{2000 - 0.2 \cdot \text{HDD}}{3000} \text{for } 4000 \ \leq \text{HDD} \leq 7000$$

$$\text{FDWR } = 0.2 \text{ for HDD} > 7000$$

Both NECB 2011 and ASHRAE 90.1-2010 allow a trade-off procedure to supplement the prescriptive method of meeting the energy requirements. The intent is to allow designers to vary from the limiting requirements for different aspects of the building enclosure as long as the building enclosure energy performance is at least equal to that of a code based building. The most common application of this procedure in Toronto and Vancouver is to increase the WWR far above the 40% maximum by improving the enclosure, mechanical, or lighting system performance such that energy consumption is unaffected. NECB allows for both a simple trade-off procedure involving a UA product balance across above grade assemblies, as well as a detailed procedure involving energy modelling. ASHRAE Standard 90.1 however only allows verification through energy modelling. In the context of this project, increasing the WWR is necessary to make the buildings more representative of typical construction. In order to do this, however, the trade-off procedures must be followed for the applicable code.

For Vancouver and Toronto, ASHRAE Standard 90.1-2010 Appendix C describes the steps associated with the trade-off path. There are specific modeling assumptions required, but the general methodology is that the proposed building enclosure can fail to meet one or more of the stated requirements as long as the HVAC and lighting energy consumption in exterior spaces and surfaces is less than or equal to a similar building which does meet all requirements. Both buildings must have the same assumptions other than the building enclosure, and must also use specific prescribed HVAC systems, setpoints, Lighting Power Densities (LPDs) and Miscellaneous Electrical Loads (MELs). Table 4-5 displays the code-based reference model enclosure properties for Vancouver and Toronto as determined through this path.

For Edmonton, the NECB 2011 simple trade-off path can be followed to adjust the enclosure to meet code while providing more than the minimum WWR of 29%. Equation 4-2 was applied based on the requirements discussed in Table 4-2 through Table 4-4, and the prescriptive path code-based reference model enclosure inputs for Edmonton can be seen in Table 4-5 (National Research Council Canada, 2011).

$$\sum_{i=1}^{n} \mathrm{U}_{iP} A_{iP} \leq \sum_{i=1}^{n} \mathrm{U}_{iR} A_{iR} \qquad \text{Eq. 4-2}$$

where: $n =$ total number of above grade assemblies

U_{iP} = USI value of assembly i of the proposed building, $[\mathrm{W}/(\mathrm{m}^2 \cdot \mathrm{K})]$

$A_{iP} =$ area of assembly i of the proposed building, $[\mathrm{m}^2]$

U_{iR} = USI value of assembly i of the reference building, $[\mathrm{W}/(\mathrm{m}^2 \cdot \mathrm{K})]$

A_{iR} = area of assembly i of the reference building, $[\mathrm{m}^2]$

Table 4-5: Building enclosure parameters for code-based reference models in Vancouver, Toronto, and Edmonton based on code compliance through the applicable trade-off paths

Parameter	Vancouver	Toronto	Edmonton
Above Grade Wall R-value	RSI-2.2 (R-12.5)	**RSI-4.0 (R-22.7)**	**RSI-5.3 (R-30)**
Below Grade Wall R-value	RSI-1.5 (R-8.4)	RSI-1.9 (R-10.9)	RSI-3.5 (R-20)
Roof R-value	RSI-3.7 (R-20.8)	RSI-5.6 (R-31.2)	RSI-6.2 (R-34.5)
Floor R-value	RSI-2.8 (R-15.6)	RSI-3.4 (R-19.6)	RSI-6.2 (R-34.5)
Window Conductance	**USI-1.53 (U-0.27)**	**USI-1.42 (U-0.25)**	**USI-1.53 (U-0.27)**
Window SHGC	0.4	0.4	0.45
Window to Wall Ratio	**65%**	**65%**	**45%**

The values in Table 4-5 achieve compliance with the applicable building codes at the time of publication, and therefore represent the minimum possible building enclosure which can currently be constructed. Although the proposed trade-offs are technically valid, the required opaque wall R-value (R-16.7 in Toronto) and window U-value (0.25 in Toronto) are well beyond common practice: for example, an aluminum-framed window system capable of 65% WWR would need to be triple-glazed and high-performance to achieve U-0.25.

While some developers may choose to simply comply with the code, any project with the intent of constructing a low-energy building would likely implement a much more robust building enclosure. A low-energy building today is likely to approximate the code-compliant building of the future. In order to accommodate buildings which exceed the code, two reference models for each city are proposed: a code compliant model, and a low-energy model. Defining the low-energy model building enclosure parameters is difficult and speculative and hence beyond the scope of this study. To provide a well-researched set of low-energy building enclosure properties a CMHC study evaluating ECMs for low-energy MURBs across Canada was used (Canadian Mortgage and Housing Corporation, 2015). Table 4-6 displays the building enclosure parameters for the low-energy reference models. These are quite aggressive targets, currently at the limit of either technical or economic viability.

Table 4-6: Building enclosure parameters for low-energy reference models in Vancouver, Toronto, and Edmonton (Canadian Mortgage and Housing Corporation, 2015)

Parameter	Vancouver	Toronto	Edmonton
Above Grade Wall R-value	RSI-4.5 (R-25.5)	RSI-5.4 (R-30.6)	RSI-5.4 (R-30.6)
Roof R-value	RSI-5.6 (R-31.7)	RSI-7.4 (R-42)	RSI-9.1 (R-51.6)
Floor R-value	RSI-4.6 (R-26)	RSI-4.6 (R-26)	RSI-4.6 (R-26)
Window Conductance	USI-0.91 (U-0.16)	USI-0.68 (U-0.12)	USI-0.68 (U-0.12)
Window SHGC	0.55	0.39	0.39
Window to Wall Ratio	35%	30%	30%

4.1.4 Summary of Model Inputs Retained from Existing Building Model

With the modifications from the existing building model established, the remaining inputs largely remain unaffected. This includes the suite heating and cooling setpoints, lighting power densities, miscellaneous equipment loads, enclosure air leakage, and domestic hot water demand.

The logic behind retaining certain input values in place of typical values from energy standards or modelling guides is twofold: some values are not explicitly stated in code, and some values stated in code are outdated and not necessarily applicable or representative of modern construction. The values from the Belmont case study building – while taken from a specific building – are reflective of real conditions, and while some values are the result of calibrations, others are the same values stated in code or modelling guidelines. Table 4-7 displays the model inputs retained from the existing building calibration in Chapter 3.

Table 4-7: Building model inputs retained from the existing building model

Parameter	Value	Source
Suite MELs (W/ft^2)	0.38	Calibration
Suite LPD (W/ft^2)	0.20	Calibration
Suite DHW Demand (Gal/Apt/Day)	52	Calibration
Corridor MELs (W/ft^2)	0.44	Calibration
Corridor LPD (W/ft^2)	0.6	ASHRAE 90.1-2010
Parkade MELs (W/ft^2)	0.18	Calibration
Parkade LPD (W/ft^2)	0.25	ASHRAE 90.1-2010
Elevator Room MELs (W/ft^2)	2	(Sachs, 2005)
Suite Heating Setpoint (°F)	72	Calibration
Suite Heating Setback (°F)	None	(Wilson et al., 2014)
Suite Cooling Setpoint (°F)	76	(Wilson et al., 2014)
Suite Cooling Setback (°F)	None	(Wilson et al., 2014)

Parameter	Value	Source
Ventilation Heating SP (°F)	64.4	Calibration
Enclosure Airtightness (ACH @ 50 Pa)	2.8	Calibration

The maximum suite LPD for multifamily buildings stated in ASHRAE 90.1-2010 is 0.6 W/ft^2, but no recommended value is actually provided – an omission which may be addressed in addendums to the standard (Scott, 2016). Furthermore, this value is a maximum and is only achievable if low efficiency incandescent lighting is primarily used – an unlikely scenario for modern construction. The MELs recommended for use in residential spaces by ASHRAE 90.1-2010 is 0.25 W/ft^2, but this is unrealistically low for modern buildings. As such, the suite LPDs and MELs were retained from the calibration exercise.

The corridor and parking garage LPDs of 0.6 W/ft^2 and 0.25 W/ft^2 respectively were retained from ASHRAE 90.1-2010, but the standard MELs of 0.25 W/ft^2 and 0 W/ft^2 respectively were found to be too low based on the common energy use of The Belmont. As such, the calibrated values are taken to be more useful, as this comprises a rather large percentage of the annual energy consumption.

The domestic hot water demand for residential dwelling units is said to be 40 US Gal/apartment/day in the ASHRAE 90.1 User's Manual, which is more or less in line with the demand calculated from consumption data of 53 US Gal/apartment/day. While the input could have been changed to reflect the standard, studies have shown that the domestic hot water demand varies far more than energy consumption between apartment buildings, and as such identifying a typical consumption rate would be difficult if not impossible (Charbonneau, 2011).

Building enclosure air leakage is a very important input, but is very difficult to estimate accurately given that the simulation cannot account for dynamically varying wind loads or occupant operation of operable windows. The value of 3.5 ACH at 50 Pa was entered during the calibration of The Belmont, which was then altered to 2.8 ACH at 50 Pa during the model simplification process. On an ongoing basis, this equates to approximately 0.26 ACH of air leakage simulated in the model based on the BS-EN-12831 methods used within DesignBuilder

(European committee for Standardization, 2003). This value is not particularly high or low, and falls within the range used in other studies such as the CMHC study of low-energy MURBs which assumed 0.1 ACH for a high performance enclosure and 0.4 ACH for a code-based enclosure (Canadian Mortgage and Housing Corporation, 2015). Regardless of the value selected, it is very difficult to ensure this input is correct, and so the emphasis is generally to select an input with the correct order of magnitude, and accept that there will inherently be a large margin of error associated with it.

4.1.5 Reference Model Load Profiles

The energy demands for each reference building are split between ventilation, heating, cooling, domestic hot water, lighting, and miscellaneous electrical loads. The space conditioning loads represent the amount of energy which must be added or removed from the space in order to maintain the temperature setpoints. The ventilation energy consumption consists of the energy required to move the volume of air specified in ASHRAE Standard 62.1 at a static pressure of 1” with no losses, along with the energy which must be added or removed from the outdoor air stream in order to meet the supply air setpoints. The domestic hot water demand similarly consists of the amount of energy required to heat the volume of water demanded to the setpoint temperature, and the pumping energy associated with moving this water against a frictional and heat pressure loss of 25 ft H_2O. The lighting and miscellaneous equipment demands are a function of the previously established inputs. Figure 4-4 displays the energy demand by category for each reference building.

The energy demand for each reference model can be normalized by floor area, as summarized in Table 4-8. Note that these are not energy usage intensities, as EUIs are a function of system energy consumption rather than space loads. The energy consumption indicated by these energy demand intensity values of the low-energy model is higher than actual measured energy use of numerous low-energy MURBs: this is expected as the mechanical and lighting systems, controls, and appliances have all been kept at code-minimum or industry practice.

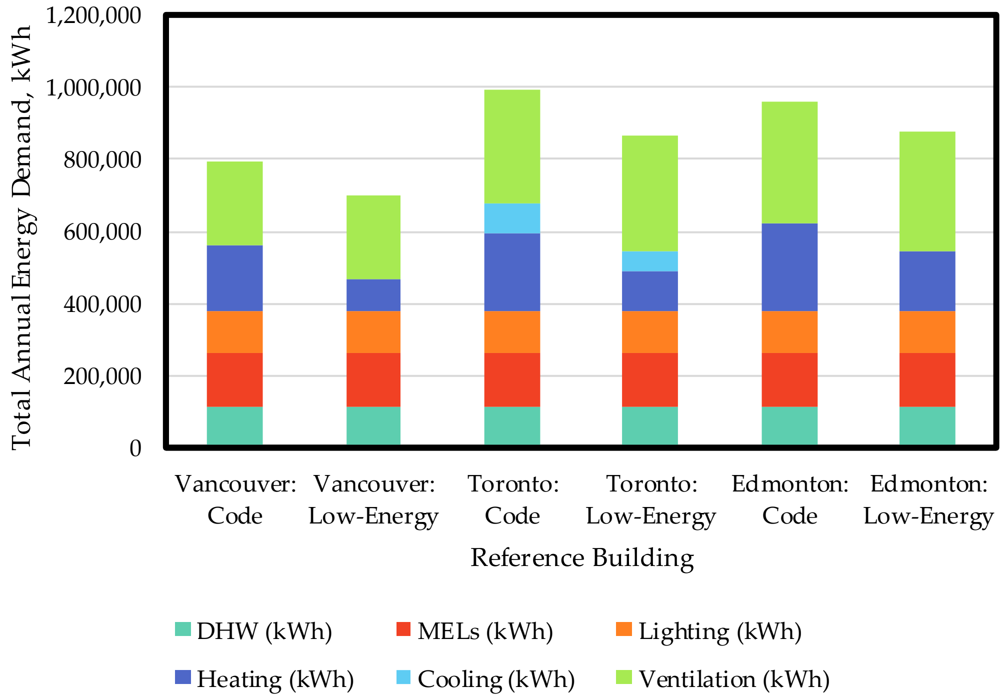


Figure 4-4: Total annual energy demand by end-use category for code-based and low=energy reference models in Vancouver, Toronto, and Edmonton

Table 4-8: Energy demand intensities for code-based and low-energy reference models in Vancouver, Toronto, and Edmonton based on a standard floor area of 5260 m²

Parameter	Vancouver	Toronto	Edmonton
Code-based Reference Models			
Total Demand Intensity (kWh/m²)	137	176	166
Heating Demand Intensity (kWh/m²)	37	37	48
Cooling Demand Intensity (kWh/m²)	-	22	-
Low-Energy Reference Models			
Total Demand Intensity (kWh/m²)	119	148	150
Heating Demand Intensity (kWh/m²)	19	17	33
Cooling Demand Intensity (kWh/m²)	-	14	-

4.2 Test Set of Mechanical Systems

With the energy demands established for each reference building, a test set of mechanical systems can be applied to the loads in question in order to establish annual energy consumption at a system level. The mechanical systems in question are categorized as discussed in Chapter 2, with approximately 50 independent systems to be considered for each location. Note that these systems are not all the same across location as each city has varying functional requirements.

The list of mechanical systems considered for each location, along with the specific system parameters and assumptions can be found in Appendix E.

Note that in general, equipment performance characteristics are based on the best commonly available equipment at the time of this analysis. This commitment to high performance is in accordance with the overarching goal of determining the mechanical systems best suited for use in low-energy buildings. Table 4-9 displays general equipment efficiencies and COPs used for this analysis, while other performance related criteria such as part load curves can be found in Appendix E for the particular system in question.

Table 4-9: Building model input efficiencies and COPs for various pieces of equipment based on the best performance commonly available

Equipment	Performance	Source
Electric Resistance Heating	100%	-
Condensing Natural Gas Boiler	η_T = 97%	(Charbonneau, 2011)
Condensing Natural Gas Furnace	η_T = 95%	(Charbonneau, 2011)
MAU Gas Heating Coil	$AFUE$ = 90%	(Crowther, 2014)
MAU DX Cooling	EER-11	(Crowther, 2014)
In-suite ASHP Heating	HSPF-8.6	(Natural Resources Canada, 2015)
In-suite Stacked WSHP Heating	COP-5	(Daikin Applied, 2015; Trane, 2015)

Equipment	Performance	Source
In-suite ASHP Cooling	SEER-17	(Natural Resources Canada, 2015)
In-suite Stacked WSHP Cooling	EER-15	(Daikin Applied, 2015; Trane, 2015)
Heat Recovery Ventilator	Sensible Effectiveness: 0.8	(Tillack, Raffray, & Pulsifer, 2001)
Energy Recovery Ventilator	Total Effectiveness: 0.8	(Tillack et al., 2001)
Instantaneous Gas Hot Water Heater	EF-0.98	(Natural Resources Canada, 2012)
Gas Hot Water Heater (With Tank)	EF-0.7	(Natural Resources Canada, 2012)
Central Rotary or Reciprocating Chiller, <100 tons	0.7 kW/ton	(Natural Resources Canada, 2002)

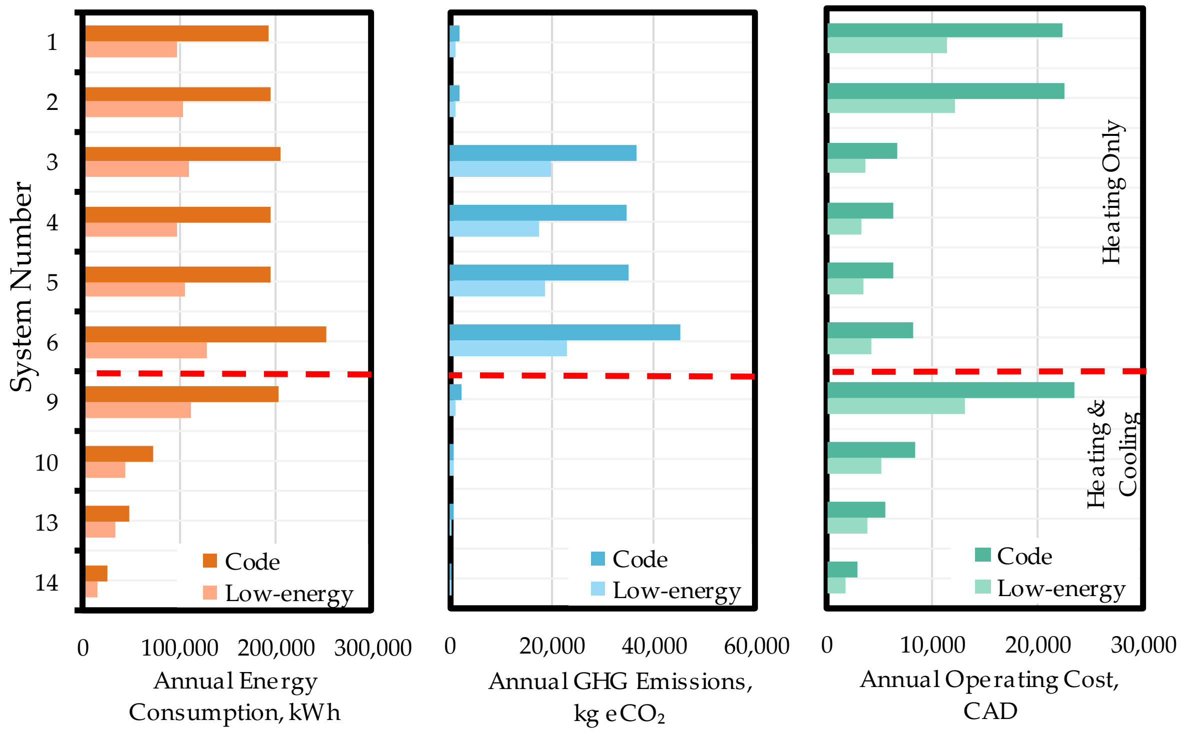
4.3 Modelling Results

The results from the modelling of each mechanical system can be found below as sorted by location and system number. Each system number corresponds to a system described in Appendix E, along with the model inputs used in the simulation. Annual energy consumption associated with each system is presented along with the associated greenhouse gas emissions and operating utility costs. The GHG emission factors as utility pricing can be found in Appendix F.

4.3.1 Vancouver

Figure 4-5 displays energy consumption, emissions, and operating cost for each of the eleven Type 1 – thermal comfort systems modelled in Vancouver. For comparative purposes, these are divided into systems which provide only heating and systems which provide both heating and cooling. It is clear that large variations are visible between systems in all three plots.

The low carbon nature of the electrical grid results in negligible emissions even for electric resistance based systems. The low cost of natural gas, however, results in substantially lower operating costs for all combustion based systems as compared to electric systems, with ground coupled VRF being the only electric system able to compete.

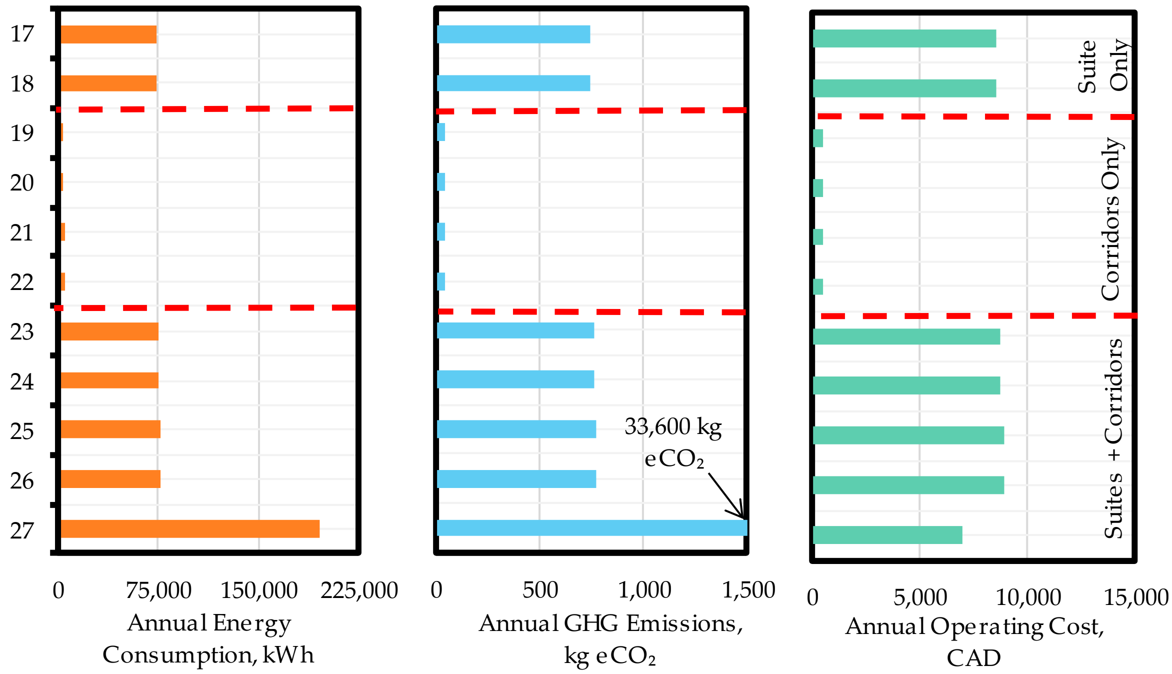


1	Electric resistance, convective heating
2	In-suite AHU with forced air electric furnace
3	In-suite AHU with forced air natural gas furnace
4	Radiant floor with centralized natural gas boiler
5	2-pipe FCUs with centralized natural gas boiler
6	Hydronic convectors with central natural gas boiler
9	PTAC, electric heating coil
10	PTHP, electric backup heating coil
13	Central VRF system, air source heat pump
14	Central VRF system, ground source heat pump

Figure 4-5: Annual energy consumption, greenhouse gas emissions, and operating costs of thermal comfort systems in Vancouver by system number

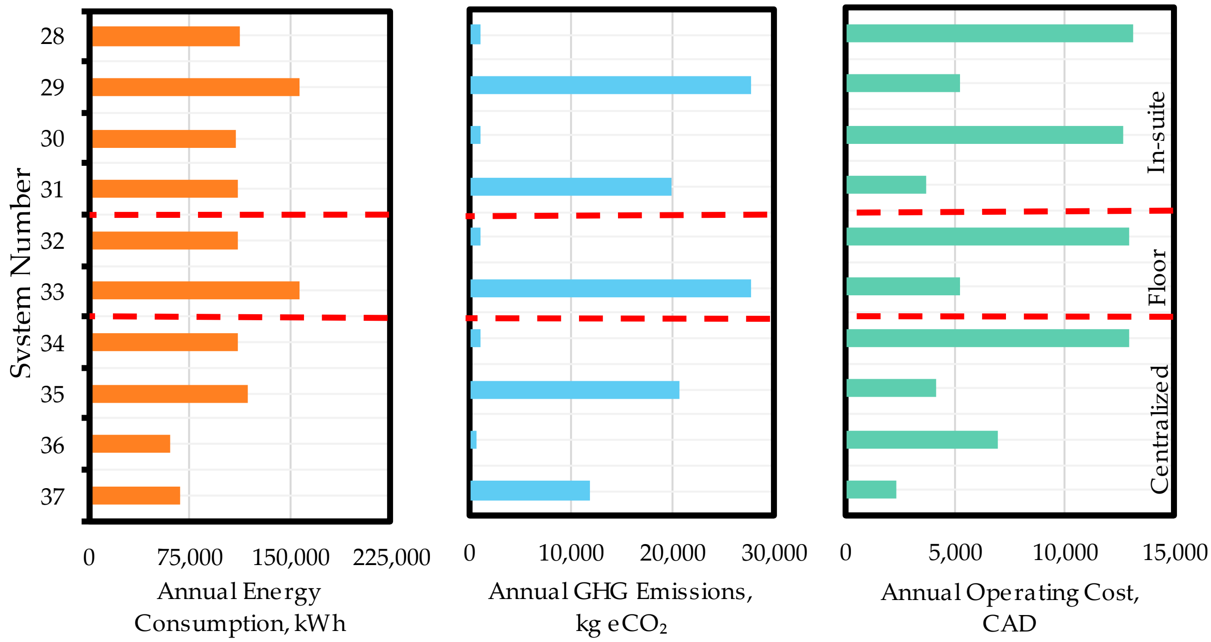
Figure 4-6 displays energy consumption, emissions, and operating cost for each of the eleven Type 2 – indoor air quality systems modelled in Vancouver. Systems are divided based on zones served, with suite only, corridor only, and suite and corridor configurations. Note that for systems employing heat recovery, it is assumed that the additional heating load imposed directly or indirectly on the heating system is addressed via electric resistance heating. This is not always, or even often, the case in practice as natural gas may be used to heat the air that is delivered by an HRV. In comparison to a traditional pressurized corridor system, all centralized and floor based heat recovery options offer lower emissions and substantially less energy use. However, the higher cost of electricity results in higher operating costs for these systems despite their energy savings.

Figure 4-7 displays energy consumption, emissions, and operating cost for each of the ten Type 3 – domestic hot water systems modelled in Vancouver. These systems are divided into in-suite, floor based, and centralized based on the location of the energy production components. Note that only the solar assisted DHW systems are involve loads which are location dependent. It is evident that all electric systems boast the lowest emissions but the highest operating costs. Solar thermal DHW with an electric backup boiler was the only electric system which boasted operating costs in the same range as all electric resistance. Furthermore, solar thermal systems appear to be beneficial in this case, with the solar system able to provide a substantial portion of the annual domestic hot water heating.



17	In-suite Heat Recovery Ventilator (HRV)
18	In-suite Energy Recovery Ventilator (ERV)
19	Floor AHU, DOAS serving corridors, heat recovery
20	Floor AHU, DOAS serving corridors, enthalpy recovery
21	Central AHU, DOAS serving corridors, heat recovery
22	Central AHU, DOAS serving corridors, enthalpy recovery
23	Floor AHU, DOAS serving suites + corridors, heat recovery
24	Floor AHU, DOAS serving suites + corridors, enthalpy recovery
25	Central AHU, DOAS serving suites + corridors, heat recovery
26	Central AHU, DOAS serving suites + corridors, enthalpy recovery
27	Central MAU, corridor pressurization, natural gas heat

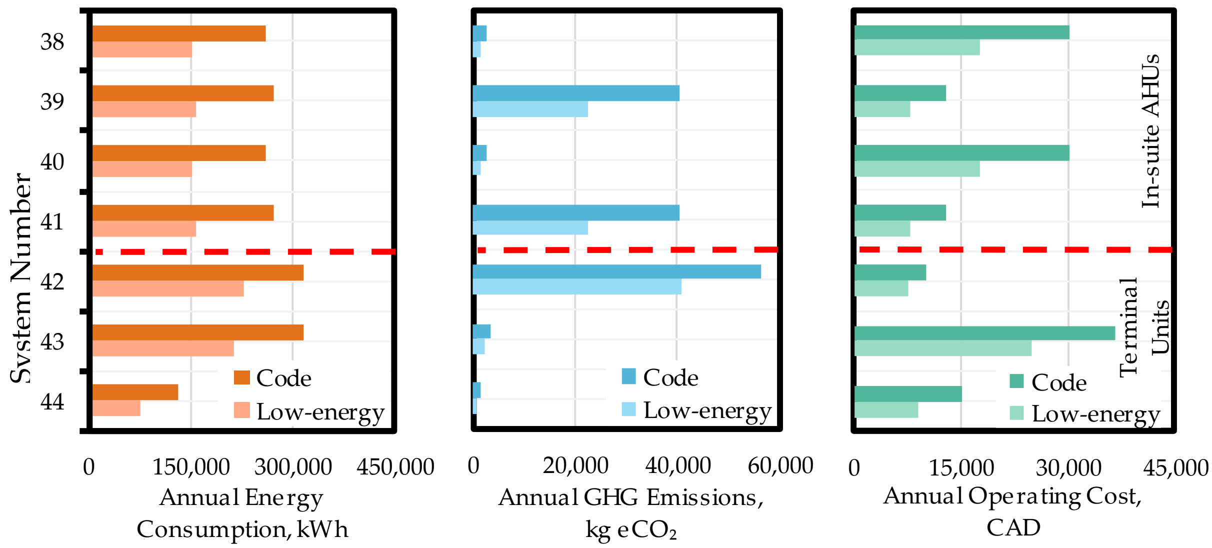
Figure 4-6: Annual energy consumption, greenhouse gas emissions, and operating costs of indoor air quality systems in Vancouver by system number



28	In-suite electric storage tank water heater
29	In-suite natural gas storage tank water heater
30	In-suite electric tankless water heater
31	In-suite natural gas tankless water heater
32	Floor electric storage tank water heater
33	Floor natural gas storage tank water heater
34	Central electric boiler with storage tanks
35	Central natural gas boiler with storage tanks
36	Central solar thermal hot water system, electric boiler
37	Central solar thermal hot water system, natural gas boiler

Figure 4-7: Annual energy consumption, greenhouse gas emissions, and operating costs of domestic hot water systems in Vancouver by system number

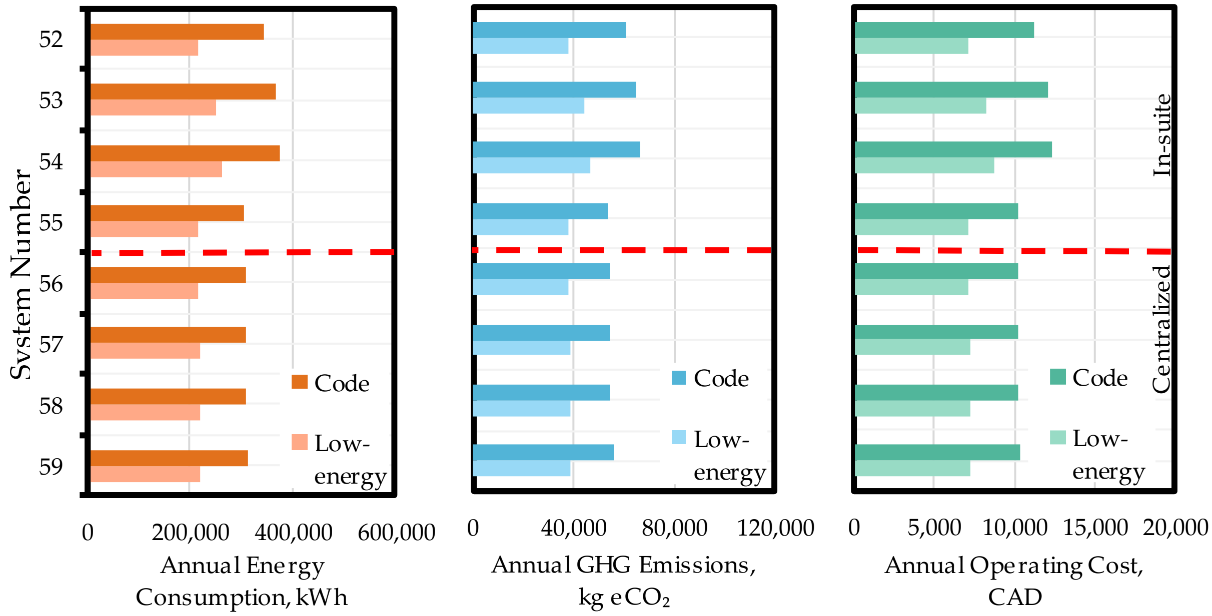
Figure 4-8 displays energy consumption, emissions, and operating cost for each of the seven combination thermal comfort and indoor air quality systems modelled in Vancouver. These are divided into in-suite AHUs and wall-mounted terminal units which incorporate outdoor air into the supply air stream. In-suite AHUs provided consistent delivery of outdoor air, but all terminal unit systems struggled to consistently meet airflow requirements due to the fact that the fan only runs when the thermostat calls for conditioning.



38	In-suite AHU w/ OA heat recovery, electric furnace
39	In-suite AHU w/ OA heat recovery, natural gas furnace
40	In-suite AHU w/ OA enthalpy recovery, electric furnace
41	In-suite AHU w/ OA enthalpy recovery, natural gas furnace
42	2-pipe FCUs w/ OA intake, centralized natural gas boiler
43	PTAC, electric heating coil, OA intake, point exhaust
44	PTHP, OA intake, point exhaust

Figure 4-8: Annual energy consumption, greenhouse gas emissions, and operating costs of combination thermal comfort and indoor air quality systems in Vancouver by system number

Figure 4-9 displays energy consumption, emissions, and operating cost for each of the eight combination thermal comfort and domestic hot water systems modelled in Vancouver. Systems are divided into in-suite and centralized, but all use natural gas as the energy source. As a result, there is not a substantial variation between many of the systems in terms of energy consumption, emissions, or operating cost. However, it can generally be observed that of the in-suite systems, hydronic fan coils with coupled with tankless water heaters provide the lowest energy consumption, with all centralized systems performing similarly.

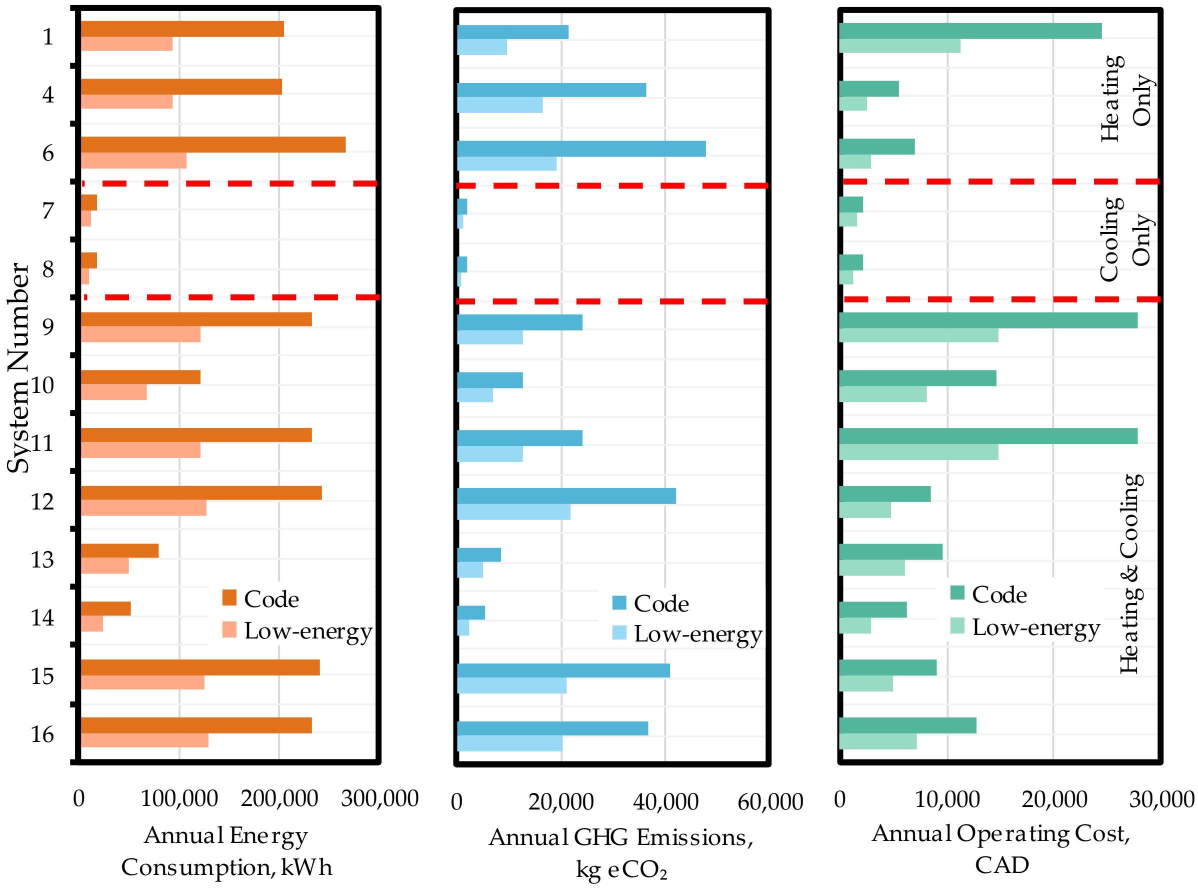


52	Radiant floor, in-suite gas tank water heater
53	Hydronic convectors, in-suite gas tank water heater
54	In-suite AHU w/ HW coil, in-suite gas tank water heater
55	In-suite AHU w/ HW coil, in-suite gas tankless water heater
56	Radiant floor, central gas boiler, providing DHW
57	2-pipe FCUs, central gas boiler, providing DHW
58	In-suite AHU w/ HW coil, central gas boiler, providing DHW
59	Hydronic convectors, central gas boiler, providing DHW

Figure 4-9: Annual energy consumption, greenhouse gas emissions, and operating costs of combination thermal comfort and domestic hot water systems in Vancouver by system number

4.3.2 Toronto

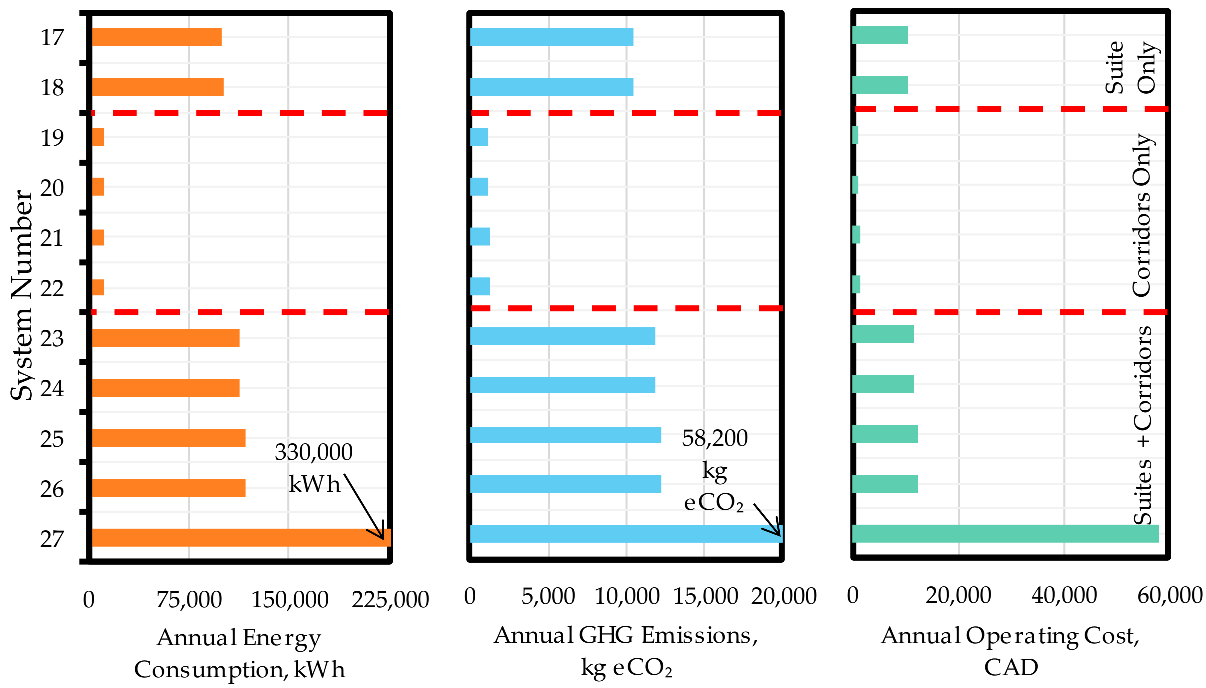
Figure 4-10 displays energy consumption, emissions, and operating cost for each of the thirteen Type 1 – thermal comfort systems modelled in Toronto. Systems are divided into heating only, cooling only, and heating and cooling based on the functions provided.



1	Electric resistance, convective heating
4	Radiant floor with centralized natural gas boiler
6	Hydronic convectors/radiators with central natural gas boiler
7	PTAC, no heating
8	Chilled ceilings with central chiller, cooling tower
9	PTAC, electric heating coil
10	PTHP, electric backup heating coil
11	In-suite AHU, electric furnace, dx cooling
12	In-suite AHU, natural gas furnace, dx cooling
13	Central VRF system, air source heat pump
14	Central VRF system, ground source heat pump
15	4-pipe FCUs, central natural gas boiler, chiller, cooling tower
16	In-suite WSHP, central natural gas boiler, cooling tower

Figure 4-10: Annual energy consumption, greenhouse gas emissions, and operating costs of thermal comfort systems in Toronto by system number

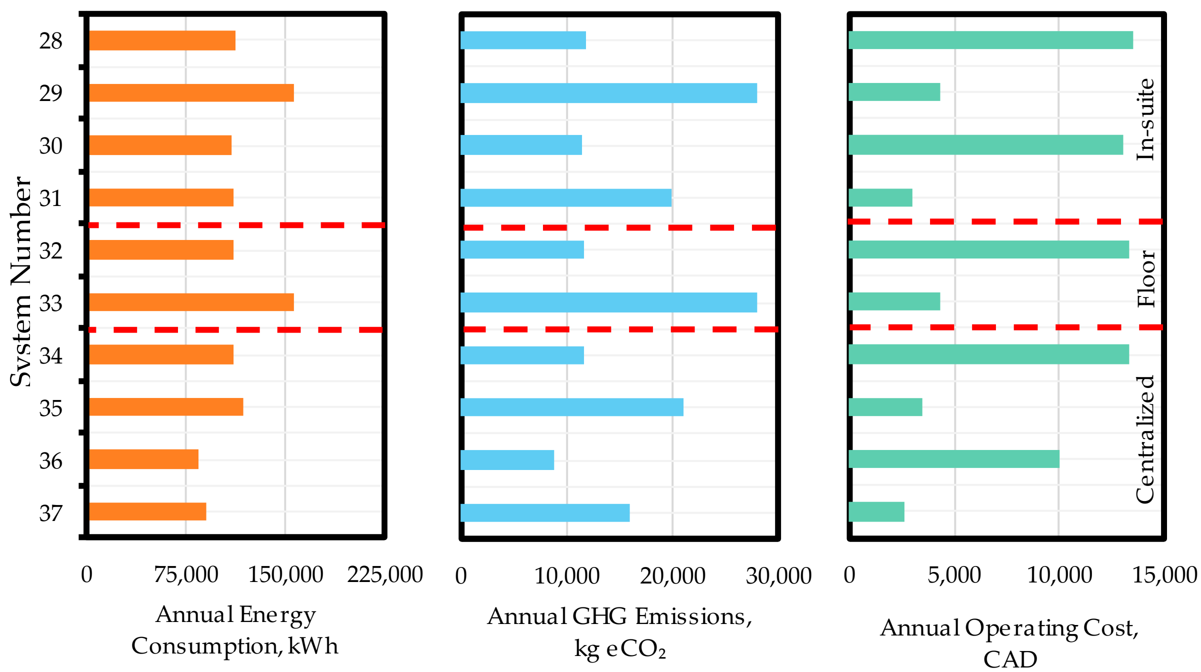
Figure 4-11 displays energy consumption, emissions, and operating cost for each of the eleven Type 2 – ventilation systems modelled in Toronto. The amount of heating required to meet supply setpoints results in significantly more energy consumption by pressurized corridor systems due to the lack of heat recovery. Despite the lower cost of natural gas used in these systems, the operating costs and GHG emissions are still higher than all systems employing some type of heat recovery.



17	In-suite Heat Recovery Ventilator (HRV)
18	In-suite Energy Recovery Ventilator (ERV)
19	Floor AHU, DOAS serving corridors, heat recovery
20	Floor AHU, DOAS serving corridors, enthalpy recovery
21	Central AHU, DOAS serving corridors, heat recovery
22	Central AHU, DOAS serving corridors, enthalpy recovery
23	Floor AHU, DOAS serving suites + corridors, heat recovery
24	Floor AHU, DOAS serving suites + corridors, enthalpy recovery
25	Central AHU, DOAS serving suites + corridors, heat recovery
26	Central AHU, DOAS serving suites + corridors, enthalpy recovery
27	Central MAU, corridor pressurization, natural gas heat

Figure 4-11: Annual energy consumption, greenhouse gas emissions, and operating costs of indoor air quality systems in Toronto by system number

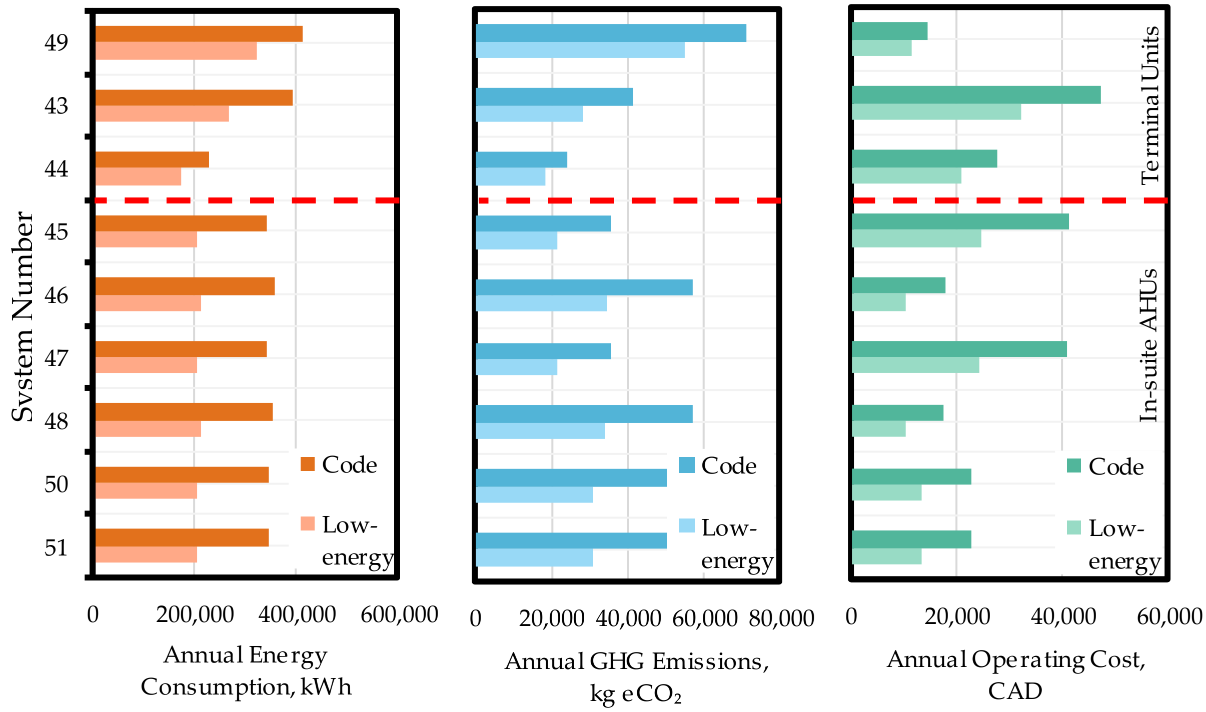
Figure 4-12 displays energy consumption, emissions, and operating cost for each of the ten Type 3 – domestic hot water systems modelled in Toronto. Solar thermal systems offer reduced energy savings in the Toronto climate, and generally electric systems cost significantly more to operate but produce fewer emissions.



28	In-suite electric storage tank water heater
29	In-suite natural gas storage tank water heater
30	In-suite electric tankless water heater
31	In-suite natural gas tankless water heater
32	Floor electric storage tank water heater
33	Floor natural gas storage tank water heater
34	Central electric boiler with storage tanks
35	Central natural gas boiler with storage tanks
36	Central solar thermal hot water system, electric boiler
37	Central solar thermal hot water system, natural gas boiler

Figure 4-12: Annual energy consumption, greenhouse gas emissions, and operating costs of domestic hot water systems in Toronto by system number

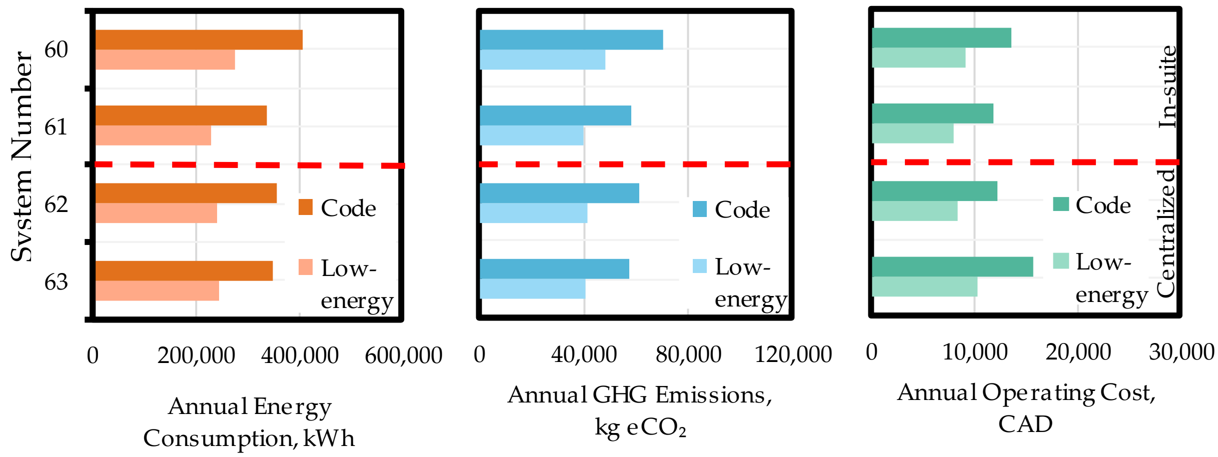
Figure 4-13 displays energy consumption, emissions, and operating cost for each of the nine combination thermal comfort and indoor air quality systems modelled in Toronto. Only the in-suite AHUs consistently met ventilation rate requirements, and all such systems did so using approximately the same amount of annual energy.



49	4-pipe FCUs w/ OA intake, central natural gas boiler, chiller, cooling tower
43	PTAC, electric heating coil, OA intake, point exhaust
44	PTHP, OA intake, point exhaust
45	In-suite AHU w/ OA heat recovery, electric furnace, dx cooling
46	In-suite AHU w/ OA heat recovery, natural gas furnace, dx cooling
47	In-suite AHU w/ OA enthalpy recovery, electric furnace, dx cooling
48	In-suite AHU w/ OA enthalpy recovery, natural gas furnace, dx cooling
50	In-suite WSHP w/ OA heat recovery, central natural gas boiler, cooling tower
51	In-suite WSHP w/OA enthalpy recovery, central natural gas boiler, cooling tower

Figure 4-13: Annual energy consumption, greenhouse gas emissions, and operating costs of combination thermal comfort and indoor air quality systems in Toronto by system number

Figure 4-14 displays energy consumption, emissions, and operating cost for each of the four combination thermal comfort and domestic hot water systems modelled in Toronto. As these systems primarily use natural gas, and Toronto functionally requires cooling, only a limited selection of systems were considered.

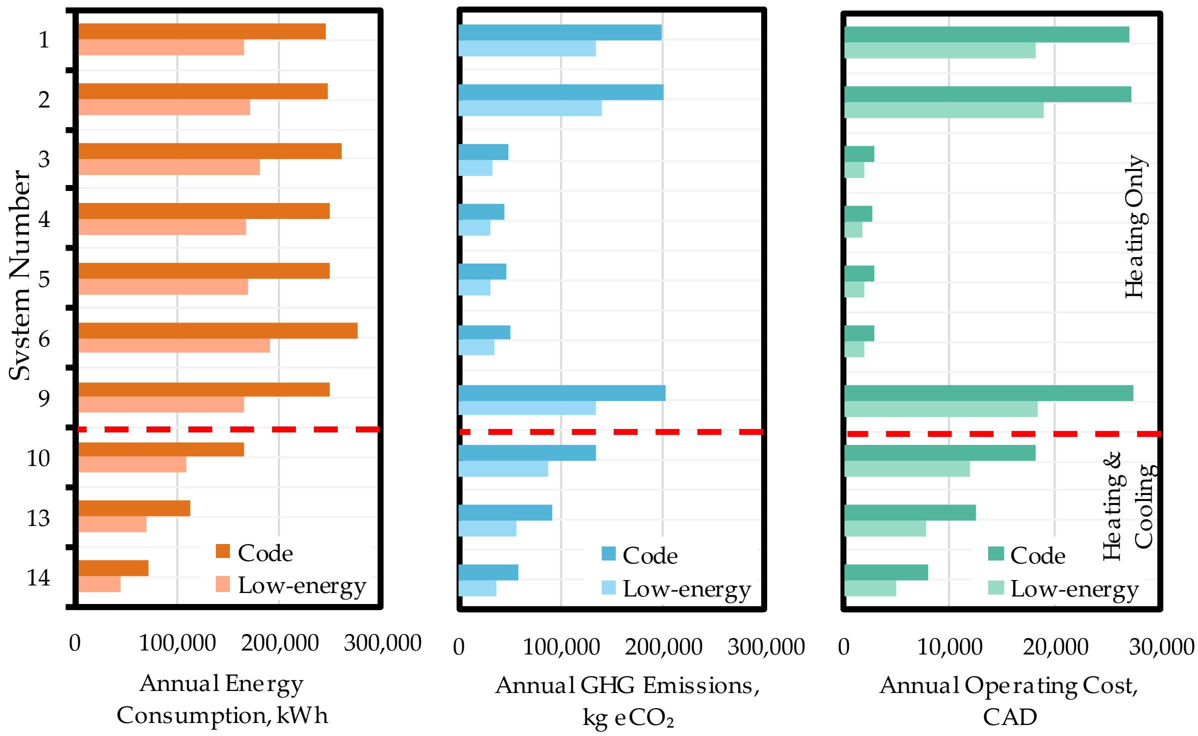


60	In-suite Ducted FCU, dx cooling, in-suite natural gas storage tank water heater
61	In-suite Ducted FCU, dx cooling, in-suite natural gas tankless water heater
62	4-pipe FCUs, central natural gas boiler with storage tanks, chiller, cooling tower, providing DHW and space conditioning
63	In-suite WSHP, central natural gas boiler with storage tanks, cooling tower, providing DHW and space conditioning

Figure 4-14: Annual energy consumption, greenhouse gas emissions, and operating costs of combination thermal comfort and domestic hot water systems in Toronto by system number

4.3.3 Edmonton

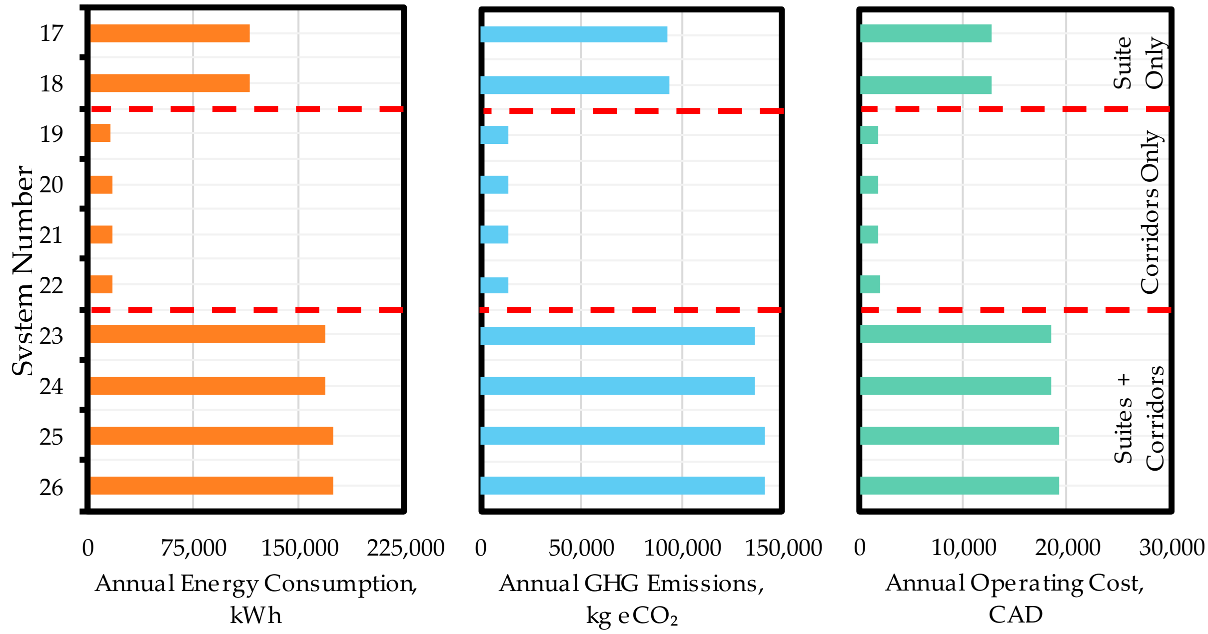
Figure 4-15 displays energy consumption, emissions, and operating cost for each of the ten Type 1 – thermal comfort systems modelled in Edmonton. Due to the high carbon emissions associated with grid electricity, systems which burn natural gas on site offer the lowest GHG emissions. Ground coupled VRF is the only electric system which provides comparable emissions. Furthermore, while electricity is not particularly expensive, natural gas is very cheap, making even ground coupled VRF substantially more expensive to operate than natural gas systems.



1	Electric resistance, convective heating
2	In-suite AHU with forced air electric furnace
3	In-suite AHU with forced air natural gas furnace
4	Radiant floor with centralized natural gas boiler
5	2-pipe FCUs with centralized natural gas boiler
6	Hydronic convectors with central natural gas boiler
9	PTAC, electric heating coil
10	PTHP, electric backup heating coil
13	Central VRF system, air source heat pump
14	Central VRF system, ground source heat pump

Figure 4-15: Annual energy consumption, greenhouse gas emissions, and operating costs of thermal comfort systems in Edmonton by system number

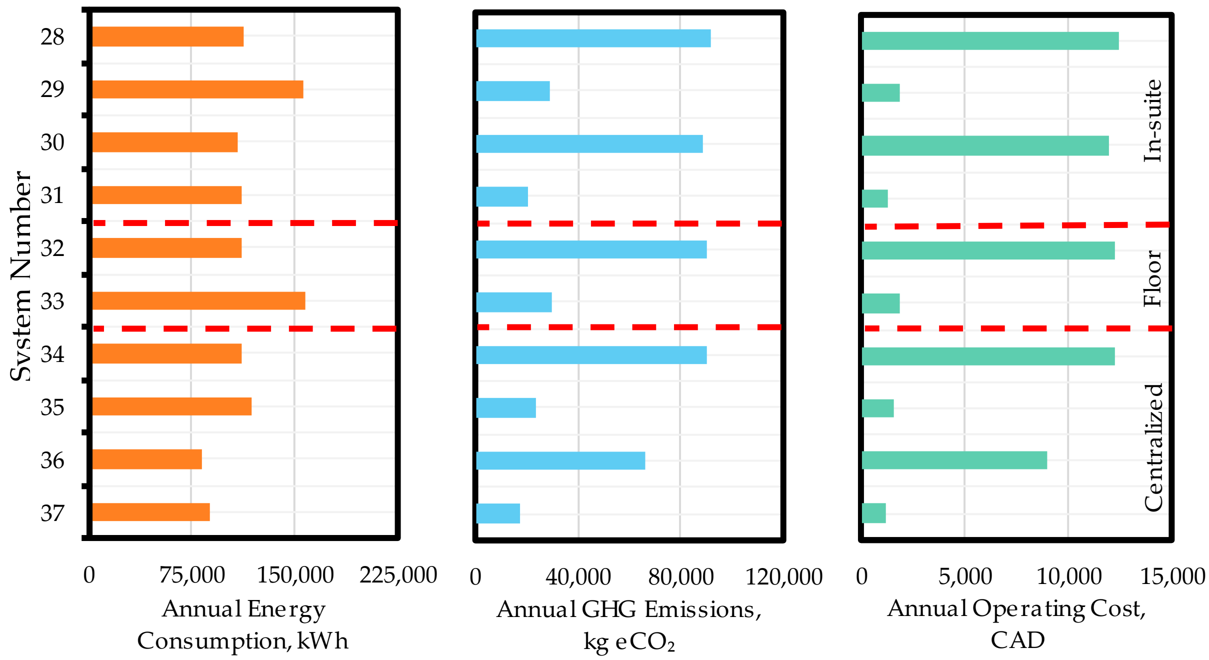
Figure 4-16 displays energy consumption, emissions, and operating cost for each of the ten Type 2 – indoor air quality systems modelled in Edmonton. Note that pressurized corridor systems were not simulated as both NECB 2011 and ASHRAE Standard 90.1-2010 require heat recovery of ventilation air in climate zone 7 and higher.



17	In-suite Heat Recovery Ventilator (HRV)
18	In-suite Energy Recovery Ventilator (ERV)
19	Floor AHU, DOAS serving corridors, heat recovery
20	Floor AHU, DOAS serving corridors, enthalpy recovery
21	Central AHU, DOAS serving corridors, heat recovery
22	Central AHU, DOAS serving corridors, enthalpy recovery
23	Floor AHU, DOAS serving suites + corridors, heat recovery
24	Floor AHU, DOAS serving suites + corridors, enthalpy recovery
25	Central AHU, DOAS serving suites + corridors, heat recovery
26	Central AHU, DOAS serving suites + corridors, enthalpy recovery

Figure 4-16: Annual energy consumption, greenhouse gas emissions, and operating costs of indoor air quality systems in Edmonton by system number

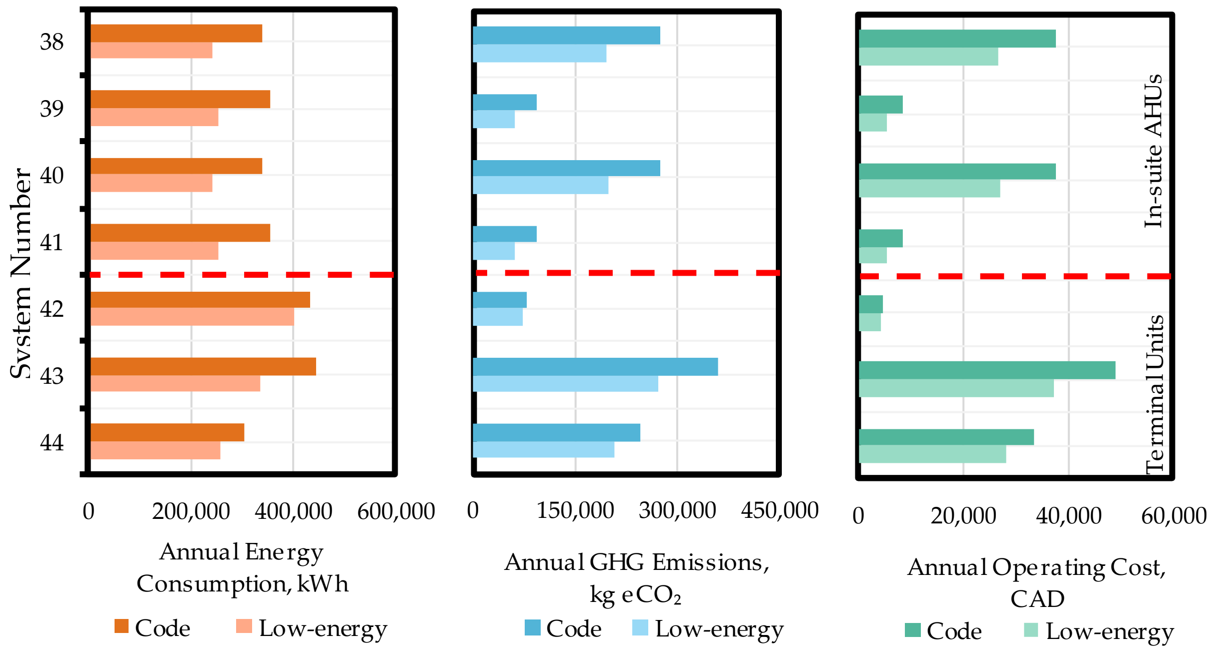
Figure 4-17 displays energy consumption, emissions, and operating cost for each of the ten Type 3 – domestic hot water systems modelled in Edmonton. The solar thermal systems are the only systems involving location dependent loads, and show minimal savings over other centralized systems.



28	In-suite electric storage tank water heater
29	In-suite natural gas storage tank water heater
30	In-suite electric tankless water heater
31	In-suite natural gas tankless water heater
32	Floor electric storage tank water heater
33	Floor natural gas storage tank water heater
34	Central electric boiler with storage tanks
35	Central natural gas boiler with storage tanks
36	Central solar thermal hot water system, electric boiler
37	Central solar thermal hot water system, natural gas boiler

Figure 4-17: Annual energy consumption, greenhouse gas emissions, and operating costs of domestic hot water systems in Edmonton by system number

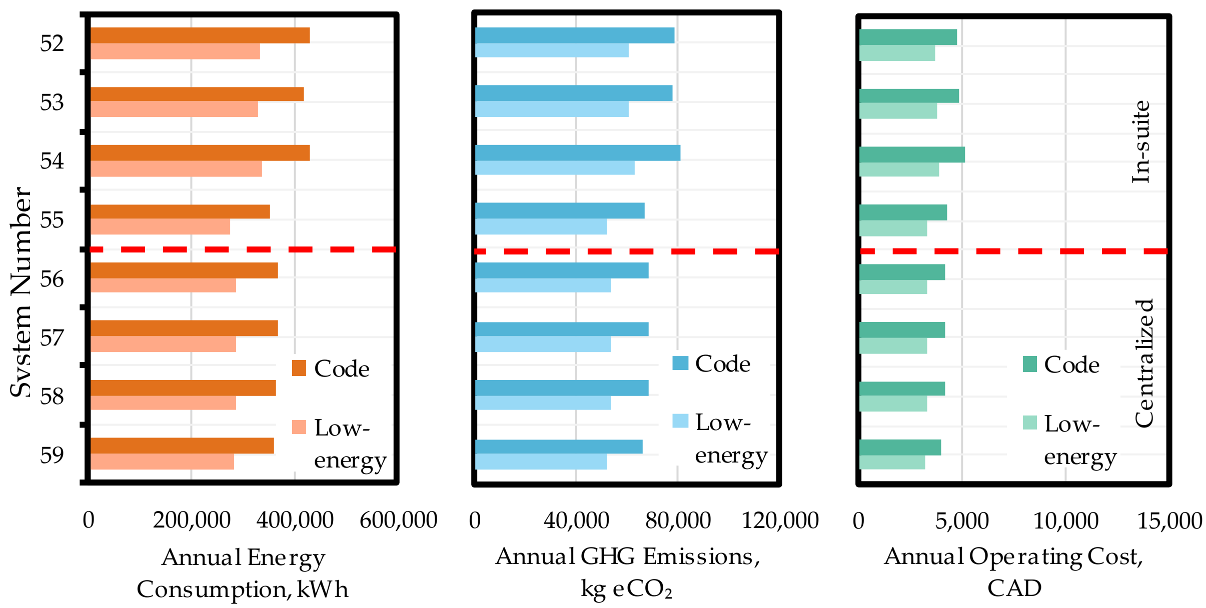
Figure 4-18 displays energy consumption, emissions, and operating cost for each of the seven combination thermal comfort and indoor air quality systems modelled in Edmonton. The in-suite AHU's were the only systems to consistently deliver the required ventilation rate, and of these natural gas furnaces offer the lowest emissions and operating costs.



38	In-suite AHU w/ OA heat recovery, electric furnace
39	In-suite AHU w/ OA heat recovery, natural gas furnace
40	In-suite AHU w/ OA enthalpy recovery, electric furnace
41	In-suite AHU w/ OA enthalpy recovery, natural gas furnace
42	2-pipe FCUs w/ OA intake, centralized natural gas boiler
43	PTAC, electric heating coil, OA intake, point exhaust
44	PTHP, OA intake, point exhaust

Figure 4-18: Annual energy consumption, greenhouse gas emissions, and operating costs of combination thermal comfort and indoor air quality systems in Edmonton by system number

Figure 4-19 displays energy consumption, emissions, and operating cost for each of the eight combination thermal comfort and domestic hot water systems modelled in Edmonton. As all of these systems use natural gas, all boast similar consumption, emissions, and cost. The annual operating cost of these systems is a small fraction as compared to the electric heating systems presented in Figure 4-15 while also providing domestic hot water.



52	Radiant floor, in-suite gas tank water heater
53	Hydronic convectors, in-suite gas tank water heater
54	In-suite AHU w/ HW coil, in-suite gas tank water heater
55	In-suite AHU w/ HW coil, in-suite gas tankless water heater
56	Radiant floor, central gas boiler, providing DHW
57	2-pipe FCUs, central gas boiler, providing DHW
58	In-suite AHU w/ HW coil, central gas boiler, providing DHW
59	Hydronic convectors, central gas boiler, providing DHW

Figure 4-19: Annual energy consumption, greenhouse gas emissions, and operating costs of combination thermal comfort and domestic hot water systems in Edmonton by system number

4.4 Discussion of Modelling Assumptions

The modelling conducted was based on specific assumptions developed throughout Chapter 3, Section 4.1 of Chapter 4, and Appendix E. While these assumptions have been previously discussed, several aspects of the simulations conducted should be addressed as they could influence the results.

Condensing and non-condensing boilers are configured in DesignBuilder with a multi-variable part load performance curve which is a function of part load factor and water temperature – either entering or leaving the boiler. The condensing curve, however, is not comprehensive enough to distinguish between periods of non-condensing operation. For example, an entering water temperature of 85°C at a part-load ratio of 0.5 would still yield a part-load factor of 1.05, which when combined with a nominal efficiency of 90% results in a thermal efficiency of 95% for that time step. As such, it is necessary to assume when configuring the model inputs whether or not the design boiler entering water temperature will typically be below 55°C. This is easily achieved with radiant floor systems, but more difficult to ascertain with FCUs as performance may vary from condensing to non-condensing depending on equipment sizing and loop design. To be conservative, a non-condensing part load curve was assumed for the convector based hydronic systems. Good design would strive to ensure that the return temperature from a convector would always result in condensing.

Radiant panel systems are different from all other heating and cooling systems as more than half of the heat transfer is in the form of radiation as opposed to convective heating of the air. Because of this, simulating system performance based on maintaining an air temperature setpoint yielded unrealistically high energy consumption. In order to address this, the operative setpoint was used for radiant panel systems. In order to achieve comparable results to the other systems, the operative temperature achieved by those systems was taken as the input. In other words, if a convective heating system with a setpoint of 72°C would typically achieve an operative temperature of 70.5°C, radiant systems would instead be simulated to maintain this operative temperature directly, irrespective of air temperature.

In-suite AHUs required a slight workaround based on the systems and equipment readily available within DesignBuilder. Packaged air handling units are easily configured, but DesignBuilder assumes that outdoor air is included in the sizing of these systems, and setting outdoor airflows to zero results in errors or inaccurate results. In order to address this, in-suite PTACs were configured to perform the functions of conventional in-suite electric and natural gas furnaces with direct expansion cooling. Fan assumptions were modified to respect the presence of supply ductwork and/or heat exchange cores.

VRF systems cannot be modelled directly in EnergyPlus. DesignBuilder includes the functionality necessary to perform these simulations, but the level of complexity associated with these systems prohibits a general case approach. Instead, manufacturer data for a specific system must be used, as complete system configurations involve many inputs, including 26 part-load performance curves. This reliance on preconfigured system data means that results for VRF systems have more uncertainty than other systems. For these simulations, LG ARUN/B outdoor units were utilized.

Solar thermal systems, as with VRF systems, are very complex to configure and require many specific inputs unique to a given collector. As such, there is a higher degree of uncertainty surrounding the solar DHW system results as compared to other DHW systems. Viessmann SV1/SH1 collector data was used for the simulations, with one rooftop panel for every 3 suites.

Wall mounted terminal units providing outdoor air were explored as a means of meeting ventilation requirements, but very limited control is possible within DesignBuilder with respect to the air volumes these units provide. This is because outdoor air is mixed into the supply air stream, but only when the fan is running based on the thermostat. As such, all such systems were inconsistent in their delivery of outdoor air, although they did typically provide comparable air change rates to the suites based on monthly averages. This was achieved in some cases by oversizing the terminal unit airflow capacity in order to ensure adequate outdoor air delivery when on.

Zone water-to-air heat pumps can be modelled directly within DesignBuilder, but the implementation is somewhat limited. It is only possible to connect the heat pump to a condenser loop which can contain cooling towers, ground exchange fields, etc. As such, it is not possible to directly connect a boiler to the condenser loop. In addition to this, while most other terminal units can be sized by the software with multiple preset part load curves to select from, zone water-to-air heat pumps only offer an equation fit method. This resulted in excessive fan and cooling energy. In order to generate reasonable results, a series of partial year runs and approximations were conducted based on simulated results from comparable systems such as 4-pipe fan-coil units.

Chapter 5 : Mechanical System Discussions

The energy consumption, greenhouse gas emissions, and operational costs of various mechanical systems in different cities across Canada were presented in Chapter 4. With these values established, the overall trends in the data can be discussed in order to establish the larger implications they hold for Canadian high-rise MURBs. Discussions in this chapter are divided into three categories: general discussions of overarching trends, the implications of specific system level design choices on system selection, and the best systems for specific stakeholder groups.

5.1 General Discussions

The overarching high-level trends that are visible in the simulation results include the effect of location and climate, the impact of the electrical grid characteristics (cost and carbon emissions), and systems which demonstrate consistently strong or poor performance across all locations.

5.1.1 Location and Climate

The main reason for considering three different Canadian cities throughout the analysis was to quantify the effect of climate on mechanical systems. Building loads are impacted by local weather, but the degree to which different types of systems are effected varies.

Indoor Air Quality systems providing ventilation demonstrate the largest correlation with climate due to the fact that energy consumption of mechanical ventilation equipment is directly influenced by the local climate through the conditioning of outdoor air. Thermal comfort systems providing heating and cooling are also affected by climate, but to a lesser degree. This is largely due to the fact that the space heating and cooling loads are connected indirectly to the outdoor climate via the building enclosure, and the building enclosure code requirements and local practices tend to reflect the local climate. In other words, energy codes impose increasingly stringent requirements for building enclosure performance with increasing climate zone number which reduces the impact climate has on thermal comfort system energy consumption.

Figure 5-1 displays the annual energy consumption of in-suite HRVs – an indoor air quality system – and electric baseboards – a thermal comfort system – across the three locations modelled. Note that the rate of increase from climate zone 5 in Vancouver to climate zone 7 in Edmonton is greater for HRVs than it is for electric baseboards.

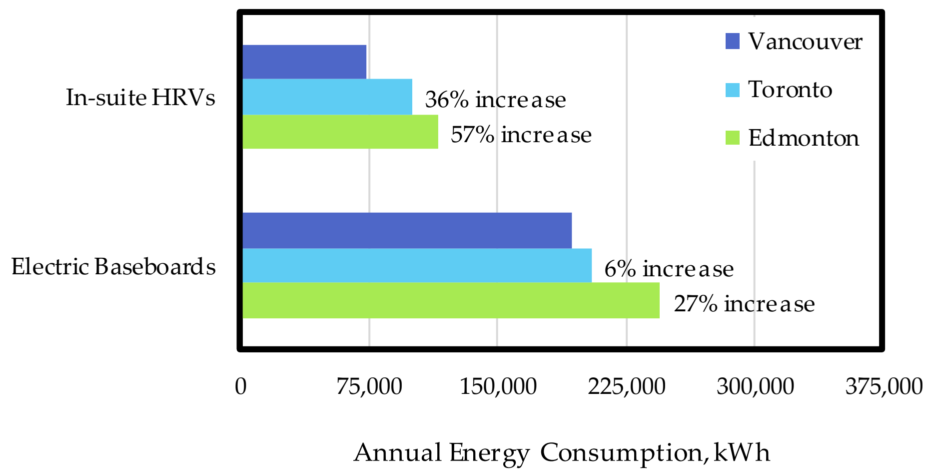


Figure 5-1: Annual energy consumption of in-suite HRVs and electric baseboards for code-based reference buildings in Vancouver (CZ5), Toronto (CZ6), and Edmonton (CZ7). Percentage increases are denoted with respect to Vancouver.

Another way in which climate directly influences mechanical systems is with respect to the functional requirements imposed by the climate which must be met by the mechanical systems. Specifically, Toronto requires cooling whereas Vancouver and Edmonton do not. While not a substantial load, this is an additional factor which shapes design choices.

Solar thermal domestic hot water system performance inherently relies on local solar conditions, and is therefore correlated with climate. Throughout the simulations, the assumptions surrounding the thermal collector array remained constant despite the fact that typical practice would normally dictate an increase in collector areas for certain regions. However, this did enable the direct comparison of the system across locations, which can be seen in Figure 5-2. It is clear that solar thermal systems perform better in Vancouver than in Toronto or Edmonton. This is likely due to higher system losses during the winter in the colder climate zones, although variation in incident solar radiation across the locations can also impact system performance.

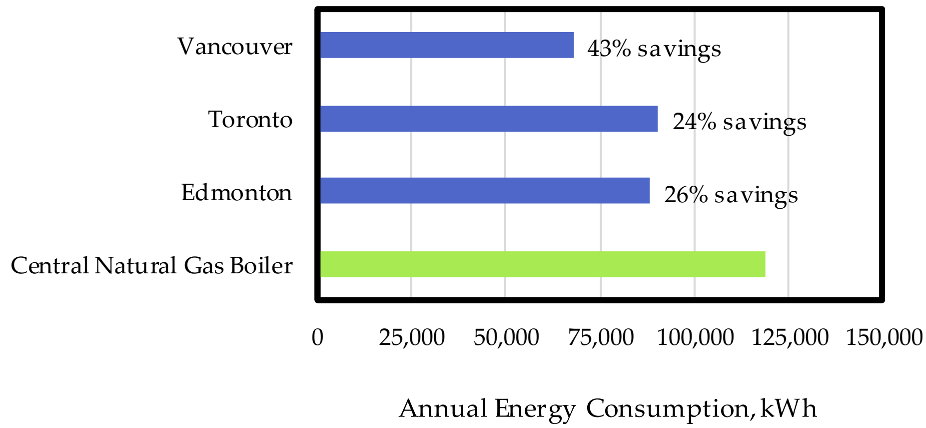


Figure 5-2: Annual energy consumption of solar thermal domestic hot water systems with natural gas backup boilers in Vancouver (CZ5), Toronto (CZ6), and Edmonton (CZ7). Percentage savings are denoted with respect to a central natural gas boiler providing all of the DHW load.

5.1.2 Electrical Grid

High-rise MURBs, by virtue of their form factor, tend to have a low ratio of roof to conditioned floor area, often meaning that the generation of sufficient on site electricity by photovoltaics to completely offset annual electricity consumption is infeasible.

The greenhouse gas emissions derived from the consumption of electricity is tied to the carbon intensity of the local electrical grid.

The greenhouse gas emissions associated with the operation of electrically powered mechanical systems is more dependent on the carbon intensity of the electrical grid than any other factor, including system efficiency. Figure 5-3 displays annual energy consumption and greenhouse gas emissions for hydronic baseboards, electric baseboards, and ground source heat pumps in Vancouver, Toronto, and Edmonton. It is clear that the high carbon intensity of the electrical grid in Edmonton results in higher GHG emissions for all electric systems despite the added efficiency of electric resistance and heat pump technology. Conversely, the electrical grid in Vancouver has such low emission factors that even electric resistance heating generates insignificant emissions, and heat pump technology only furthers this trend.

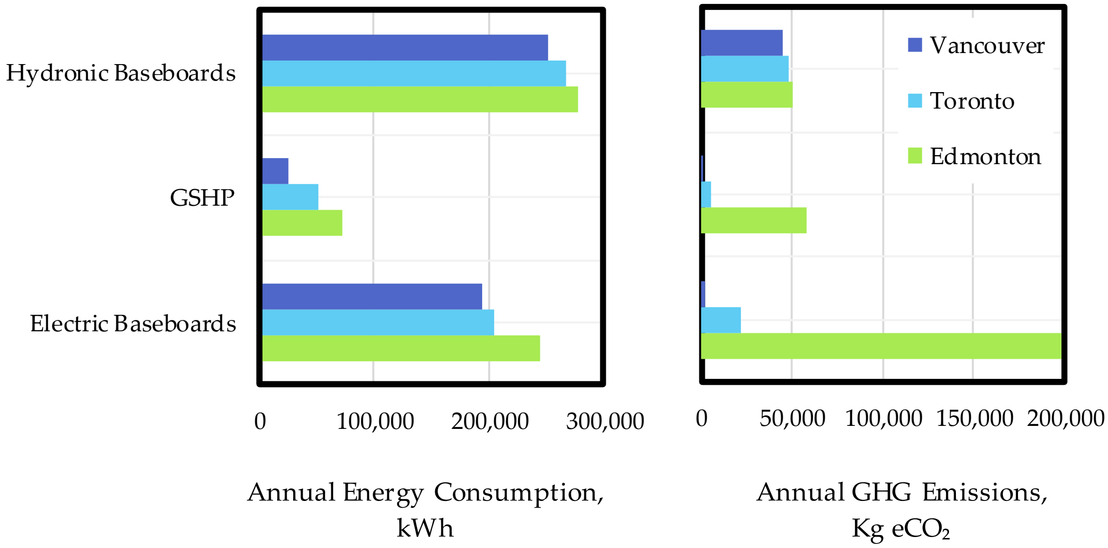


Figure 5-3: Annual energy consumption and greenhouse gas emissions for hydronic baseboards, electric baseboards, and ground source heat pumps in code-based reference buildings in Vancouver (CZ5), Toronto (CZ6), and Edmonton (CZ7)

5.1.3 Consistently Strong and Poor Performing Systems

Some specific systems demonstrated consistent performance across all locations. Heat pump technology along with low temperature natural gas systems consistently demonstrated low site energy consumption. Conversely, combination systems employing terminal units supplying outdoor air consistently performed poorly in terms of site energy consumption, along with pressurized corridor systems.

5.1.3.1 Strong Performing Systems

Heat pump technology, whether implemented in the form of PTHPs, in-suite AHUs, or VRF systems, consistently offered the lowest site energy for thermal comfort systems. This is in spite of the fact that heat pumps also offer cooling while many of the thermal comfort systems considered are heating only. The merit of heat pump technology with respect to greenhouse gas emissions and operating costs in comparison to other systems varied by location.

All hydronic natural gas thermal comfort systems employing low temperature operation and a condensing boiler offered lower site energy consumption than high temperature non-condensing systems or natural gas furnaces. While not quantified in the model, lower water temperatures would also reduce distribution losses. Radiant floors are inherently low temperature systems, while fan coil units and hydronic baseboards are typically high temperature and require special design considerations in order to function effectively at low temperatures. For hydronic convectors this can be especially difficult, requiring increased terminal unit heat transfer area along with low space heating loads derived either from warmer climates, high performance enclosures, outdoor reset controls, or some combination. Furthermore, in order to achieve low temperature operation with FCUs and convectors, higher distribution flow rates are often required, which will increase pumping energy if piping design is not modified. When achieved, however, all low temperature hydronic natural gas systems offer low site energy consumption comparable to electric baseboards. In most Canadian locations, natural gas systems offer higher emissions than electric systems in exchange for lower operating costs, although this is not true in Alberta.

5.1.3.2 Poor Performing Systems

Among the combination thermal comfort and indoor air quality systems, many systems fell into the category of wall-mounted terminal units providing outdoor air such as fan coil units, PTACs, and PTHPs. All of these systems incorporate some amount of outdoor air into the supply air stream when recirculating room air for conditioning purposes. Outdoor air can only be provided when the fan is operating, however, which by default is only when the room thermostat calls for conditioning. As a result, these systems tend to over ventilate during peak periods and under ventilate during shoulder seasons. Furthermore, they impose a design trade-off between adequate ventilation with high energy consumption or moderate energy consumption while under ventilating the space.

Pressurized corridor ventilation systems have a long history of poor performance with respect to delivery of outdoor air to suites, acoustics, and control of building pressures. Modelling also demonstrated that pressurized corridors use significantly more site energy than any other ventilation option due to the lack of heat recovery. Generally, this increased energy consumption results in higher operational costs and GHG emissions in comparison to other indoor air quality systems as natural gas is used in the MAU for heating. However, in Vancouver specifically, the operating cost of the pressurized corridor system fell below that of systems employing heat recovery due to the assumption that supplemental heating is provided electrically in said systems. In all other cases, or if natural gas was used for supplemental heating in Vancouver, the operational cost of a pressurized corridor system would exceed all options employing heat recovery.

5.2 System Level Design Choices

System level design choices are early stage, high level decisions made at the beginning of the design phase. Decisions which often dictate the selection of mechanical systems include only providing electricity in suites, plumbing natural gas in addition to electricity to suites, and completely separating each suite through the exclusive use of suite by suite mechanical systems. Often these choices are made based on ownership structures or the billing policies of utilities. However, it should be noted that modern building software and monitoring equipment enables sub-metering of centralized system energy consumption, allowing the suite energy use to be proportioned, provided the additional capital cost is acceptable to the owners/developers.

5.2.1 Only Electricity in Suites

Only providing electricity in suites is a common design choice given that plumbing of natural gas to each suite can be quite expensive. This choice limits the selection of mechanical systems to either those using electricity as the primary fuel, or centralized natural gas systems.

For electric systems, suite-by-suite solutions are often preferable as they eliminate distribution losses while only requiring the inclusion of some extra electrical capacity as opposed to the incremental cost of plumbing natural gas. Figure 5-4 provides a summary of select electric thermal comfort systems for the various locations.

PTACs and PTHPs can be more expensive than an in-suite AHU with heat pump technology if multiple units are required to serve each perimeter zone within each suite. As such, if suite-by-suite heat pump technology is desired, it is often implemented in the form of an in-suite AHU with either an electric furnace and direct expansion cooling or an air source heat pump with an outdoor condensing unit mounted on the balcony, exterior wall, roof, or at grade. The largest problem with suite-by-suite ASHPs is the placement of this outdoor unit as locating it on the balcony takes up space, on an exterior wall detracts from aesthetics, and on the roof or at grade is limited by vertical refrigerant piping distances in addition to significantly increasing the refrigerant charge of each system. Due to these limitations, suite-by-suite heat pump technology is usually only selected if cooling is required. In the absence of the need for cooling, electric baseboards or cove heating are a lower capital cost but higher operating cost solution.

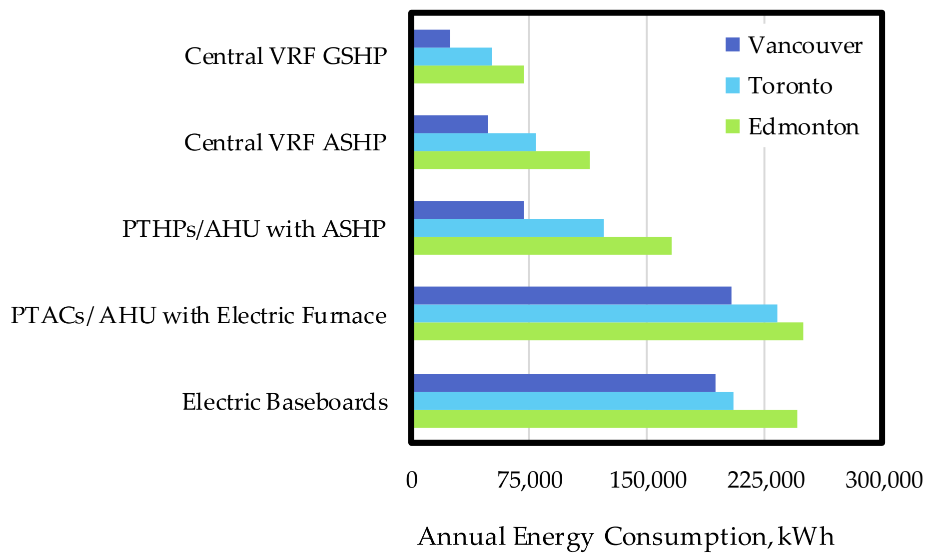


Figure 5-4: Annual energy consumption for select electric thermal comfort systems in code-based reference buildings in Vancouver (CZ5), Toronto (CZ6), and Edmonton (CZ7)

Central heat pump solutions such as air source or ground coupled water source VRF systems offer the lowest site energy in exchange for higher capital costs, less industry familiarity, and more complex sub-metering. Some of the concerns surrounding suite-by-suite heat pump technology are alleviated by these central solutions, however, the maximum vertical refrigerant pipe run is still an issue, requiring interstitial mechanical rooms for taller buildings. Furthermore, the construction of a ground exchange field represents a substantial incremental cost that is difficult to justify even in areas with high utility prices and cooling requirements.

To meet ventilation requirements, in-suite HRVs are the lowest energy electric solution, with some form of centralized heat recovery system serving the corridors. For DHW, in-suite electric water heaters are the lowest energy electric system.

For natural gas systems, only centralized options are possible in the absence of natural gas distribution. All centralized systems rely on hydronic distribution, and provided low temperature operation is achieved with a condensing gas boiler, the energy performance when heating is comparable for all terminal unit options. Figure 5-5 displays annual energy consumption of select centralized natural gas thermal comfort systems across the various locations modelled.

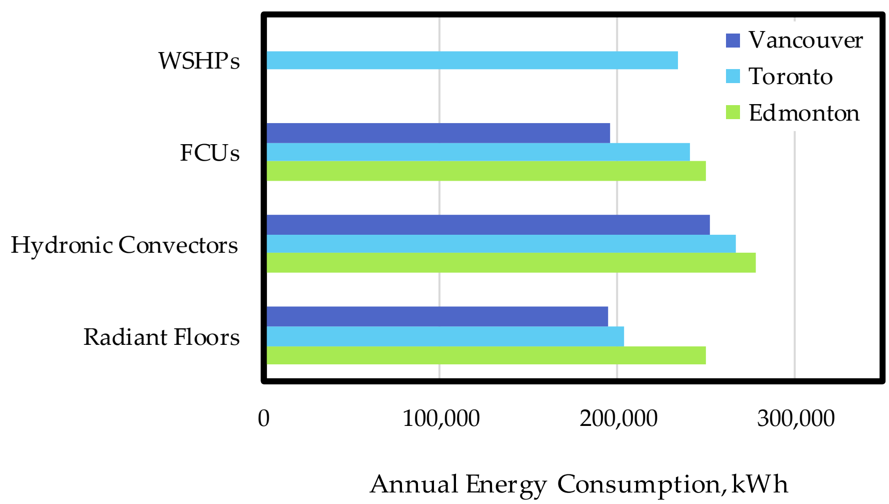


Figure 5-5: Annual energy consumption for select centralized natural gas thermal comfort systems in code-based reference buildings in Vancouver (CZ5), Toronto (CZ6), and Edmonton (CZ7). Note that the FCUs and WSHPs in Toronto include cooling, while all other systems are heating only.

Radiant floors offer low maintenance, low space requirements within suites, and better control of space operative temperatures in exchange for higher capital costs. Water source heat pumps are another more capital cost intensive option, but offer some potential energy savings through the ability to simultaneously heat and cool different spaces, as well as the capital cost savings of only requiring one set of supply and return piping to each unit. Ducted fan coil units are a cheaper option, and like WSHPs, FCUs enable the additional functions of filtration and cooling if desired. These benefits come at the expense of more noise, and FCUs require design as well as specification in order to achieve low temperature operation.

The only centralized natural gas based indoor air quality system modelled was a pressurized corridor system, which has high site energy consumption, GHG emissions, and often operating costs in addition to all of the previously discussed performance issues in exchange for low capital costs and ease of maintenance. A centralized DOAS with heat recovery and supplemental gas heating would be a superior option from an energy and IAQ standpoint, but would be difficult to balance in addition to having significantly higher capital costs. A more realistic alternative to pressurized corridors would be floor by floor DOAS with heat recovery and supplemental natural gas heating, though this would still be much more capital intensive and require distribution of natural gas to each floor.

For natural gas DHW, a central condensing boiler with storage tanks is the cheapest and lowest energy solution. Capital costs can potentially be lowered even further by combining the DHW system with the thermal comfort system in order to reduce the number of boilers. Combining suite-by-suite heat recovery ventilation with such a comfort system provides an effective affordable system: using condensing DHW and space heating equipment would minimize energy use.

5.2.2 Electricity and Natural Gas in Suites

The decision to pipe natural gas to each suite represents a significant incremental cost, and is often only taken if suite-by-suite natural gas systems are desired.

The most traditional in-suite natural gas thermal comfort system is an AHU with a natural gas furnace. These systems are easily sub-metered, less complex, and can provide filtration and cooling via direct expansion refrigerant coils in addition to heating.

The availability of in-suite natural gas does not have a significant influence over the choice of indoor air quality systems, although if in-suite HRVs/ERVs are to be used, combining the supply of outdoor air into the AHU supply stream can alleviate the risk of thermal comfort issues from poor air mixing or cold/hot ventilation air temperatures.

If DHW is also to be provided on a suite-by-suite basis, the lowest energy option is a condensing hot water heater. While these systems are efficient, and in the case of tankless heaters take up minimal space, they are significantly more expensive than non-condensing storage tank hot water heaters. Combination DHW and thermal comfort systems offer potential here, but if centralized systems are possible, a central condensing boiler providing DHW would be a cheaper and easier to maintain option with the downside that distribution losses can become significant.

5.2.3 Separate Suite-by-suite Systems

In some cases, whether driven by ownership structures, billing of utilities, or other extenuating circumstances, it can be desirable to completely separate all mechanical systems by suite. In this way, each suite contains all of the equipment necessary to provide all required mechanical system functions.

Many suite-by-suite thermal comfort systems are available, but due to space limitations, combination thermal comfort and DHW systems are very desirable, particularly if using natural gas. Figure 5-6 displays a summary of all in-suite combination thermal comfort and DHW systems modelled. Note that high efficiencies are only achieved through use of condensing water heaters. While tankless water heaters could in theory be combined with any hydronic system, they require more careful design than tanked systems. In addition, warmer climates such as Toronto cannot provide a complete system with just radiant floor or hydronic convector based systems as these cannot provide space cooling.

In the case of electric space conditioning, the best trade off of capital cost and energy performance is provided by electric baseboards for heating only, and heat pumps with direct expansion cooling if necessary. Note that as electric baseboard systems would not benefit from increased efficiency through the use of combination systems, along with the fact that electric baseboards already consume minimal suite area, a separate electric storage tank water heater is the best choice for all-electric systems using electric baseboards.

For suite-by-suite indoor air quality systems, HRVs or ERVs, either ducted independently or tied into the supply air stream of an in-suite AHU, provide the lowest energy consumption. Operating costs and GHG emissions would be largely dependent on whether natural gas or electricity was used for space heating.

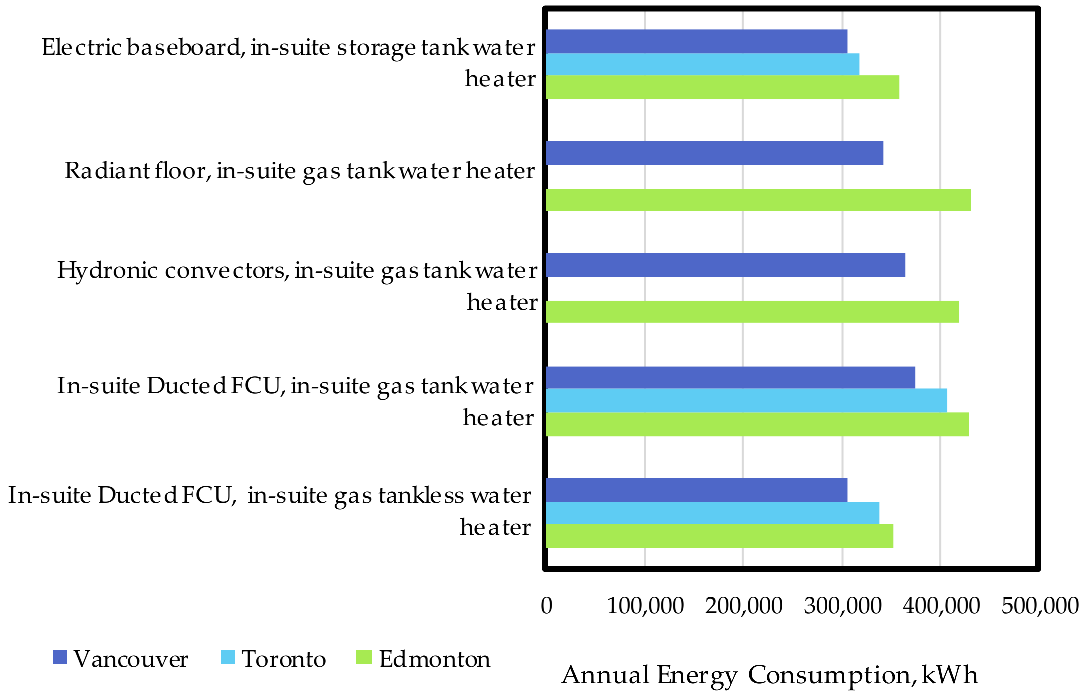


Figure 5-6: Annual energy consumption for in-suite combination thermal comfort and domestic hot water systems in code-based reference buildings in Vancouver (CZ5), Toronto (CZ6), and Edmonton (CZ7). Note that the FCUs in Toronto include cooling, while all other systems are heating only.

5.3 Stakeholders

Stakeholders represent different parties involved in the construction and operation of high-rise MURBs, each with different priorities. As these priorities dictate the relative ranking of different mechanical system characteristics, each stakeholder group will have a different viewpoint on what constitutes the best mechanical system. By considering each group separately, one can form recommendations for a wide variety of use cases.

5.3.1 Condo Owners

Condo owners are people who choose to purchase a suite in a given high-rise MURB, thereby taking ownership over that portion of the building along with obligations to condition and maintain the common spaces. Condo owners generally are more concerned with the long term value of the property rather than the initial sale. Furthermore, condo owners typically prioritize ease of maintenance, low operating costs, aesthetics, and acoustics. However, condo owners rarely, if ever, understand, or have influence over, the myriad factors that influence the performance of a building, or are in position to judge the often very favourable cost-benefit trade-offs for investing slightly more to gain a much lower operating cost solution.

The choice of thermal comfort system varies depending on whether cooling is required or not. Without a need for cooling, radiant floors with central natural gas boilers offer low energy use, low operating costs, central access for maintenance, no noise, and no impact on suite aesthetics other than some restrictions on floor coverings. If cooling is required, in-suite ducted 4-pipe FCUs offer low operating costs and low in-suite maintenance requirements. Aesthetic impact can be minimized by placing the unit in a mechanical closet and hiding ducts in bulkheads, however the acoustic impact is dependent on the design of the air distribution ductwork.

A floor by floor dedicated outdoor air system with ducted supply and return from each unit would typically offer the lowest operating cost and the lowest in-suite maintenance of any of the indoor air quality systems modelled. The impact on suite aesthetics can be minimized through the use of bulkheads to conceal ductwork. Acoustics can be a concern as noise transfer between units is dependent on the design of the air distribution ductwork.

A central condensing natural gas boiler providing DHW is the cheapest domestic hot water system from an operating cost perspective if distrivution piping losses and recirculating pumping energy are tightly managed. Furthermore, no space is required within each suite for equipment, and maintenance is centralized. This system is commonly implemented without any form of sub-metering, requiring communal sharing of DHW operating costs. If sub-metering of DHW is desired, it is typically achieved via in-suite systems. The lowest operating cost in-suite DHW system is a condensing natural gas water heater.

5.3.2 Managers of Rental Properties

Managers of rental properties either retain ownership of the entire building or act on behalf of the building owner, and oversee daily operations and maintenance. In some cases, the manager is also the developer behind the project. As such, maintenance costs as well as ease of access to perform maintenance are both important system characteristics, along with minimizing operating costs. Ease of sub-metering is not as important because utilities are often handled directly by the property manager. Furthermore, capital costs may also be of importance depending on the relationship between the manager and the developer.

Selecting a thermal comfort system which offers low capital costs, low operating costs, and low maintenance is a difficult balance. Electric baseboards are often selected for their low maintenance and low capital cost, but the price of electricity results in high operating costs in all locations. Hydronic baseboards represent a compromise which still offers fairly low capital cost, low maintenance, as well as low operating cost despite the fact that many systems still operate in non-condensing mode. Note that high temperature non-condensing hydronic systems, while notably less efficient than condensing systems, are still fairly cheap to operate in comparison to electric systems given the low cost of natural gas. For a higher capital cost but lower operating cost, radiant floors would offer even lower maintenance requirements as there are no convectors to become damaged or dirty. If cooling is required, ducted 4-pipe FCUs would offer cooling and filtration with minimal additional in-suite maintenance beyond filter changes.

There is no clear choice for indoor air quality system beyond the inclusion of heat recovery. It is difficult to recommend pressurized corridor systems because of their poor ventilation performance and the complaints associated with odour and noise transmission from corridors to suites. In-suite HRVs/ERVs would offer low operating costs, but have higher capital costs than pressurized corridor systems and require suite access for maintenance. Floor by floor DOAS with heat recovery would also offer low operating costs while removing the need for suite access, but the capital costs associated with these systems can be high due to the need for extensive supply and return ductwork, fire dampers between units, and ceiling space within corridors.

For domestic hot water, the lowest capital and operating cost solution would a central condensing natural gas boiler. In this case, given the need for a boiler plant as part of the thermal comfort system anyways, some capital cost could be saved by using the same boiler plant to also provide domestic hot water.

5.3.3 Developers of Condo Properties

Developers of condo properties fund the construction of high-rise MURBs for the express purpose of selling condo properties for profit. As such, capital cost, constructability, and aesthetics rank highly in terms of typical priorities. However, developers do try to cater to a market need, and so as other system characteristics such as greenhouse gas emissions become more important to general consumers, some developers will try to adjust their product to stay competitive, while many continue to focus on meeting code and selling visible features.

The lowest capital cost thermal comfort system for heating only climates is electric baseboards, with hydronic baseboards providing a slightly more expensive alternative if there is market demand for natural gas heating. Both systems take up minimal space within units, and are simple from a controls and constructability standpoint. If cooling is required, in-suite AHUs with electric furnaces and direct expansion cooling represents one of the cheapest and simplest options. If natural gas heating is desired, 2-pipe ducted FCUs with a central boiler and chiller would have relatively low capital cost compared to other heating and cooling systems.

The lowest capital cost indoor air quality system is pressurized corridor ventilation, although it is not permitted by building and energy codes in the coldest areas of Canada (CZ7 and CZ8). There are many well demonstrated performance issues with these systems, however, and as the demand for better indoor air quality increases, the increased capital cost of in-suite HRVs will likely become justified to meet market demand.

Central natural gas boilers offer the lowest capital cost domestic hot water solution, while also being typical practice within the industry.

5.3.4 Policy Makers

Policy makers are responsible for setting targets and requirements for the building industry through building codes and standards. Priorities of policy makers vary over time, but current high priorities involve reducing site energy consumption, reducing greenhouse gas emissions, and ensuring adequate indoor air quality.

Greenhouse gas emissions, as discussed in Section 5.1.2, are highly dependent on the carbon intensity of the electrical grid from which a given building sources its power. However, as the movement continues towards lower carbon grids in keeping with provincial and national carbon reduction objectives, the carbon intensity of grid electricity will play less of a factor and site energy consumption will become more important in all jurisdictions.

Within thermal comfort systems, heat pump technology provides the lowest site energy consumption. VRF heat pumps offer some added performance over typical packaged, distributed heat pumps given the ability to provide simultaneous heating and cooling during shoulder seasons. This comes at the price of higher risk due to lack of familiarity within the industry, as well as more potential for refrigerant leakage given the large charge of each system. Furthermore, ground source heat pumps improve performance over air source heat pumps given that heat pump COPs are a function of source temperature, and the ground temperature never drops below freezing in most Canadian cities. While VRF systems can be marginally to moderately more expansive than traditional FCU based hydronic systems, ground exchange fields are very capital cost intensive to construct making payback difficult to justify.

Electric resistance heating can offer a compelling balance of low risk, low maintenance, simple controls, and low capital cost. Provided additional resources are expended reducing heat loss by improving HRV’s and the building enclosure, electric resistance heating systems may become popular again across Canada. Heat pump technology would further reduce GHG emissions, but for low carbon grids in heating only climates, the incremental reduction likely is not warranted by the emissions reductions alone.

Within indoor air quality systems, heat recovery is the most effective means of reducing energy consumption and GHG emissions in comparison to traditional pressurized corridor systems. The three most common ways of implementing heat recovery are in-suite HRVs or ERVs, in-suite AHUs providing space conditioning as well as ventilation, and floor based dedicated outdoor air systems with ducted supply and return from each suite.

Solar thermal systems offer the lowest domestic hot water energy consumption of any of the systems modelled, particularly if an electric backup boiler is implemented. However, these systems are more expensive than other options, and energy savings vary by location for the same load and solar thermal array. Furthermore, due to the form factor of high rise MURBs, as the number of floors increases, the ratio of roof area to DHW load decreases. This results in a decrease in savings due to insufficient solar resource. Solar thermal systems are therefore more suited for use in low- and mid-rise MURBs.

In-suite electric storage tank water heaters offer the lowest site energy consumption following solar thermal systems with lower capital costs and less system complexity. For low carbon grids, these systems would also offer GHG reductions over traditional central natural gas boilers.

Chapter 6 : Conclusions and Recommendations

Mechanical systems currently implemented in Canadian high-rise MURBs are diverse and numerous, each with specific characteristics driving their selection. Through the review of literature and building simulations, conclusions can be drawn with respect to the selection of mechanical systems, and recommendations can be formed with respect to future work.

6.1 Conclusions

Location and climate tend to impact ventilation loads significantly, while only modestly impacting space conditioning loads as the building enclosure performance, because of building codes and local construction practices, reflect the severity of climate in which they are situated.

The carbon intensity of the electrical grid is the largest determining factor for mechanical system greenhouse gas emissions in applications using electricity as the primary fuel source.

Heat pump technology, however it is implemented, delivers the lowest site energy consumption of all available technologies. Operating cost and greenhouse gas emissions are not necessarily lower than other options, and are dependent on the climate and electrical grid.

All low temperature hydronic systems with condensing natural gas boilers deliver comparable energy performance, regardless of terminal unit.

Air-to-air heat recovery, however it is implemented, significantly reduces ventilation energy consumption and greenhouse gas emissions relative to pressurized corridor systems. Operating cost savings are dependent on location and climate.

Combination thermal comfort and domestic hot water systems powered by natural gas offer a suite-by-suite alternative to centralized natural gas systems that may require more maintenance but offer reduced distribution losses, sub-metering of domestic water and space heating at a small increase in site energy consumption.

Solar thermal domestic hot water systems offer potential reduction in site energy consumption, greenhouse gas emissions, and operating cost over traditional systems in low- and mid-rise MURBs. In high-rise construction, the ratio of roof area to load decreases with building height such that the savings potential drops off from lack of available solar resource.

Rational mechanical system selection should be based on the relative importance of competing system characteristics. However, the ranking of important characteristics varies amongst different stakeholder groups, and is partly subjective. Thus, system recommendations for different stakeholder groups vary and no clear best practice option emerged from the analysis.

6.2 Recommendations

While the scope of this thesis was quite broad, it could be expanded in a number of ways to further explore this area. Low- and mid-rise MURBs could be evaluated to determine lower building height might impact system selections. Furthermore, more reference buildings could be added to the modelling analysis to reflect different form factors, lower enclosure to conditioned floor area ratios, and lower suite areas.

The energy modelling analysis demonstrated little variation in energy consumption between centralized and distributed hydronic systems due to the fact that pumps were assumed to be perfectly sized, operating at ideal part load ratios, with no thermal distribution losses through the pipework. These assumptions were necessary for this analysis, but field experience suggests the relative magnitude of the distribution losses is large and poorly quantified. A targeted study could measure the thermal output of the central plant while also measuring the heat transferred to or from terminal units within each suite in a representative high-rise MURB. Through these measurements, the magnitude of distribution losses could be quantified.

Heat pump technology demonstrated the lowest site energy, and can be implemented for space conditioning as well as domestic hot water. Few systems are available for DHW supply in North America. The added complexity of the system tends to make this performance more capital cost intensive, and the use of electricity over natural gas can make operating costs more expensive than competing traditional technologies. A targeted study could focus on the use of heat pump technology specifically in order to identify key factors and scenarios in which such technology can be cost competitive in high-rise MURBs.

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Appendix A: Energy Use in Buildings

Energy use in buildings has been an area of increasing study over the past few decades. Between the residential and commercial sector, buildings use 30% of secondary energy in Canada (Natural Resources Canada, 2014). In order to discuss energy and buildings, several key concepts must be introduced, including energy sources, energy sinks, source vs. site energy, global warming potential, the Canadian energy grid, normalized energy metrics, and the definition of a low-energy building.

A.1 Energy Sources

Before energy can be used in buildings, it must first be captured from an energy source. In a broad sense, all energy on earth originally came from the sun, but the specific intermediaries through which it is captured can vary. Typically, primary energy is sourced through one of the following practices:

1. Fossil fuel combustion to release thermal energy
2. Biomass or biogas combustion to release thermal energy
3. Nuclear decay of radioactive materials to release thermal energy
4. Solar energy, captured either as thermal energy or as electricity via photovoltaics
5. Gravitational energy, captured from falling water (hydro), wind, or waves as kinetic energy
6. Geothermal energy from the Earth's core captured as thermal energy

Note that many of the above energy sources provide thermal or kinetic energy which is difficult to transport over large distances and is of low energy quality. For this reason, the energy derived from these sources is often converted into other forms which have more desirable characteristics such as electricity or hydrogen. It is incorrect to refer to electricity or hydrogen as energy sources however as they are more correctly identified as forms of energy transmission.

A.2 Energy Sinks

In contrast to energy sources, energy sinks are places to which unwanted thermal energy is rejected – typically in space cooling applications. In the context of buildings, these usually are limited to the following:

1. Air surrounding a building
2. Bodies of water in close proximity to a building, such as ponds, rivers, or ground water.
3. Soil adjacent to or underneath a building

Note that in the specific case of vapour compression refrigeration technology, these energy sinks can also serve as thermal energy sources.

A.3 Source vs. Site Energy

Converting energy to different forms, along with transporting energy over large distances has associated losses as required by the second law of thermodynamics. Energy from one of the sources discussed in Section A.1 is referred to as source energy, and serves as a reference point. From there it is frequently converted to a more preferable energy transport medium such as electricity with substantial losses. The energy is then transported from the location of the energy source to the building, which may be as small a distance as a few meters in the case of rooftop photovoltaic panels, or as large a distance as hundreds of kilometers in the case of large scale power plants.

The proportion of source energy consumed per unit of energy available at a given building site is referred to as the source-to-site ratio, and varies by location, time, and form of energy transmission. As such, most published values only discuss conversions at a national or provincial level as the true source-to-site ratio at a specific building is often very difficult to calculate.

While any energy source discussed in Section A.1 could be used at a building level, typical discussions of source-to-site ratio involve three forms of energy transmission: electricity purchased from the grid, electricity generated on site, and natural gas purchased from a utility.

Natural gas is not just a means of energy transmission, but a source of energy itself, and so the only losses reflected in the source to site ratio are associated with the procurement and transportation of the fuel.

Electricity generated on a building site is typically limited to photovoltaic panels or local wind installations for practical reasons, and the source-to-site ratio is often considered to be unity. While there are thermodynamic losses inherent with the energy conversion process, as there is no financial cost associated with these losses, on site electricity generation is considered to be completely efficient.

Electricity purchased from the grid for use in buildings is one of the main reasons the concept of source-to-site ratio has become a mainstay in discussions of building energy consumption. General discussions in a North American context refer to the electrical grid as being about 30% efficient, with 10% of the losses associated with transportation and the remainder being due to energy conversions (K. Ueno & Straube, 2010).

Energy Star – a US Environmental Protection Agency (EPA) program – produced a summary of source-to-site ratios for energy sources in Canada based on national data from 2007-2011, which can be seen in Table A-1.

Table A-1: Canadian national average source-to-site ratios for electricity and natural gas (Energy Star, 2013)

Fuel Type	Canadian source-to-site ratio
Electricity (Grid Purchase)	2.05
Electricity (on-site solar or wind installation)	1.00
Natural gas	1.02

A.4 Global Warming Potential

Globally, temperatures have been increasing, which is viewed negatively as many natural systems – both on a microscopic and macroscopic scale – rely on a stable climate. In comparison to 1951-1980 averages, the global temperature has risen to date by 0.75°C (NASA, 2014). The scientific consensus for the primary cause of this warming is the buildup of greenhouse gasses (GHGs) in the atmosphere. There are a number of GHGs, but the most common is carbon dioxide (CO_2) as it is emitted by organic life, the combustion of organic matter, and exists naturally in the atmosphere. As such, carbon dioxide is used as a metric to describe global warming potential for all GHGs in terms of kg CO_2 equivalent.

The first two energy sources discussed in Section 0 are differentiated from the rest as they require combustion of organic matter in order to release thermal energy, resulting in the direct release of GHGs. Indirect contributions can be made by these or any other energy source if the energy transport infrastructure utilized in the movement from the source location to the site location also requires the combustion of organic matter.

In the context of building energy use, annual kg CO_2 equivalent is often used as a metric to describe the global warming potential of building operations. Other markers exist to describe a given building's environmental impact such as annual water consumption or building material types, but kg CO_2 equivalent is the metric most closely related to building energy consumption.

A.5 Canadian Energy Grid

The Canadian energy grid is fairly diverse, and relies on a number of different energy sources to provide electricity to built facilities. Nationally, the majority of electricity generated in Canada comes from hydroelectricity, but the percentage breakdown can be seen in Figure A-1.

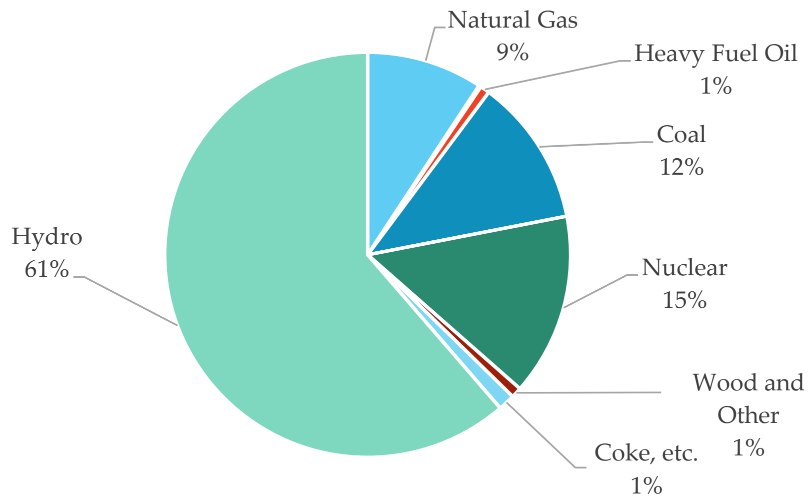

Figure A-1: 2011 Canadian annual electricity generation by energy source (Natural Resources Canada, 2014)

Hydro and nuclear may be the largest energy sources for electricity generation in Canada, but they do not contribute to GHG emissions in any substantial fashion. Figure A-2 displays the annual GHG emissions from electricity generation in metric tons CO_2 equivalent. Note that coal only provides 12% of national electricity generation, but is responsible for 65% of GHG emissions.

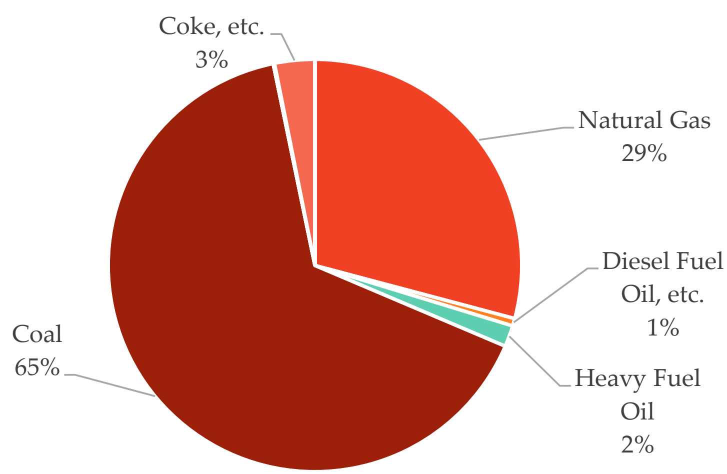

Figure A-2: 2011 Canadian annual natural gas emissions from electricity generation by energy source (Natural Resources Canada, 2014)

The breakdown of generation sources influences local energy prices, GHG emissions, and source-to-site ratios. As such, it is important to understand the energy infrastructure on a provincial scale because this influences design decisions when selecting energy sources at a building level. Within the scope of this research, Ontario, Alberta, and British Columbia are of note.

In Ontario in 2015, the total electricity generated was predominantly from nuclear generation at 60%, with hydro being the second largest source at 24% (Independent Electricity System Operator, 2016). The remaining sources include natural gas at 10%, and wind at 6%, with minimal installations of solar and biofuel. Alberta relies more heavily on fossil fuels for electricity, with 55% of electricity generated in 2014 being derived from coal, and another 35% from natural gas (Government of Alberta, 2015). The remaining 10% comes from a combination of hydro, wind, biomass and biogas. British Columbia achieves roughly 90% of its electricity generation through hydro, with the remainder coming largely from natural gas (Whiticar, 2012).

Hydro and nuclear generation do have environmental impacts, but these are beyond the scope of this discussion. In the context of building energy use, hydro and nuclear both have no global warming potential while also maintaining relatively low source-to-site ratios. Fossil fuel generation through the combustion of coal and natural gas do have significant GHG emissions and result in high source-to-site ratios. As such, British Columbia and Ontario have very different energy grids than Alberta, which influences system design decisions.

Table A-2 displays the conversion factors associated with converting site energy consumption to greenhouse gas (GHG) emissions based on fuel source and location (BC Ministry of Environment, 2014). Conveniently, the GHG intensity varies by about an order of magnitude as one moves from BC, to Ontario, and another order of magnitude when considering Alberta. Hence, the study in this thesis covers a broad representative range.

Table A-2: Greenhouse Gas conversion factors for various fuel sources across Canada (BC Ministry of Environment, 2014)

Fuel Source	kg CO_2e/GJ
Natural Gas, stationary fuel combustion	49.75
Electricity, BC Hydro	2.8
Electricity, Ontario average	29
Electricity, Alberta average	225

A.6 Normalized Energy Metrics

Total annual energy consumption can be useful in some instances, but when comparing buildings of different size, the number can be misleading. This is because a larger more efficient building can use more total energy than a smaller less efficient building within the same building type simply because the larger building has higher loads. In order to generate consumption values for fair comparisons, normalized metrics are often implemented.

Energy usage intensity (EUI) is one of the most widely used normalized energy metrics. It is calculated by dividing the total annual energy consumption by the building floor area. While this concept seems simple, there are still inconsistencies which arise from variances in calculation assumptions such as the use of site or source energy or the inclusion of unconditioned or semi-conditioned floor area (Kohta Ueno, 2010a). Furthermore, EUIs still do not account for variances in climate, and tend to penalize smaller dwellings.

Within Canadian MURBs, the average EUI varies from around 200 kWh/m^2 in milder climates such as Vancouver to 300 kWh/m^2 in colder climates such as Toronto (RDH Building Engineering, 2012; Touchie et al., 2013).

Energy usage per dwelling or energy usage per occupant can also be useful metrics for residential buildings. Similar to energy usage intensity, the annual energy consumption can be divided by the number of dwelling units or occupants within the building.

A.7 Low-Energy Buildings

The term low-energy building has been widely used, and can have many different definitions. In the simplest of terms, a low-energy building is a building that uses less energy than similar buildings within that building type.

In Europe, countries which have adopted low-energy standards or guidelines often define low-energy as some percentage reduction in site energy consumption with respect to the minimum requirements of the applicable building code. The value varies from 30% better than code in Austria all the way to 75% better than code in Denmark, with many countries falling in-between (Thomsen, Wittchen, & EuroACE, 2008). Furthermore, some countries such as Belgium require air tightness testing for conformance with the standard.

In Canada, building codes typically cite the National Energy Code for Buildings (NECB) or ASHRAE Standard 90.1 – Energy Standard for Buildings Except Low-rise Residential Buildings. These codes represent a baseline conformance level, but no national low-energy building standard exists to govern buildings which exceed the minimum compliance levels. Instead, low-energy buildings are typically governed by compliance with various building certification programs.

Leadership in Energy and Environmental Design (LEED) is a certification program ran by the Canadian Green Building Council in Canada. The program is largely voluntary, but certain cities require some level of LEED certification for specific new construction projects, such as the City of Vancouver (City of Vancouver, 2014). Points are awarded within a number of different areas, but energy performance points – if pursued by the design team – are achieved by demonstrating percentage improvements over a baseline building (Canada Green Building Council, 2010).

Energy Star is another North American certification program ran by the US Department of Energy for classifying energy efficient products ranging from small appliances to large buildings. Certification of houses and multifamily residences requires a 15% improvement over building code compliance (Energy Star, 2016).

Passive house is a certification program which originated in Germany and is operated in Canada by the Canadian Passive House Institute (CanPHI). Unlike other programs, Passive House is specifically for low-energy residential buildings in cold climates, and puts an emphasis on energy usage intensities and measured air tightness. For certification, a building must have less than a 15 kWh/m^2 heating demand, and less than a 120 kWh/m^2 total site energy consumption, along with an enclosure airtightness of less than 0.6 Ac/h at 50 Pa (Canadian Passive House Institute, 2016).

Appendix B: Belmont Drawings

This Appendix contains two complete sets of drawings:

- The Belmont – Architectural Drawings – Issued for Tender and Permits, February 23, 2012 – RDH Building Engineering
- The Belmont – Mechanical Drawings – Issued for Construction – May 6, 1985 – Sterling, Cooper & Associates

Appendix B: Belmont Drawings

RDH | Building Engineering Ltd.

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VANCOUVER BC V5Y 1N5

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FAX 604 873 0933

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WWW.RDHBE.COM

THE BELMONT
BUILDING ENCLOSURE REHABILITATION

OWNER:
STRATA PLAN VR1647

ADDRESS:
5425 Yew Street,
VANCOUVER, BC

LIST OF GENERAL DRAWINGS:

A-0.00	COVER SHEET
A-1.00	SITE PLAN / GROUND FLOOR PLAN
A-1.01	TYPICAL FLOOR PLAN
A-1.02	12TH FLOOR PLAN & PENTHOUSE FLOOR PLAN
A-1.03	ROOF PLAN & ELEVATOR MACHINERY ROOM PLANS
A-2.01	WEST & SOUTH ELEVATIONS
A-2-01A	**ALTERNATE PRICE** - EAST & WEST ELEVATIONS (EXTENT OF METAL PANEL)
A-2.02	EAST & NORTH ELEVATIONS
A-2.02A	**ALTERNATE PRICE** - EAST & NORTH ELEVATIONS (EXTENT OF METAL PANEL)
A-3.01	WINDOW & DOOR SCHEDULES
A-3.02	CURTAIN WALL SCHEDULE

LIST OF SCHEDULES & DETAIL DRAWINGS (Bound Separately):

SCH-0.00 SCHEDULES:

SCH-0.00	DETAIL DRAWING & SCHEDULES LIST
SCH-0.01	WALL ASSEMBLY SCHEDULE
SCH-0.02	WALL ASSEMBLY SCHEDULE
SCH-0.03	DECK / ROOF ASSEMBLY SCHEDULE

D-1.00 EXTERIOR WALLS:

D-1.01	TYPICAL CROSS-CAVITY FLASHING AT SLAB EDGE
D-1.01a	TYPICAL CROSS-CAVITY FLASHING AT SLAB EDGE (a)
D-1.02	TYPICAL BASE OF WALL AT GROUND FLOOR
D-1.03	TYPICAL INSIDE CORNER
D-1.04	TYPICAL OUTSIDE CORNER
D-1.05	TYPICAL CROSS-CAVITY FLASHING AT CORNERS
D-1.06	TYPICAL CROSS-CAVITY FLASHING AT TERMINATION
D-1.07	PARKADE AIR INTAKE VENT
D-1.08	TOP OF FIREPLACE WALL AT DECK
D-1.09	TYPICAL FIBREGLASS GIRT SYSTEM
D-1.10	-- NOT USED --
D-1.11	TYPICAL CONTROL JOINT
D-1.12	TYPICAL VERTICAL CONTROL JOINT

D-2.00 BALCONIES, DECKS & PATIOS:

D-2.01	TYPICAL BASE OF CONCRETE WALL AT DECK
D-2.02	TYPICAL DECK PARAPET
D-2.03	TYPICAL DECK AT BASE OF FIREPLACE WALL
D-2.04	TYPICAL SADDLE FLASHING

D-4.00 ROOFS:

D-4.01	TYPICAL ROOF PARAPET
D-4.02	TYPICAL ROOF AT BASE OF MECHANICAL ROOM WALL
D-4.03	ROOF MEMBRANE TIE-IN AT RETAINED METAL DOOR
D-4.04	MECHANICAL ROOM ROOF PARAPET

D-5.00 CANOPIES, SKYLIGHTS & ASSOCIATED GLAZING:

D-5.01	-- NOT USED --
D-5.02	TYPICAL SLOPED GLAZING HEAD AT PARAPET
D-5.03	TYPICAL SLOPED GLAZING TRANSITION TO CURTAIN WALL WINDOW HEAD
D-5.04	TYPICAL JAMB AT SLOPED GLAZING
D-5.05	TYPICAL SLOPED GLAZING TRANSITION TO CURTAIN WALL WINDOW HEAD AT SLIDING DOOR
D-5.06	VERTICAL CURTAIN WALL SILL AT DECK
D-5.07	TYPICAL CURTAIN WALL CORNER POST
D-5.08	CURTAIN WALL CORNER POST AT SLIDING DOOR JAMB
D-5.09	CURTAIN WALL JAMB AT SLIDING DOOR JAMB
D-5.10	CURTAIN WALL JAMB
D-5.11	CURTAIN WALL JAMB AT RATED FIREPLACE SHAFT
D-5.12	SKYLIGHT RAFTER OVER PARTITION (UNIT 1202)
D-5.13	SKYLIGHT JAMB AT CONCRETE SHEAR WALL (GRID LINE 5)
D-5.14	TYPICAL CURTAIN WALL SILL
D-5.15	CURTAIN WALL JAMB AT COPLANAR WALL
D-5.16	CURTAIN WALL JAMB AT INSIDE CORNER
D-5.17	CURTAIN WALL JAMB AT CONCRETE SHEAR WALL (GRID LINE 6)
D-5.18	CURTAIN WALL JAMB AT PARTITION (NORTH ELEVATION)

D-6.00 WINDOWS & DOORS:

D-6.01	TYPICAL WINDOW HEAD
D-6.01a	TYPICAL WINDOW HEAD (a)
D-6.02	TYPICAL WINDOW SILL
D-6.02a	TYPICAL WINDOW SILL AT ENCLOSED BALCONY
D-6.03	TYPICAL WINDOW JAMB AT CONCRETE SHEAR WALL (GRID LINE 6)
D-6.03a	TYPICAL BASE OF METAL CLOSURE AT WINDOW SILL FLASHING (GRID LINE 6)
D-6.04	TYPICAL WINDOW JAMB AT COPLANAR WALL
D-6.05	TYPICAL WINDOW JAMB AT BEDROOM INSIDE CORNER
D-6.06	TYPICAL WINDOW JAMB AT CONCRETE COLUMN
D-6.07	TYPICAL WINDOW JAMB AT ENCLOSED BALCONY INSIDE CORNER
D-6.08	TYPICAL WINDOW JAMB AT INSIDE CORNER
D-6.09	TYPICAL WINDOW JAMB AT LIVING ROOM INSIDE CORNER
D-6.10	TYPICAL WINDOW JAMB AT OUTSIDE CORNER POST
D-6.11	TYPICAL WINDOW JAMB AT PARTITION (NORTH ELEVATION)
D-6.12	WINDOW SILL AT KITCHEN COUNTER
D-6.13	WINDOW HEAD AT PENTHOUSE ROOF OVERHANG
D-6.14	WINDOW JAMB AT CONCRETE WALL (UNIT 101 - GRID 6)
D-6.20	SLIDING DOOR HEAD AT CANOPY - LEVEL 13
D-6.21	SLIDING DOOR SILL AT DECK
D-6.22	SLIDING DOOR JAMB AT FIREPLACE WALL
D-6.23	RETAINED METAL DOOR JAMB

D-7.00 PENETRATIONS:

D-7.01	TYPICAL IN-SLAB EXHAUST VENT
D-7.02	TYPICAL UNDER-SLAB EXHAUST VENT
D-7.03	TYPICAL ROOF DRAIN
D-7.04	TYPICAL ROOF PLUMBING VENT
D-7.05	TYPICAL ROOF VENT
D-7.06	OVERFLOW SCUPPER AT MECHANICAL ROOM ROOF PARAPET

D-8.00 STRUCTURAL:

D-8.01	TYPICAL DECK PARAPET
D-8.02	WINDOW SILL AT KITCHEN COUNTER

D-9.00 ALTERNATE PRICE:

D-9.01	ALTERNATE PRICE - TYPICAL CANOPY - LEVEL 13
D-9.02	ALTERNATE PRICE - TYPICAL METAL PANEL CONTROL JOINT
D-9.03	ALTERNATE PRICE - TYPICAL METAL PANEL AT INSIDE CORNER
D-9.04	ALTERNATE PRICE - TYPICAL WINDOW HEAD AT METAL PANEL
D-9.05	ALTERNATE PRICE - TYPICAL WINDOW SILL AT METAL PANEL

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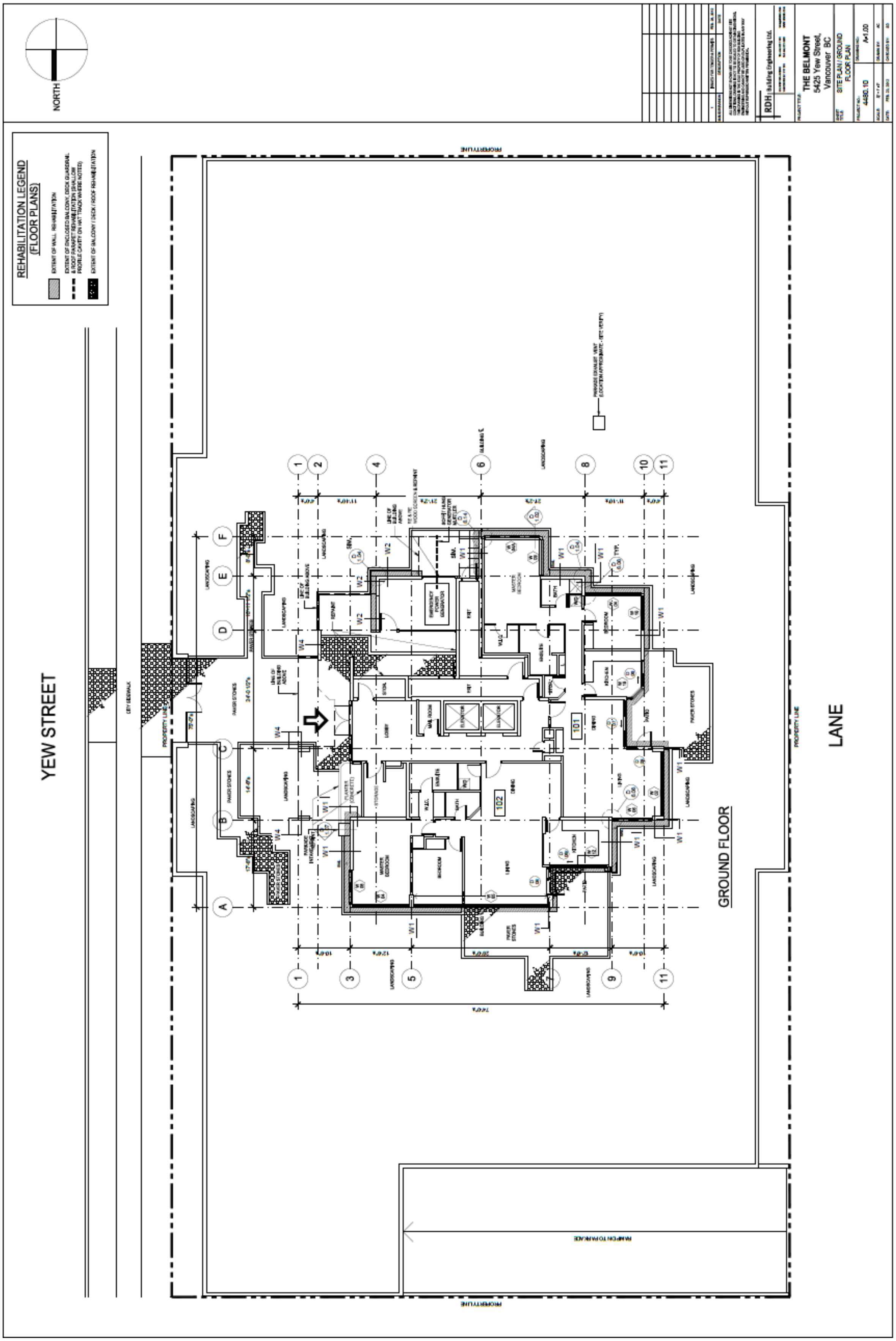
THE BELMONT
5425 Yew Street,
Vancouver BC

COVER SHEET

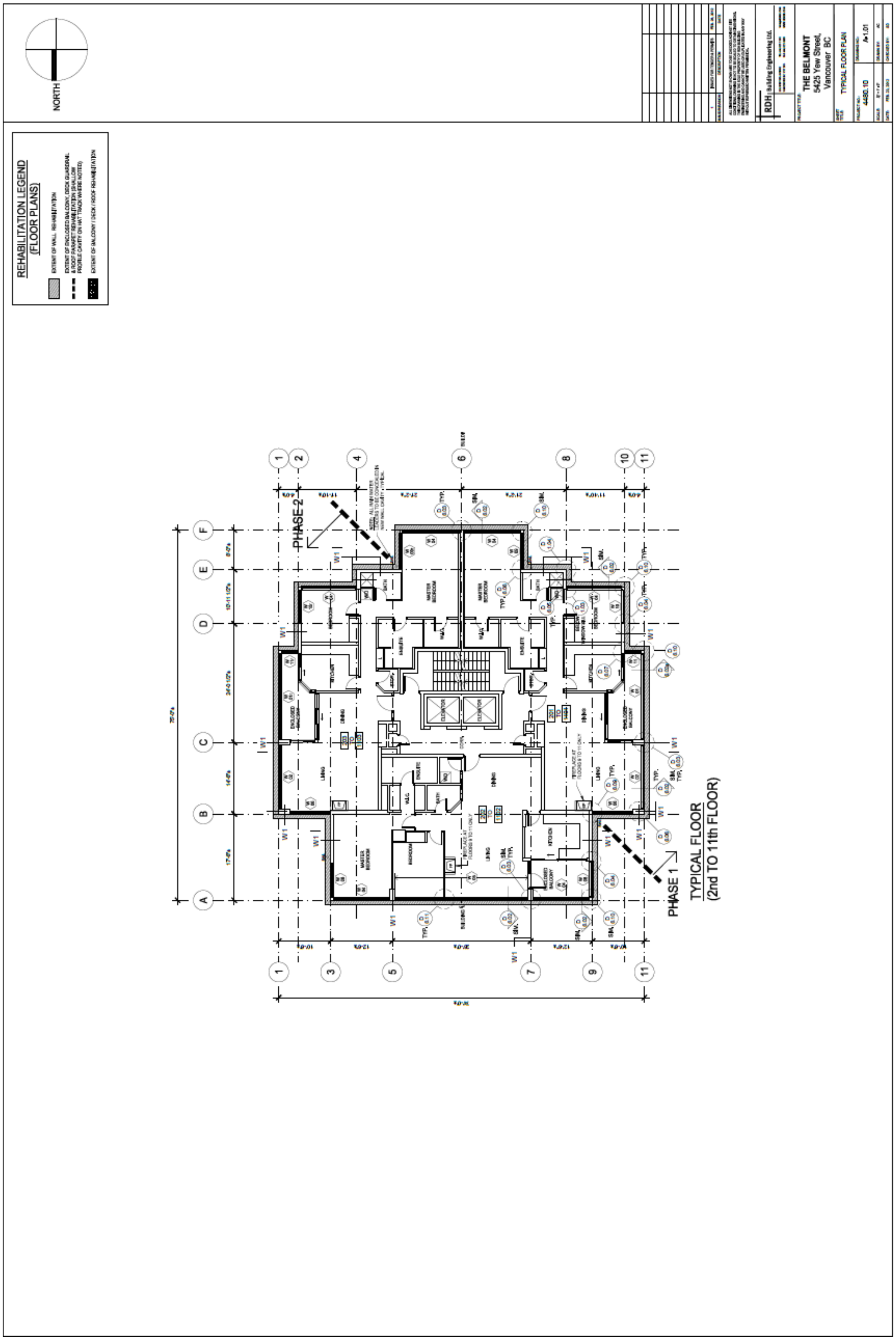
4480.10

A-0.00

Appendix B: Belmont Drawings



Appendix B: Belmont Drawings



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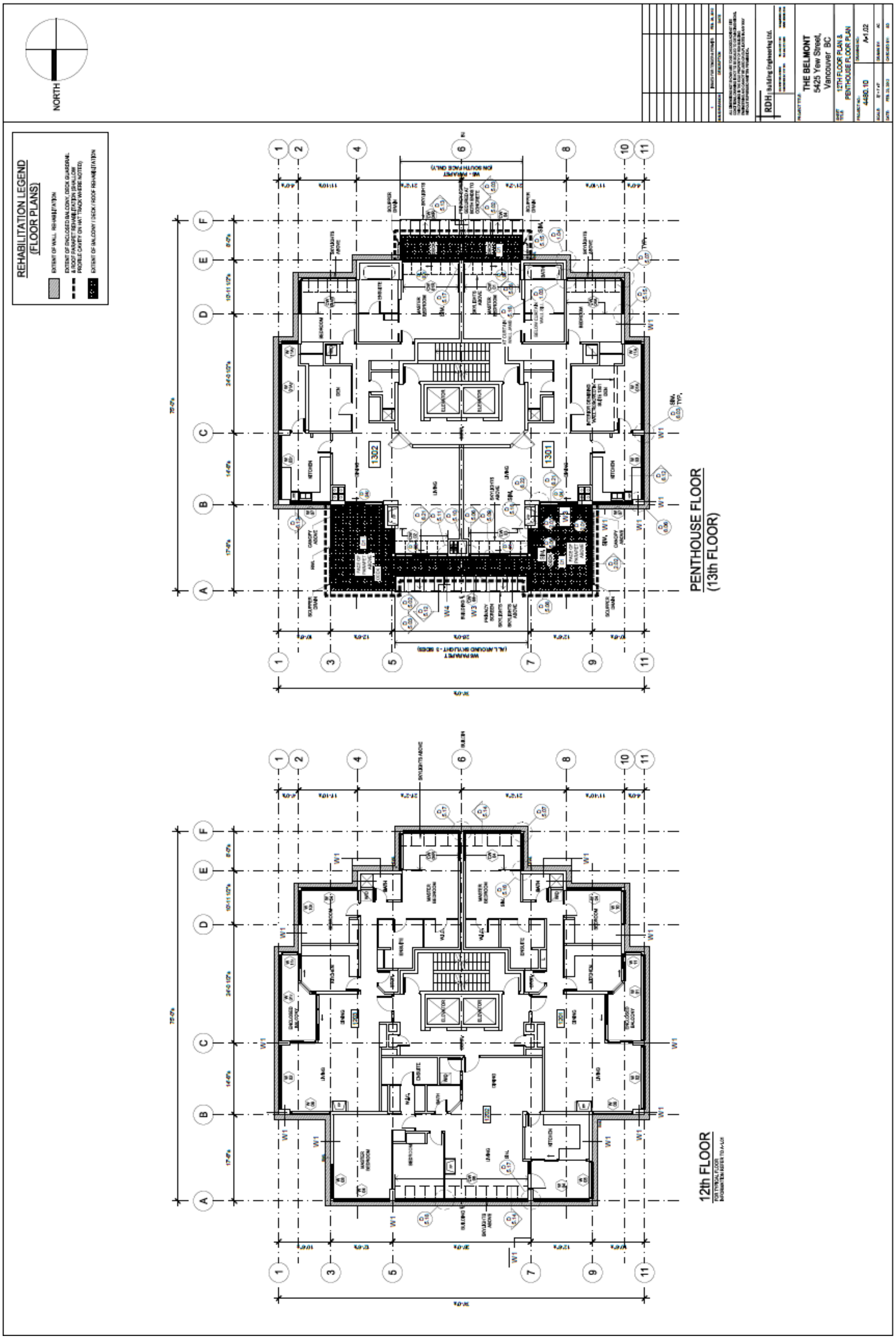

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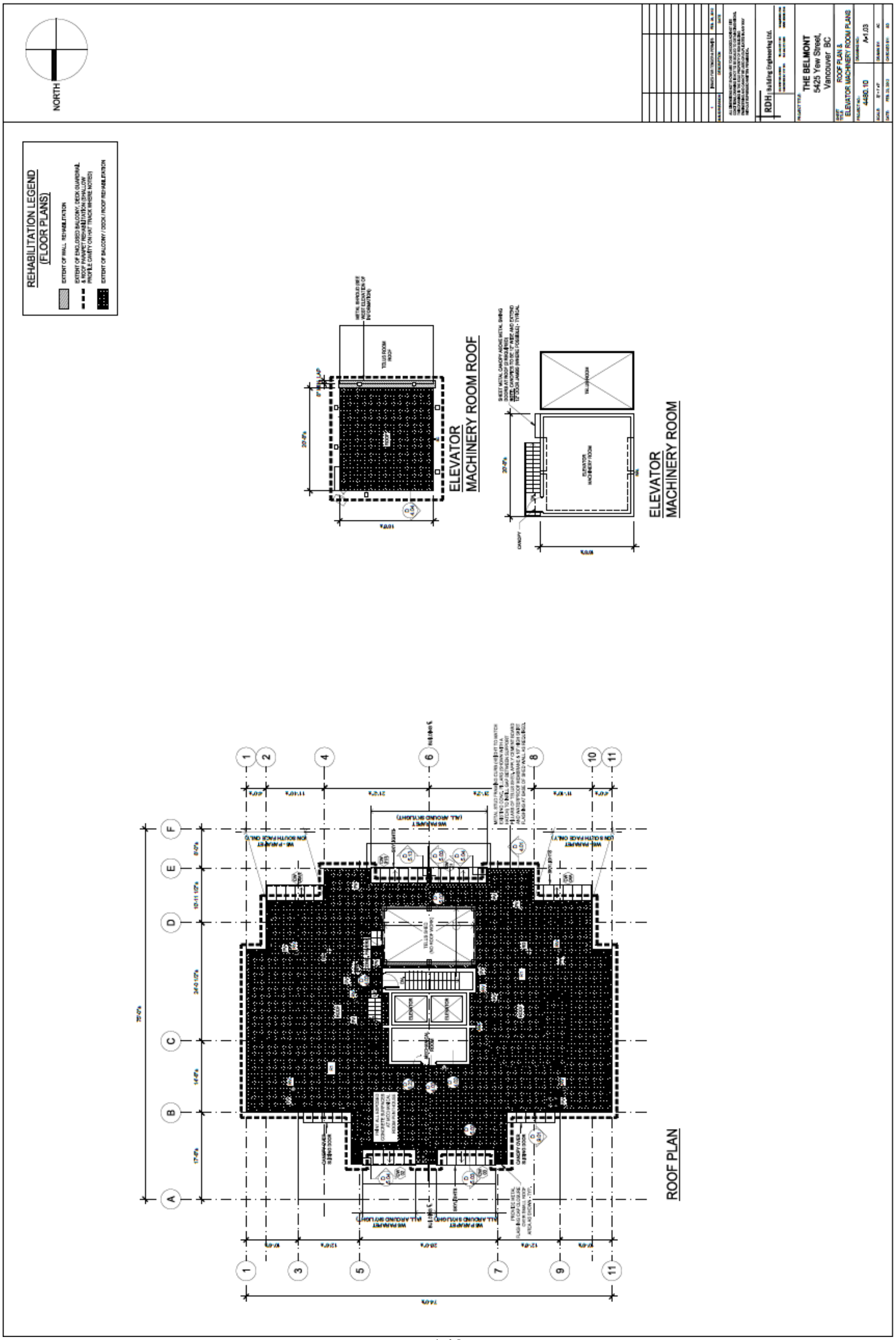

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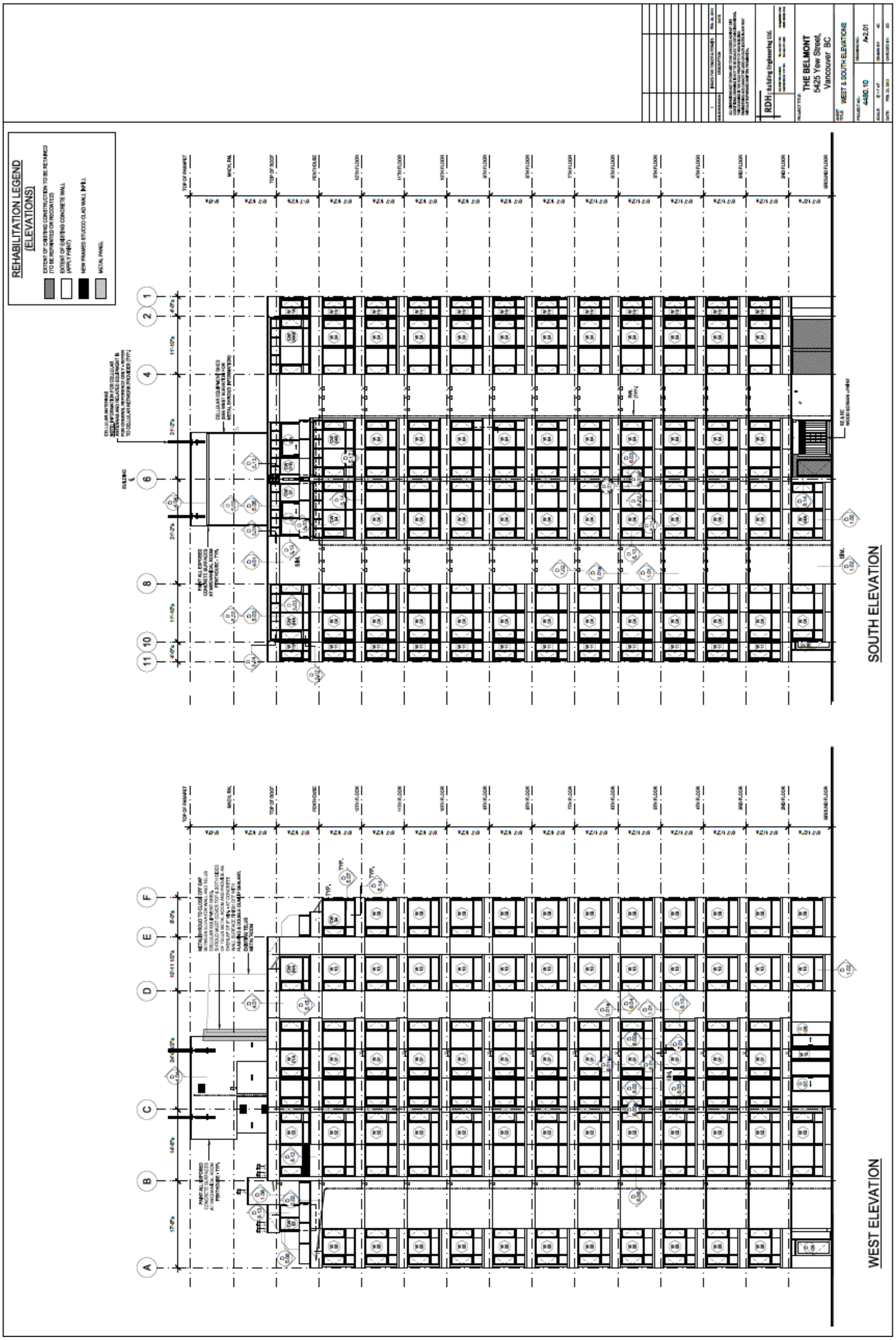
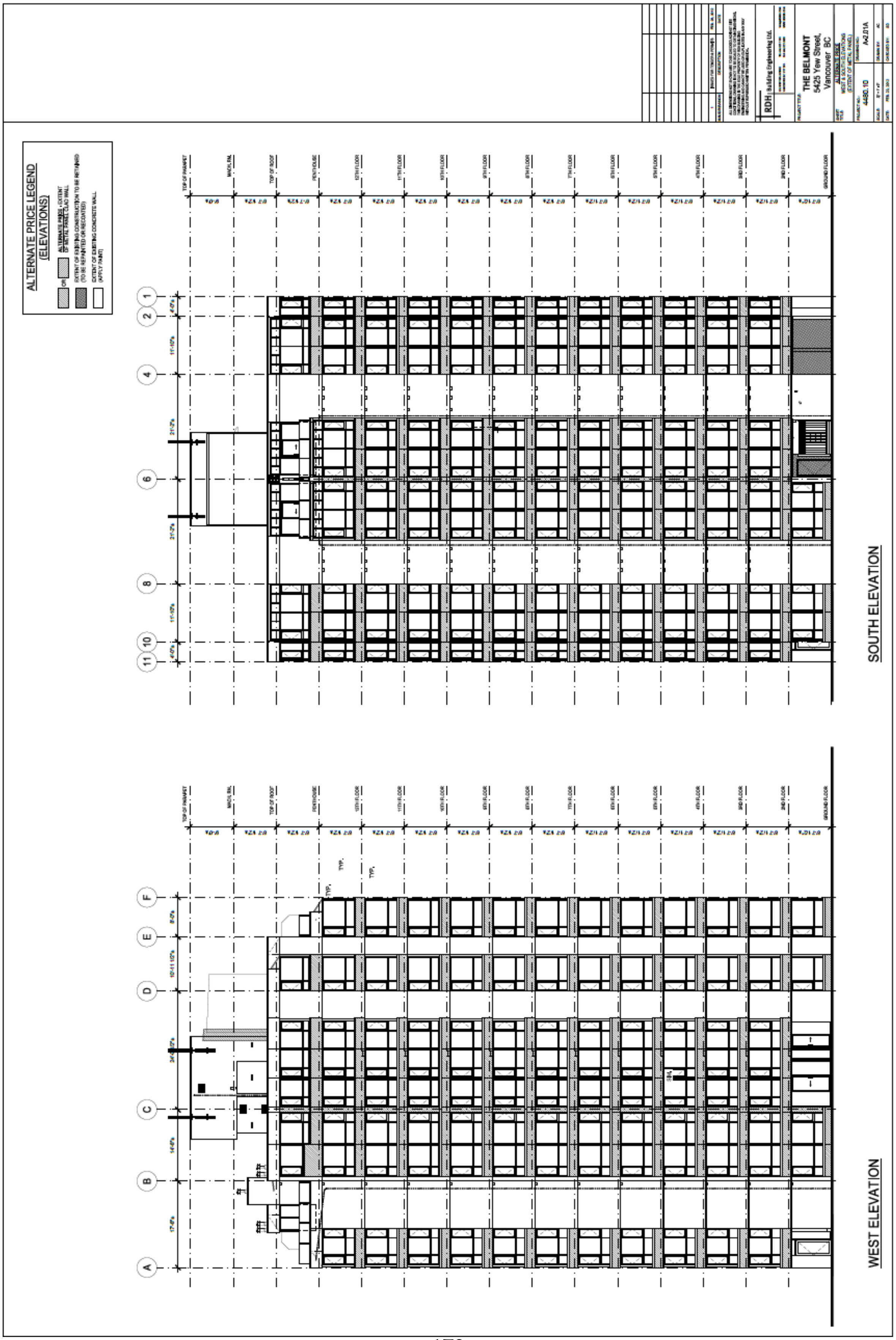


Appendix B: Belmont Drawings



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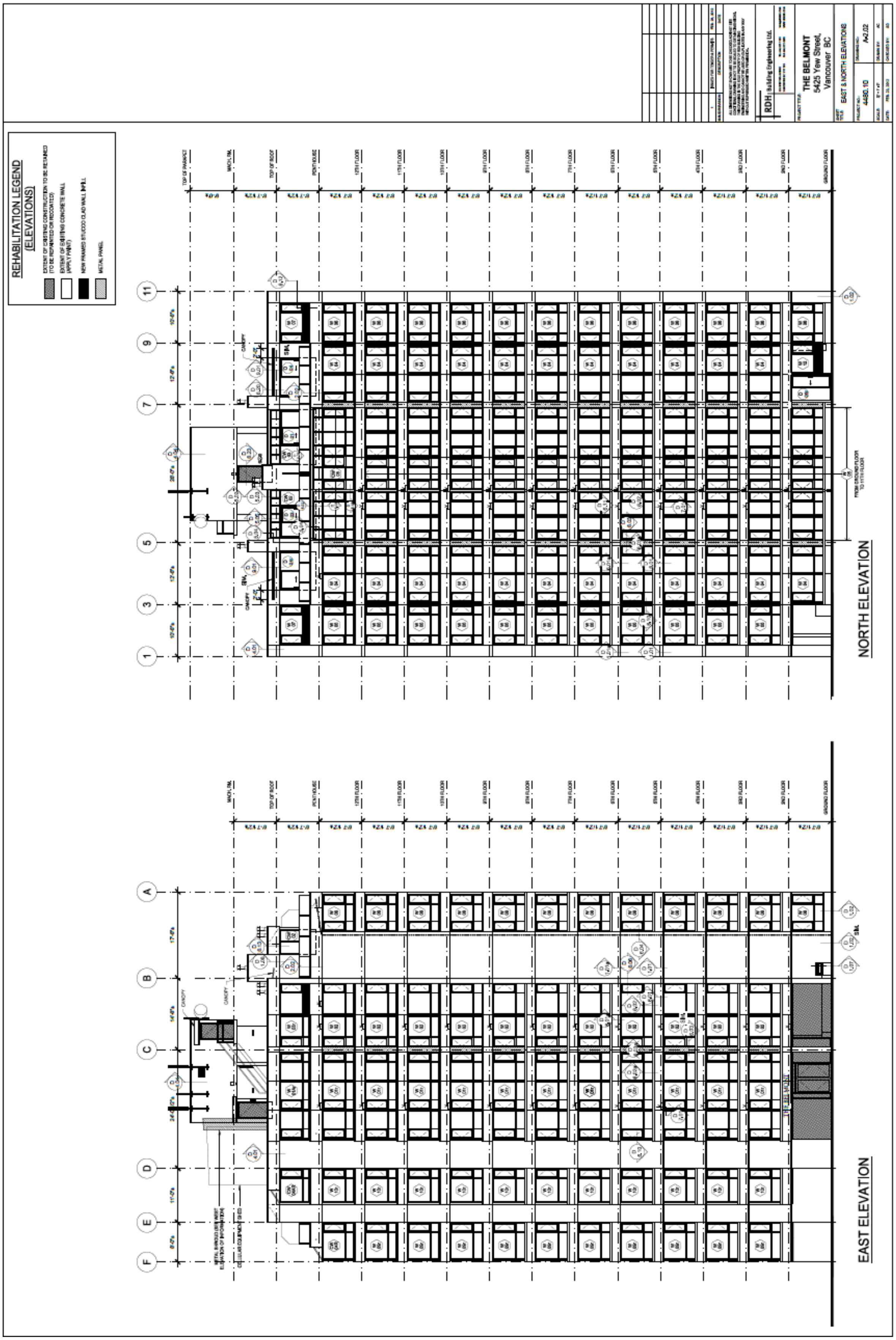
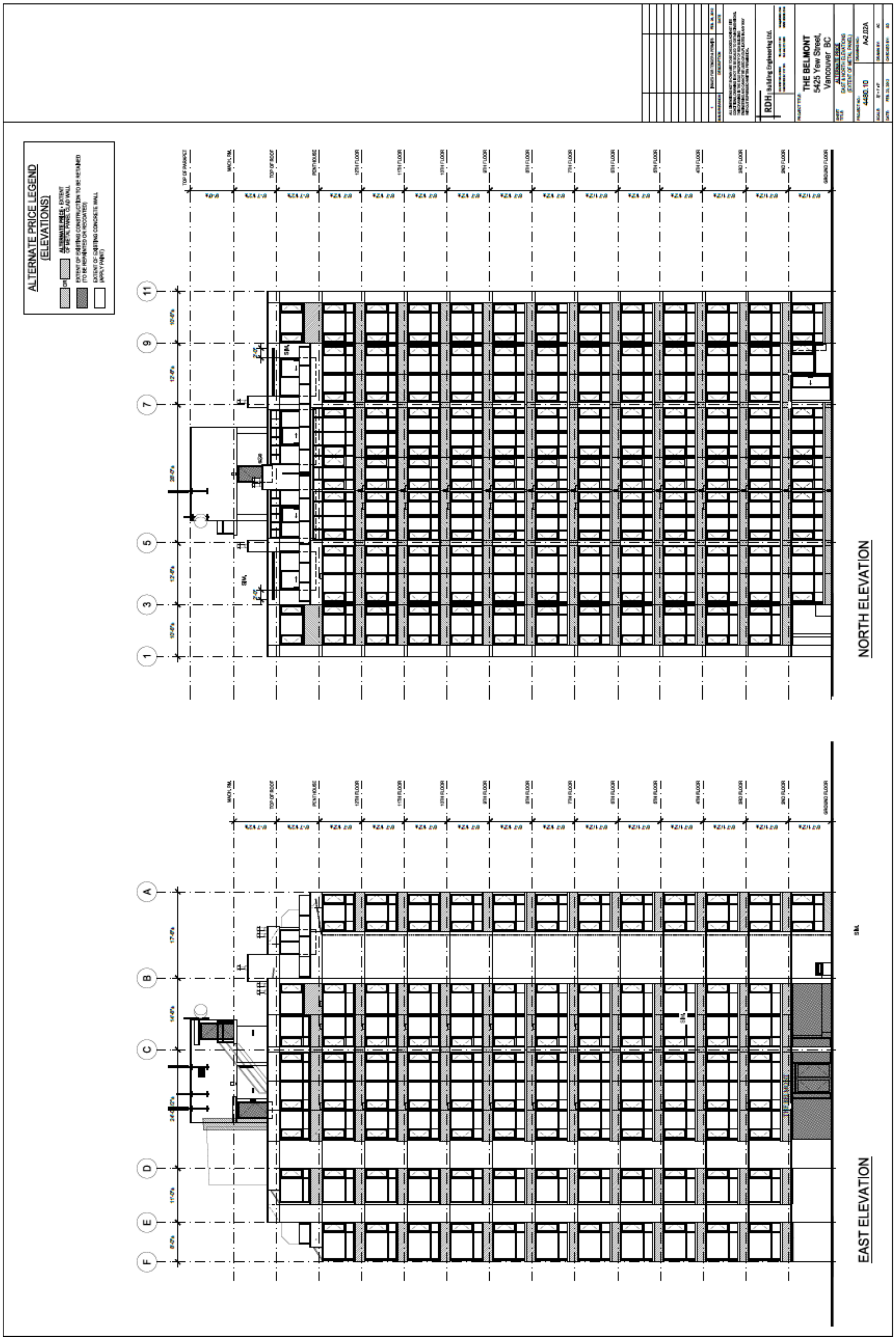
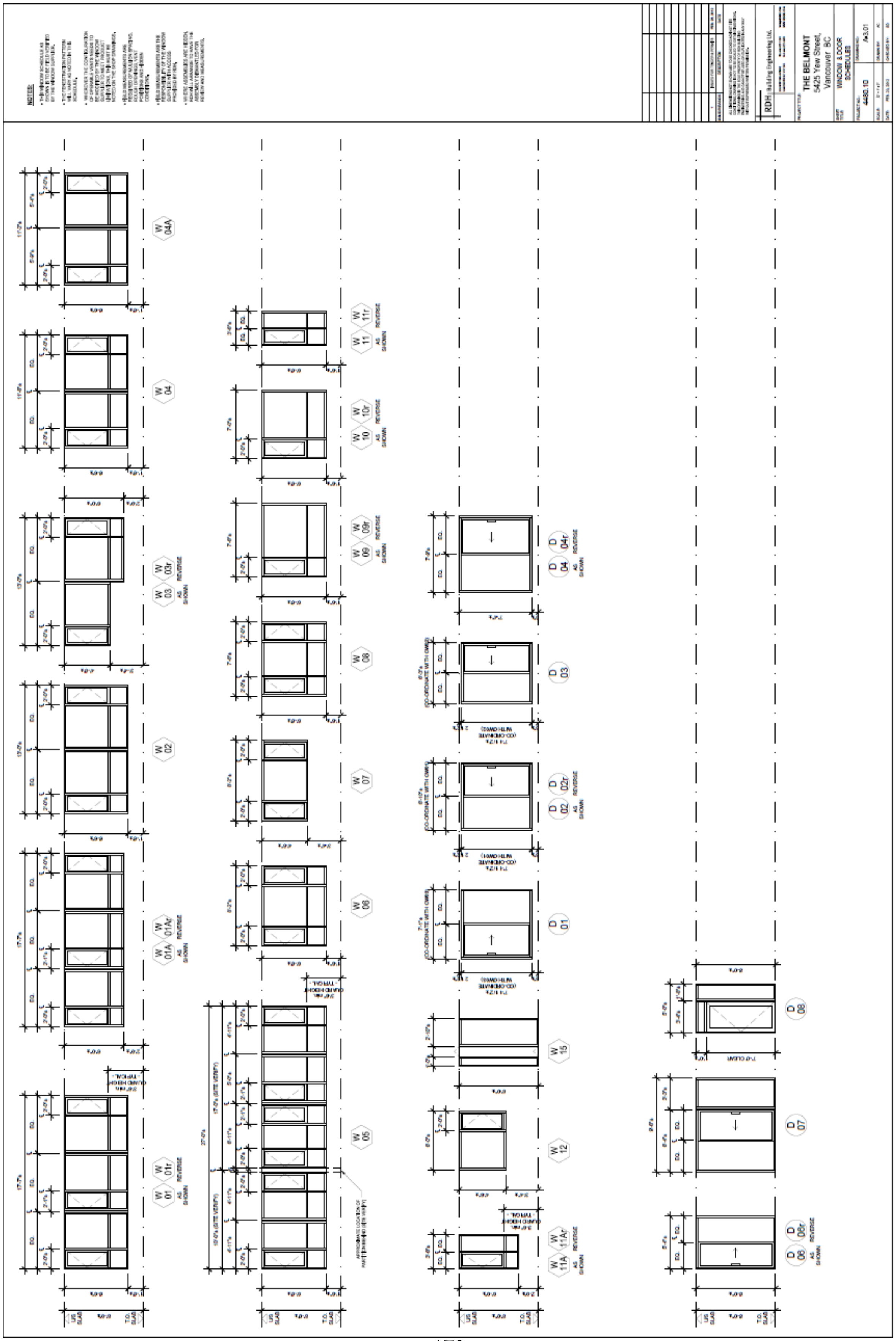


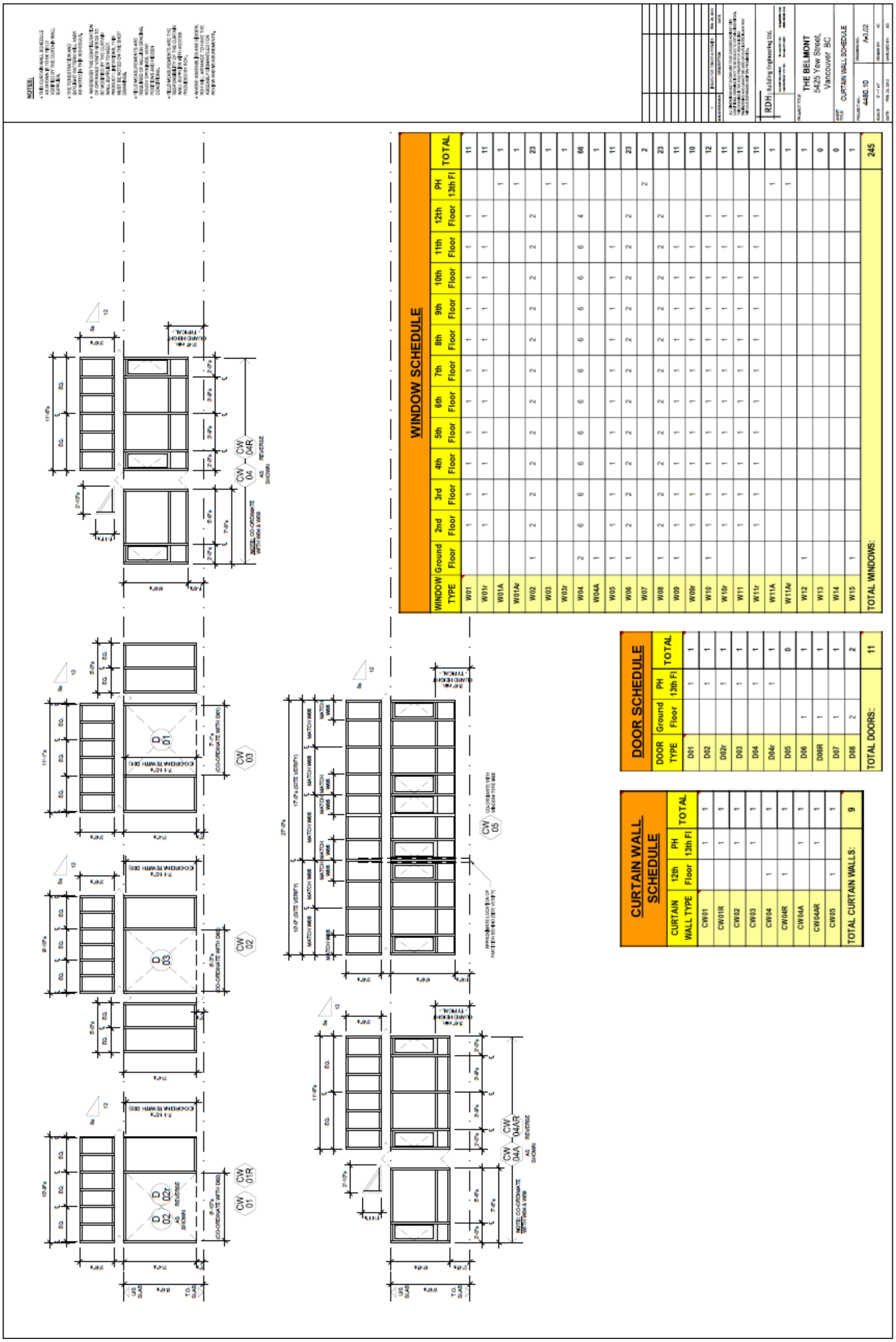
Appendix B: Belmont Drawings



Appendix B: Belmont Drawings



Appendix B: Belmont Drawings



WINDOW SCHEDULE

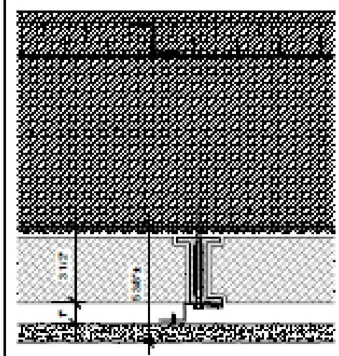
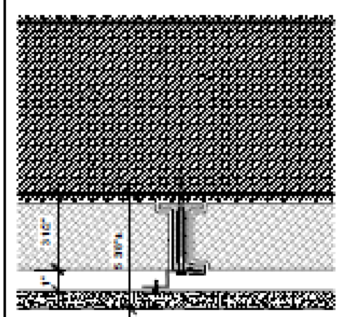
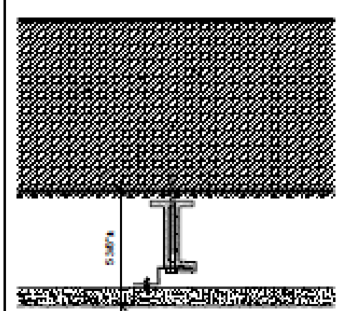
WINDOW TYPE	Ground Floor	2nd Floor	3rd Floor	4th Floor	5th Floor	6th Floor	7th Floor	8th Floor	9th Floor	10th Floor	11th Floor	12th Floor	PH 13th Fl	TOTAL
W01		1	1	1	1	1	1	1	1	1	1	1		11
W01r		1	1	1	1	1	1	1	1	1	1	1		11
W01A													1	1
W01Ar													1	1
W02	1	2	2	2	2	2	2	2	2	2	2	2		23
W03													1	1
W03r													1	1
W04	2	6	6	6	6	6	6	6	6	6	6	4		66
W04A	1													1
W05	1	1	1	1	1	1	1	1	1	1	1			11
W06	1	2	2	2	2	2	2	2	2	2	2	2		23
W07													2	2
W08	1	2	2	2	2	2	2	2	2	2	2	2		23
W09	1	1	1	1	1	1	1	1	1	1	1			11
W09r		1	1	1	1	1	1	1	1	1	1			10
W10	1	1	1	1	1	1	1	1	1	1	1	1		12
W10r		1	1	1	1	1	1	1	1	1	1	1		11
W11		1	1	1	1	1	1	1	1	1	1	1		11
W11r		1	1	1	1	1	1	1	1	1	1	1		11
W11A													1	1
W11Ar													1	1
W12	1													1
W13														0
W14														0
W15	1													1
TOTAL WINDOWS:														245

DOOR SCHEDULE

DOOR TYPE	Ground Floor	PH 13th Fl	TOTAL
D01		1	1
D02		1	1
D02r		1	1
D03		1	1
D04		1	1
D04r		1	1
D05			0
D06	1		1
D06R	1		1
D07	1		1
D08	2		2
TOTAL DOORS:			11

CURTAIN WALL SCHEDULE

CURTAIN WALL TYPE	12th Floor	PH 13th Fl	TOTAL
CW01		1	1
CW01R		1	1
CW02		1	1
CW03		1	1
CW04	1		1
CW04R	1		1
CW04A		1	1
CW04AR		1	1
CW05	1		1
TOTAL CURTAIN WALLS:			9

TYPE	LOCATION	DESCRIPTION (ALL MATERIALS ARE NEW UNLESS NOTED OTHERWISE)	SCHEMATIC DETAILS (n.t.s.) (EXIST. CONSTRUCTION TO BE RETAINED SHOWN TONED)
W1	TYPICAL CONCRETE EXTERIOR WALL	- EXISTING INTERIOR GYPSUM WALLBOARD - EXISTING 1 1/2" RIGID INSULATION - EXISTING FRAMING - EXISTING CONCRETE WALL (THICKNESS VARIES) - EXISTING ACRYLIC COATING (REPAIR DETERIORATED ACRYLIC COATING AS DIRECTED BY CONSULTANT) - INTERMITTENT 3 1/2" FIBREGLASS SPACERS @ 16" O.C. - 3 1/2" MINERAL FIBRE INSULATION - CONTINUOUS 1" VERTICAL GALVANIZED METAL Z-GIRT, HORIZONTALLY FASTENED TO EXISTING CONCRETE - 1" x 1 1/2" CONTINUOUS MINERAL WOOL STRIPS MIDWAY BETWEEN Z-GIRTS (NOT SHOWN FOR CLARITY) - 1" AIR SPACE – 7/8" STUCCO ASSEMBLY C/W ACRYLIC FINISH	INTERIOR  INTERIOR
W1A	TYPICAL CONCRETE EXTERIOR WALL AT ENCLOSED BALCONIES	- EXISTING ACRYLIC COATING - EXISTING CONCRETE WALL (THICKNESS VARIES) - EXISTING ACRYLIC COATING (REPAIR DETERIORATED ACRYLIC COATING AS DIRECTED BY CONSULTANT) - INTERMITTENT 3 1/2" FIBREGLASS SPACERS @ 16" O.C. - 3 1/2" MINERAL FIBRE INSULATION - CONTINUOUS 1" VERTICAL GALVANIZED METAL Z-GIRT, HORIZONTALLY FASTENED TO EXISTING CONCRETE - 1" x 1 1/2" CONTINUOUS MINERAL WOOL STRIPS MIDWAY BETWEEN Z-GIRTS (NOT SHOWN FOR CLARITY) - 1" AIR SPACE – 7/8" STUCCO ASSEMBLY C/W ACRYLIC FINISH	INTERIOR  INTERIOR
W2 & W2 sim.	EXTERIOR WALL (NOT INSULATED)	- EXISTING CONCRETE WALL (THICKNESS VARIES) - EXISTING ACRYLIC COATING (REPAIR DETERIORATED ACRYLIC COATING AS DIRECTED BY CONSULTANT) - INTERMITTENT 3 1/2" FIBREGLASS SPACERS @ 16" O.C. - CONTINUOUS 1" VERTICAL GALVANIZED METAL Z-GIRT, HORIZONTALLY FASTENED TO EXISTING CONCRETE - 7/8" STUCCO ASSEMBLY C/W ACRYLIC FINISH	EXTERIOR  INTERIOR

RDH Building Engineering Ltd.

ALL DIMENSIONS NOT SHOWN ARE TO BE CHECKED AGAINST SITE CONDITIONS. DRAWING IS NOT TO BE SCALED TO OBTAIN DIMENSIONS.

PROJECT: **THE BELMONT**
5425 Yew Street, Vancouver, BC

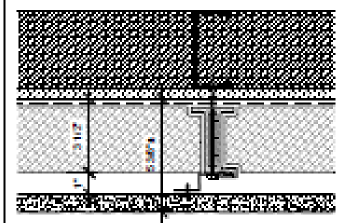
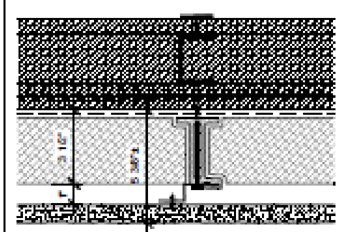
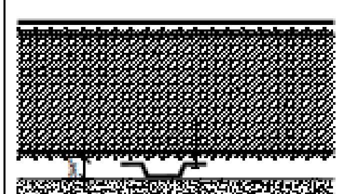
DRAWING TITLE: WALL ASSEMBLY SCHEDULE

DRAWING NO.: SCH-0.01

PROJECT NO.: 4480.10

ISSUE	DESCRIPTION	DATE
1	ISSUED FOR TENDER & PERMITS	FEB. 23, 2012

SCALE: —
DATE: FEB. 23, 2012
DRAWN BY: AC
CHECKED BY: SD

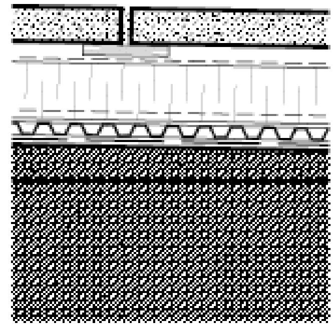
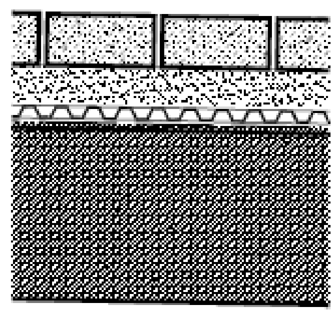
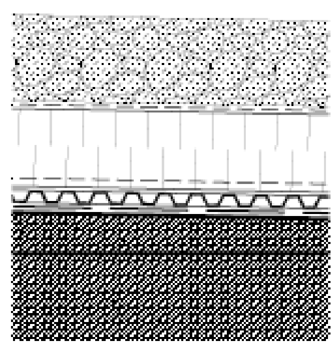
TYPE	LOCATION	DESCRIPTION (ALL MATERIALS ARE NEW UNLESS NOTED OTHERWISE)	SCHEMATIC DETAILS (n.t.s.) (EXIST. CONSTRUCTION TO BE RETAINED SHOWN TONED)
W3	EXTERIOR STUD WALL AT FIREPLACES	- EXISTING 3 5/8" STEEL STUDS @ 16" O.C. (REPLACE / REPAIR DETERIORATED FRAMING AS DIRECTED BY CONSULTANT) - 1/2" EXTERIOR GYPSUM WALLBOARD SHEATHING - SELF ADHESIVE MEMBRANE - INTERMITTENT 3 1/2" FIBREGLASS SPACERS @ 16" O.C. - 3 1/2" MINERAL FIBRE INSULATION - CONTINUOUS 1" VERTICAL GALVANIZED METAL Z-GIRT, HORIZONTALLY FASTENED TO EXISTING STUD - 1" x 1 1/2" CONTINUOUS MINERAL WOOL STRIPS MIDWAY BETWEEN Z-GIRTS (NOT SHOWN FOR CLARITY) - 1" AIR SPACE - 7/8" STUCCO ASSEMBLY C/W ACRYLIC FINISH NOTE: 1. REMOVE EXISTING STUCCO CLADDING AND RELATED ACCESSORIES, SHEATHING PAPER, EXTERIOR GYPSUM WALLBOARD, BATT INSULATION AND POLY VAPOUR BARRIER.	INTERIOR  INTERIOR
W4	2hr RATED EXTERIOR WALL AT FIREPLACE SHAFT	- EXISTING 3/4" TYPE 'X' SHAFTLINER - EXISTING 2 1/4" STEEL STUDS @ 2'-0" O.C. - EXISTING 2-LAYERS 5/8" GWB (IF EXISTING OUTER LAYER IS DETERIORATED, ADD 1 LAYER 1/2" EXTERIOR GYPSUM SHEATHING AS DIRECTED BY CONSULTANT) - SELF ADHESIVE MEMBRANE - INTERMITTENT 3 1/2" FIBREGLASS SPACERS @ 16" O.C. - 3 1/2" MINERAL FIBRE INSULATION - CONTINUOUS 1" VERTICAL GALVANIZED METAL Z-GIRT, HORIZONTALLY FASTENED TO EXISTING STUD - 1" x 1 1/2" CONTINUOUS MINERAL WOOL STRIPS MIDWAY BETWEEN Z-GIRTS (NOT SHOWN FOR CLARITY) - 1" AIR SPACE - 7/8" STUCCO ASSEMBLY C/W ACRYLIC FINISH NOTE: 1. REMOVE EXISTING STUCCO CLADDING AND RELATED ACCESSORIES, SHEATHING PAPER, EXTERIOR GYPSUM WALLBOARD, BATT INSULATION AND POLY VAPOUR BARRIER.	INTERIOR  INTERIOR
W5	TYPICAL WALL AT GUARDRAIL & ROOF PARAPET WHERE skylights TERMINATE OR BUTT	- METAL FLASHING (REFER TO DETAILS) - EXISTING ACRYLIC COATING - EXISTING CONCRETE WALL (THICKNESS VARIES) - EXISTING ACRYLIC COATING (REPAIR DETERIORATED ACRYLIC COATING AS DIRECTED BY CONSULTANT) - 1" HAT TRACK @ 8" O.C. (SECURED TO CONCRETE) - 3/4" AIR SPACE - 7/8" STUCCO ASSEMBLY C/W ACRYLIC FINISH OR METAL FLASHING (REFER TO DETAILS)	DECK / ROOF  EXTERIOR

RDH Building Engineering Ltd.

PROJECT:	THE BELMONT 5425 Yew Street, Vancouver, BC	DRAWING NO.:	SCH-0.02
DRAWING TITLE:	WALL ASSEMBLY SCHEDULE	PROJECT NO.:	4480.10

ALL DIMENSIONS NOT SHOWN ARE TO BE CHECKED AGAINST SITE CONDITIONS. DRAWING IS NOT TO BE SCALED TO OBTAIN DIMENSIONS.

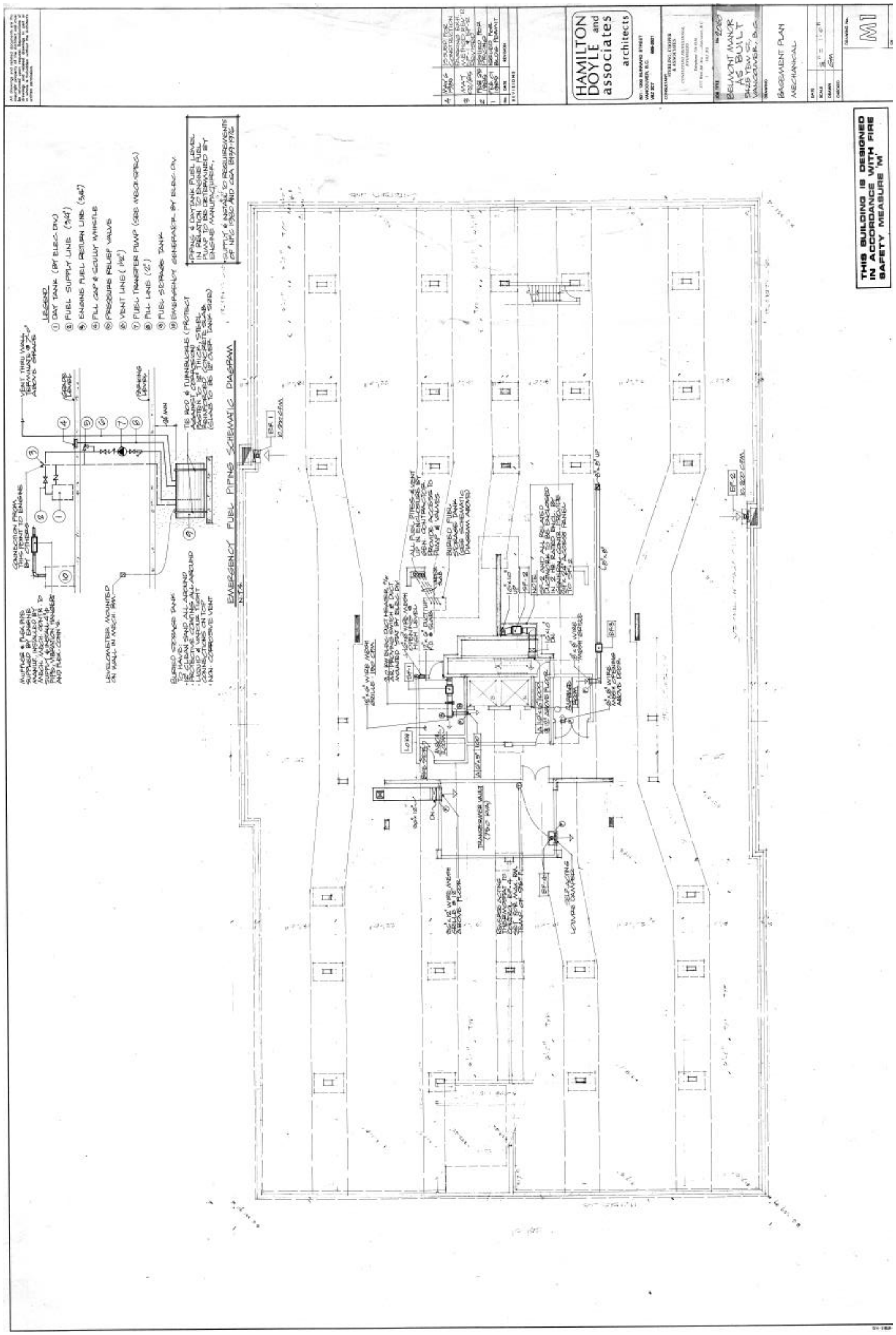
ISSUE	DESCRIPTION	DATE	
1	ISSUED FOR TENDER & PERMITS	FEB. 23, 2012	SCALE: —
			DATE: FEB. 23, 2012
			DRAWN BY: AC
			CHECKED BY: SD

TYPE	LOCATION	DESCRIPTION (ALL MATERIALS ARE NEW UNLESS NOTED OTHERWISE)	SCHEMATIC DETAILS (n.t.s.) (EXIST. CONSTRUCTION TO BE RETAINED SHOWN TONED)
D1	TYPICAL DECK	- RE & RE 18" x 18" x 1 5/8" CONCRETE PAVERS - PAVER PEDESTALS - FILTER CLOTH - 3" EXTRUDED POLYSTYRENE INSULATION - DRAINAGE MAT - DECK MEMBRANE - EXISTING SLOPED CONCRETE TOPPING (SLOPED TO SCUPPERS) - EXISTING STRUCTURAL CONCRETE SLAB **NOTES:** - REMOVE, STORE AND REUSE EXISTING PAVERS - REMOVE INSULATION & MEMBRANE.	EXTERIOR  INTERIOR
D2	TYPICAL PODIUM (PATIO)	- RE & RE EXISTING PRECAST INTERLOCKING PAVERS - RE & RE COMPACTED GRAVEL - DRAINAGE MAT - EXISTING PODIUM MEMBRANE - EXISTING SLOPED STRUCTURAL CONCRETE SLAB **NOTES:** - REMOVE AND STORE EXISTING INTERLOCKING PAVERS AND GRAVEL	EXTERIOR  PARKING
R1	ROOF	- RE & RE GRAVEL BALLAST - FILTER CLOTH - 4" EXTRUDED POLYSTYRENE INSULATION - DRAINAGE MAT - ROOF MEMBRANE - EXISTING SLOPED CONCRETE TOPPING (SLOPED TO DRAINS) - EXISTING STRUCTURAL CONCRETE SLAB **NOTE:** - REMOVE AND STORE EXISTING GRAVEL BALLAST - REMOVE AND DISPOSE OF EXISTING INSULATION & ROOF MEMBRANE	EXTERIOR  INTERIOR

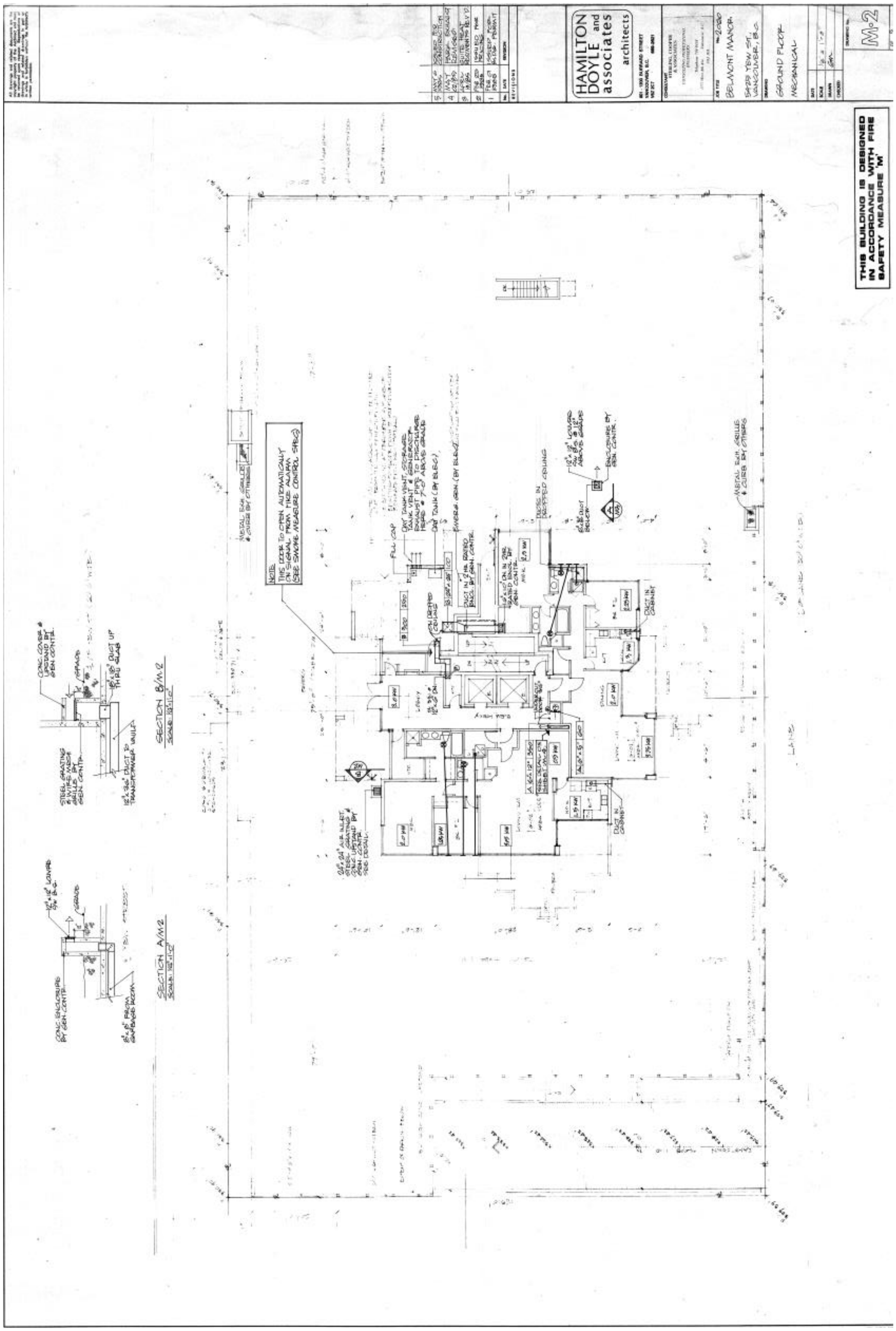
RDH Building Engineering Ltd.

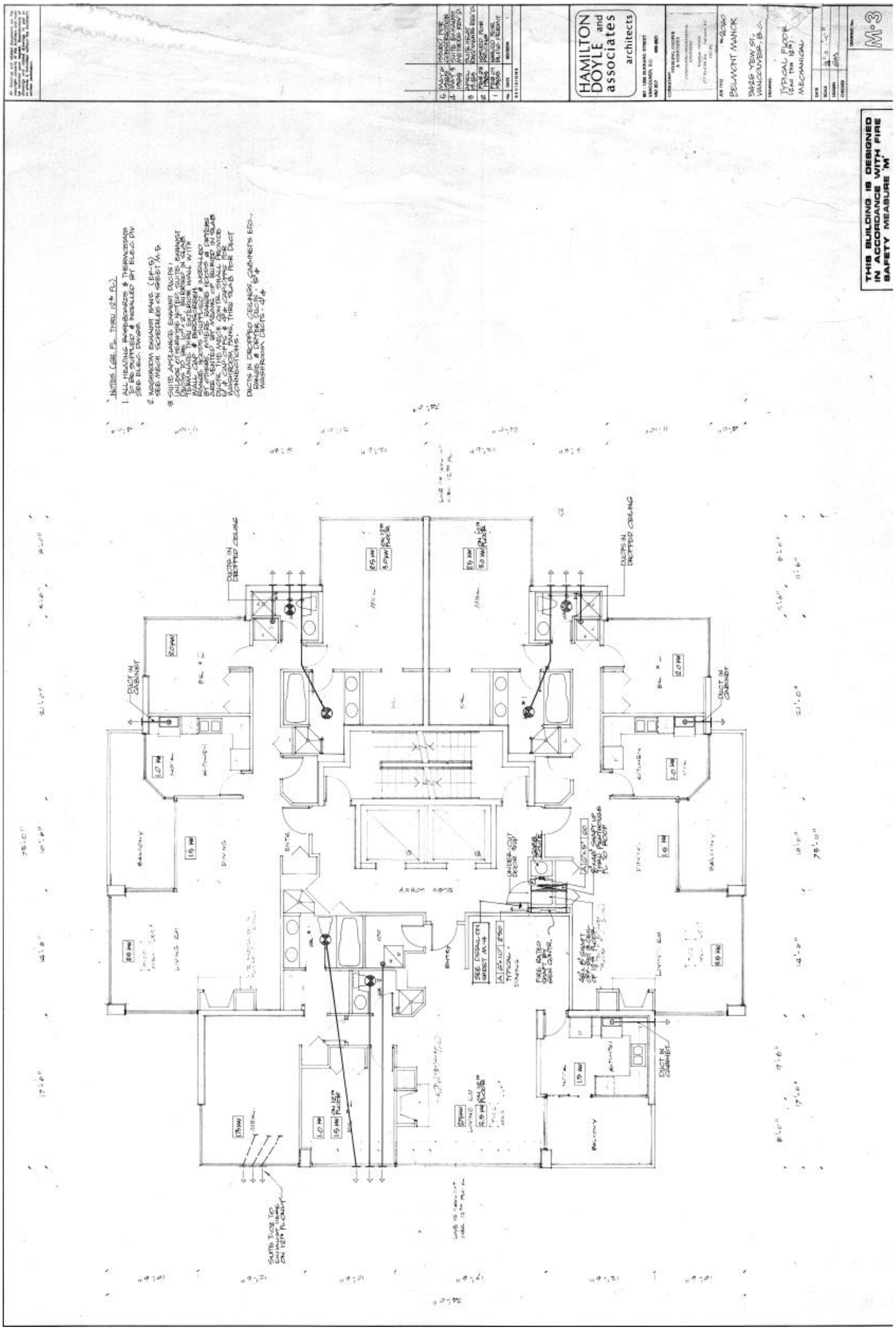
PROJECT:	THE BELMONT 5425 Yew Street, Vancouver, BC			DRAWING NO.: SCH-0.03
DRAWING TITLE:	DECK / ROOF ASSEMBLY SCHEDULE			PROJECT NO.: 4480.10
ISSUE	DESCRIPTION	DATE		SCALE: —
1	ISSUED FOR TENDER & PERMITS	FEB. 23, 2012		DATE: FEB. 23, 2012
				DRAWN BY: AC
				CHECKED BY: SD

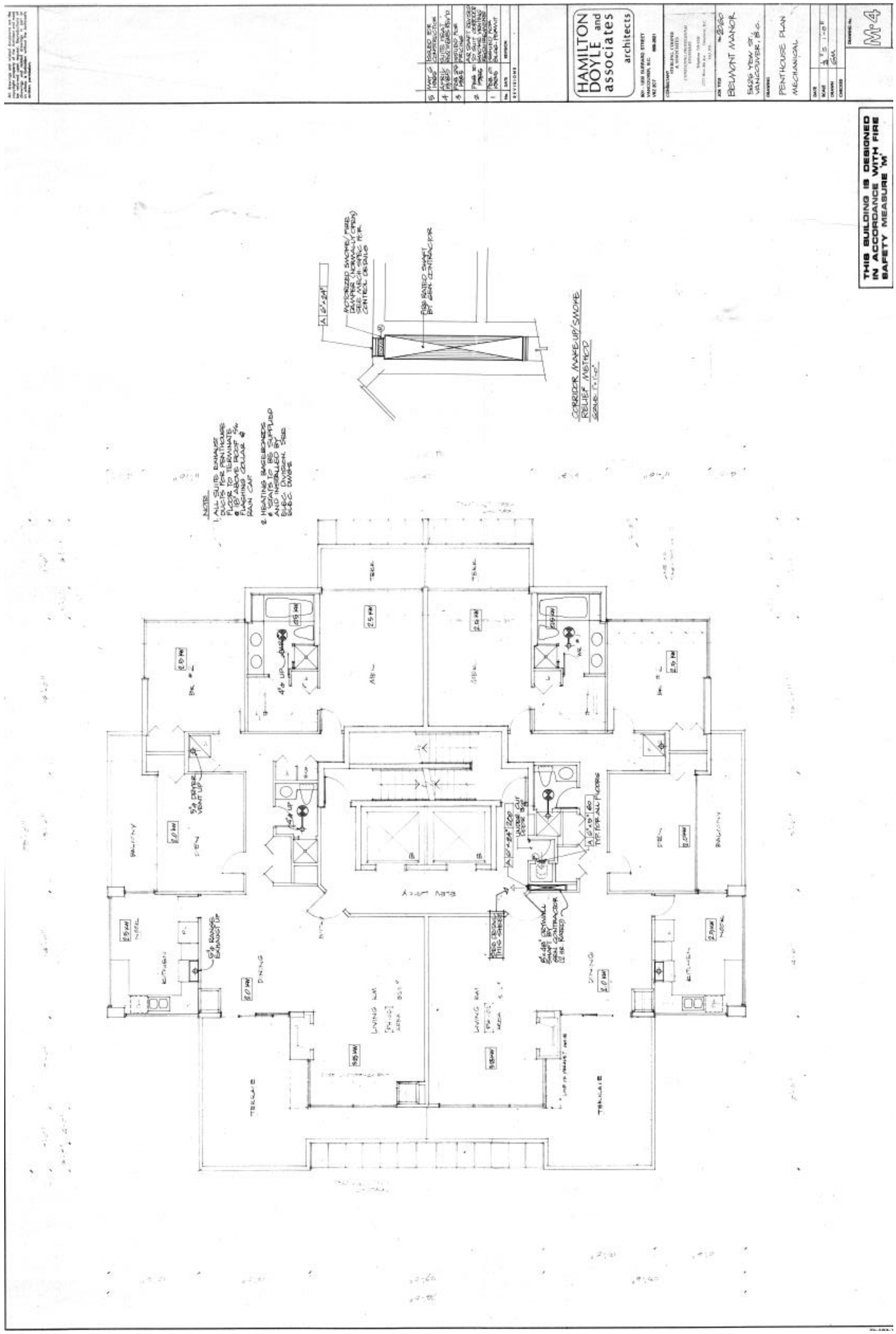
ALL DIMENSIONS NOT SHOWN ARE TO BE CHECKED AGAINST SITE CONDITIONS. DRAWING IS NOT TO BE SCALED TO OBTAIN DIMENSIONS.

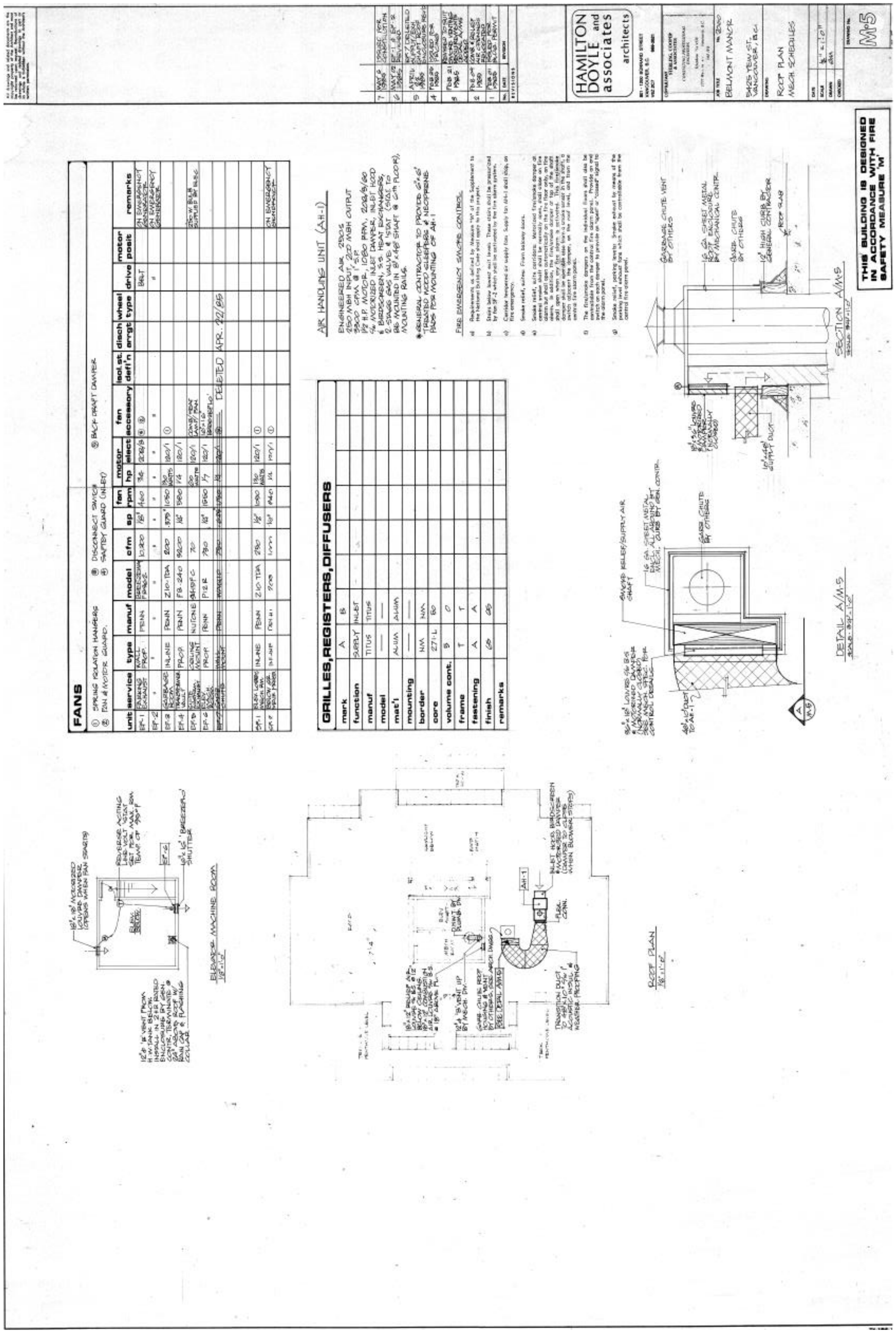

HAMILTON DOYLE and associates
architects
BELMONT MANOR AS BUILT
BASEMENT PLAN
MECHANICAL
M1
THIS BUILDING IS DESIGNED IN ACCORDANCE WITH FIRE SAFETY MEASURE 'M'
EMERGENCY FUEL PIPING SCHEMATIC DIAGRAM
LEGEND
TRANSFORMER VAULT

Appendix B: Belmont Drawings




HAMILTON DOYLE and associates architects
BELMONT MANOR
TYPICAL FLOOR
MECHANICAL
M-3
THIS BUILDING IS DESIGNED IN ACCORDANCE WITH FIRE SAFETY MEASURE 'M'


HAMILTON
DOYLE and
associates
architects
BELMONT MANOR
PENTHOUSE PLAN
MECHANICAL
THIS BUILDING IS DESIGNED
IN ACCORDANCE WITH FIRE
SAFETY MEASURE 'M'
CORRIDOR MAKE-UP/SMOKE
RELIEF METHOD


FANS
GRILLES,REGISTERS,DIFFUSERS
AIR HANDLING UNIT (AH-1)
SECTION A/M-5
DETAIL A/M-5
ROOF PLAN
THIS BUILDING IS DESIGNED IN ACCORDANCE WITH FIRE SAFETY MEASURE 'M'
HAMILTON DOYLE and associates architects
BELMONT MANOR
ROOF PLAN
MECH SCHEDULES
M-5

Appendix C: Simulation Schedules

Simulation schedules used in all models were taken from the 1999 Model National Energy Code for Buildings. Four specific schedules for multifamily residential buildings govern all occupant dependant loads in suites:

- Occupancy
- Miscellaneous Electrical (Receptacle) Loads
- Lighting
- Domestic Hot Water

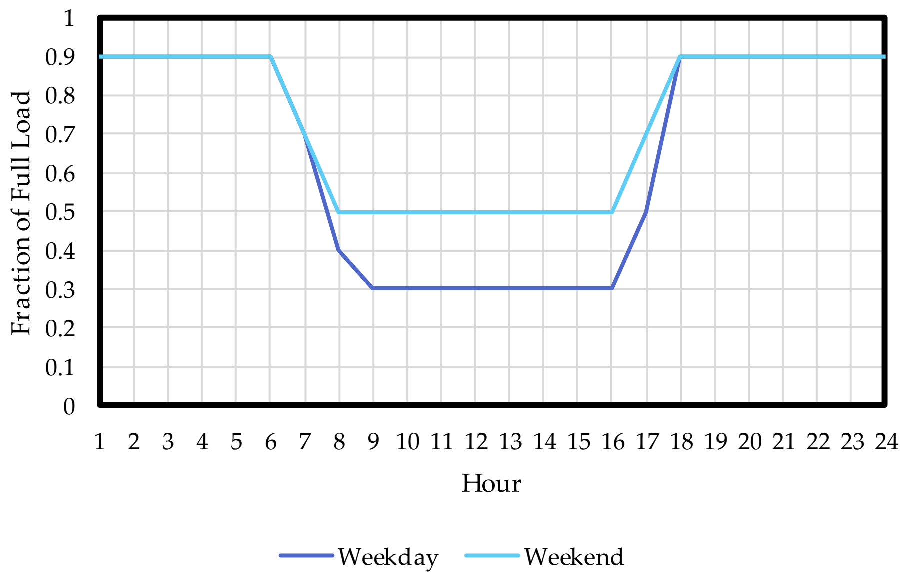


Figure C-1: Occupancy schedule for multifamily residential buildings (National Research Council of Canada, 1999)

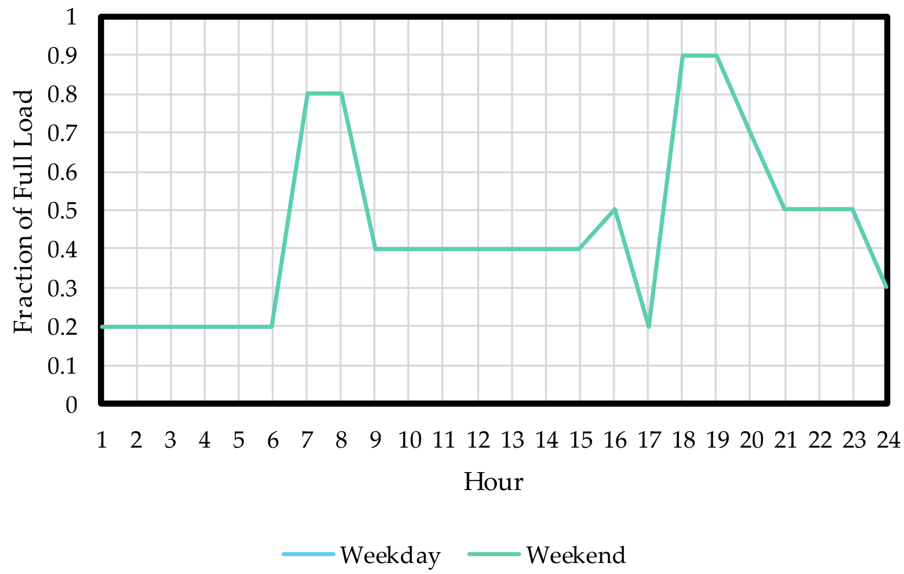


Figure C-2: Miscellaneous electrical load (MEL) schedule for multifamily residential buildings (National Research Council of Canada, 1999)

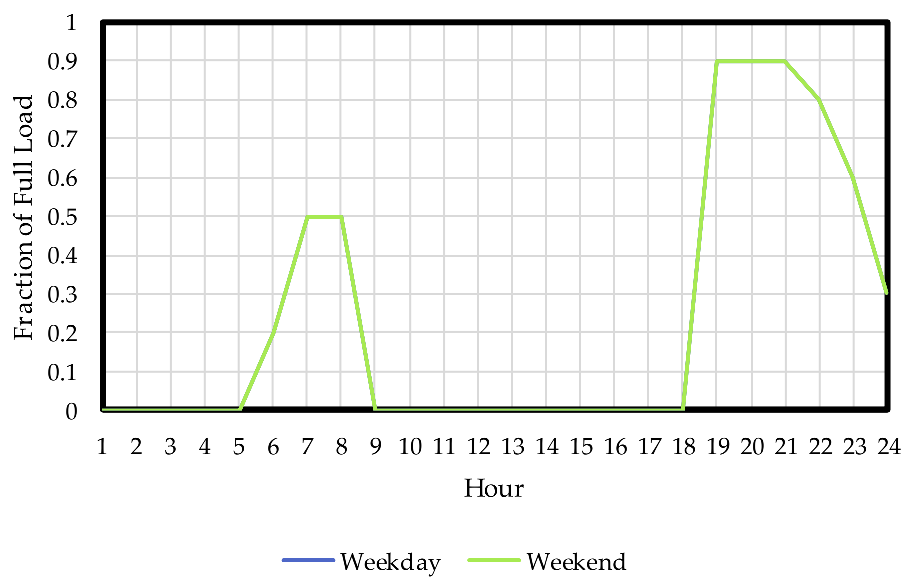


Figure C-3: Lighting schedule for multifamily residential buildings (National Research Council of Canada, 1999)

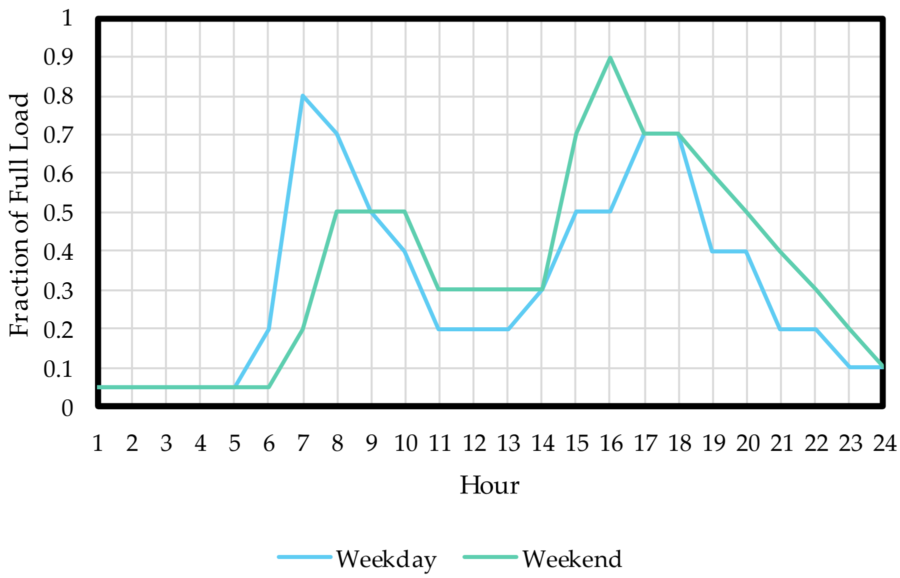


Figure C-4: Domestic hot water schedule for multifamily residential buildings (National Research Council of Canada, 1999)

Appendix D: Existing Building Model Development

This appendix runs in conjunction with Chapter 3, and covers the development of the existing building model of The Belmont. However, where Chapter 3 focused on the final model inputs, this section aims to chronicle the development from the initial model to the final model in order to highlight all of the difficulties encountered.

The model was developed in three phases: initial, second pass, and third pass. As a form of nomenclature, the initial model shall be referred to as iteration 1.0. The second pass model will be denoted with a 2, with calibrations ranging from 2.1 to 2.9. Similarly, the third pass model will be denoted with a 3, and calibrations range from 3.1 to 3.5.

D.1 Initial Energy Model

By taking the available information from the original and updated drawings, site visits, pictures, and correspondence with condo owners, an energy model was built using the DesignBuilder software package. Where insufficient information was available, assumptions were made based on energy standards and modelling guidelines.

D.1.1 Building Geometry

The building geometry was input based on the 2012 rehabilitation issued for construction drawings. Note that as the parkade was not within the scope of the rehabilitation, basement dimensions were obtained from the original 1985 issued for construction drawings. Outside wall dimensions were taken, and the program was configured to calculate the wall thickness and offset it inwards when calculating the interior floor area. Figure D-1 shows a visualization of the input geometry.

For the initial model, not all internal partitions were drawn, but instead each typical floor was broken down only into the 3 suites and the corridor. Figure D-2 shows the typical floor geometry. Note that the drawings indicate a total conditioned floor area of 5000 m2 (54,000 ft2), and the modeled floor area is a close 5043 m2 (54280 ft2). The difference is likely the result of rounding error and undervaluing the wall thickness.

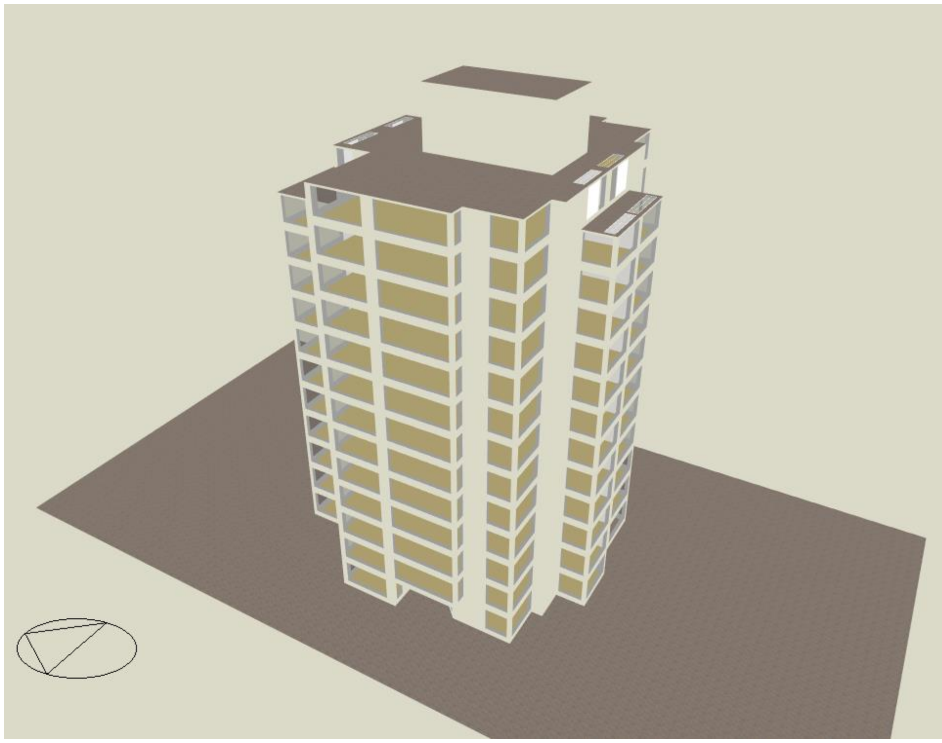


Figure D-1: Initial Belmont model input geometry

For the location, Vancouver BC was selected and the default EnergyPlus weather file for that location was used. This file is based on the Canadian Weather year for Energy Calculation (CWEC) dataset and represents 30-year historical average temperatures as recorded by the Environment Canada weather station located at the Vancouver International Airport (YVR) (US Department of Energy, 2015).

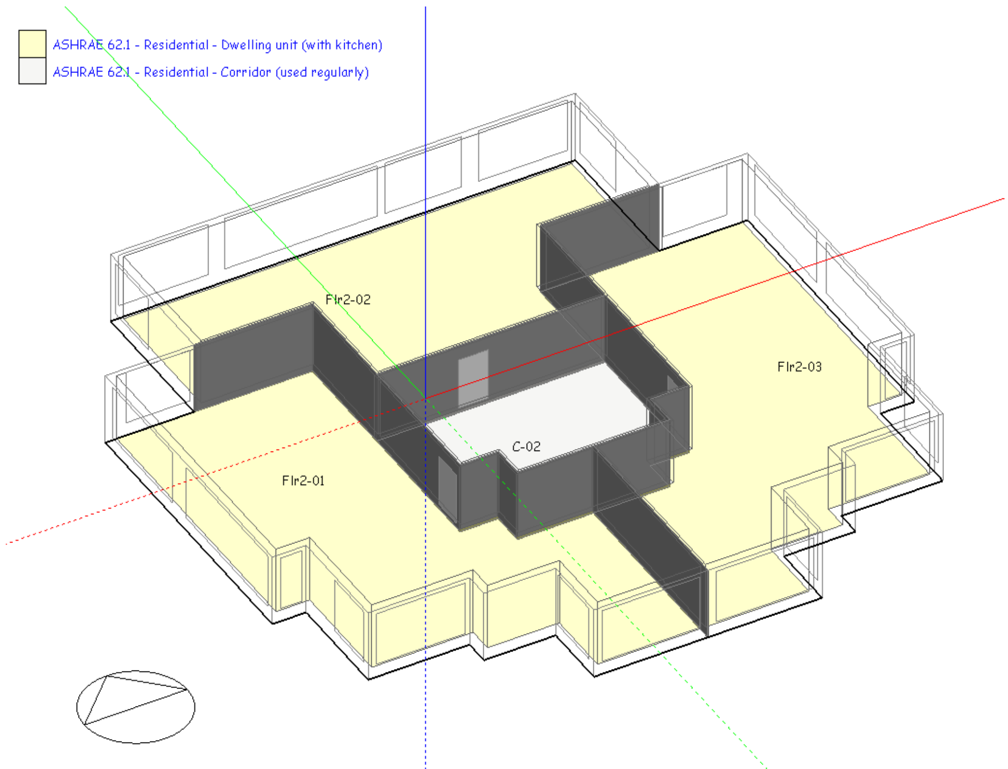


Figure D-2: Initial Belmont model typical floorplan

D.1.2 Constructions and Openings

The key assemblies in an energy model are those that comprise the enclosure as they act as an environmental separator and have a direct impact on the building heating and cooling loads. For The Belmont, these constitute the above grade walls, the roof and decks, the below grade walls, the ground floor, and the windows and doors. Internal floors and internal partition walls also need to be defined however as they impact heat flow between internal zones.

One of the challenges associated with defining the constructions is that the user must input the assemblies as layers of predefined materials, and the insulation value is then calculated based on one-dimensional heat flow. The problem with this approach is that often the effective three-dimensional heat flow differs considerably from the one-dimensional analysis due to thermal bridging, thermal flanking, and other three-dimensional phenomena. In order to input the correct R-value for each assembly, it was therefore necessary to modify the thicknesses of certain layers to decrease the nominal value. For thermal purposes this practice is effective, but due to the method through which geometry is calculated in DesignBuilder, decreasing wall thickness results in an increase in indoor conditioned floor area. As the model only differed from the actual floor area by 43 m2 (280 ft2), this effect was considered to have negligible impact on the hourly calculations.

Table D-1 below lists the assemblies used in the initial Belmont model. Note that the modifications column describes changes made to the actual assembly in order to decrease the nominal R-value to match the effective R-value calculated by RDH.

Table D-1: Initial Belmont Model Assembly Constructions

Assembly	Description	Modifications	RSI-value $m^2{\cdot}K/W$	R-value $ft^2{\cdot}°F{\cdot}hr/Btu$
Typical Exterior Wall	• 22mm (7/8") Stucco • 89mm (3.5") Mineral Fibre Insulation • 152mm (6") Concrete • 38mm (1.5") XPS • 16mm (5/8") Gypsum Wallboard	Modified to 70mm (2.75") MF, 13mm (0.5") XPS	2.82	16.0
Typical Roof	• 4" Gravel • 4" XPS • 6" Concrete	N/A	3.47	19.7
Typical Below Grade Wall	• 6" Concrete • 38mm (1.5") XPS • 16mm (5/8") Gypsum Wallboard	Modified to 13mm (0.5") XPS	0.78	4.4
Typical Internal Partition Wall	• 16mm (5/8") Gypsum Wallboard • 100mm (4") Air Gap • 16mm (5/8") Gypsum Wallboard	Modified from 100mm (4”) Fiberglass	0.42	2.4
Typical Internal Floor	• 13mm (0.5") Carpet • 13mm (0.5") Underlay • 152mm (6") Concrete	N/A	0.74	4.2
Ground Floor	• 2" Flooring Screed • 4" Concrete • 1" Brick Slips • 30" Clay Underfloor	N/A	0.93	5.3

Defining glazing's in DesignBuilder is much more intuitive than with assemblies as one can enter the window properties and the opening locations are either automatically populated are drawn in on the enclosure surfaces. In this case, the window dimensions and locations were taken from the elevations in the 2012 issued for construction drawing set found in Appendix B. The window properties were defined based on the manufacturer shop drawings with an overall USI-value of $0.97\ \mathrm{W/m^2\ K}$ (U-value of $0.171\ \mathrm{Btu/ft^2 \cdot °F \cdot hr}$), a solar heat gain coefficient of 0.2, and a visible light transmittance of 0.7.

Infiltration is an important consideration in energy modelling as the air leakage can correspond to a significant amount of energy consumption. Some energy codes and modelling standards require constant air leakage rates to be incorporated in the model, while other times it is left to the modeller to set an input value. For example, the Canadian Model National Energy Code for Buildings (MNECB) requires a constant infiltration rate of $0.25\ \mathrm{l/s/m^2}$ wall area (National Research Council of Canada, 1999). In DesignBuilder, the user can input an airtightness value which is converted to an air leakage rate in accordance with BS EN12831 (European committee for Standardization, 2003). For The Belmont, this approach was taken as the enclosure was measured by RDH to have a whole building air tightness of 1.4 Ac/h at 50 Pa. This air leakage rate is then modified by a usage schedule in DesignBuilder, but for the initial model this was simply turned on for all hours.

D.1.3 Mechanical Systems

In the initial model, the mechanical systems consist of three independently defined services: the air loop serving the corridors, the domestic hot water loop serving the suites, and the electric baseboards serving the suites.

Defining an air loop in DesignBuilder involves starting from a stock template with a customizable air handler which can then be connected to a group of zones. In this case, the zones are the corridors on every floor. Note that The Belmont has no return ductwork to the AHU, but due to the limitations of the air loop definition, a return connection was required in the model. Table D-2 lists some of the key properties defining the air loop.

Table D-2: Initial Belmont model – air loop properties

Property	Value	Notes
Design Flow Rate	1557 l/s (3300 cfm)	From drawings, verified by field testing performed by RDH
Supply Fan External Static Pressure	250 Pa (1″ H2O)	From drawings
Supply Fan Efficiency	70%	Assumption
Corridor Mechanical Ventilation	3.136 Ac/h	Based on design flow rate divided by volume of corridors
Heating Coil Capacity	73.2 kW (250 MBH)	Coil rated input from drawings
Coil Part Load Curve	Standard Gas Coil PLC	DesignBuilder default
Heating Fuel Source	Natural Gas	Known
Heating Burner Efficiency	80%	From drawings
Air Loop Setpoint Schedule	Air Loop Heating Schedule – Always 35°C	DesignBuilder default
Corridor Heating Setpoint	18°C (64.4°F)	Known from monitoring
Unit Availability Schedule	Always On	Known
Corridor Ventilation Schedule	Always On	Known

Similarly to the air loop, defining a domestic hot water loop involves starting from an initial template containing a customizable water heater and pump which can then be connected to water outlet zones. In this case, the outlet zones are the suites as further resolution of bathrooms and kitchens was not built into this initial model. Table D-3 lists some of the key properties defining the domestic hot water loop. Note that the demand is based on the recommended design value of 0.15 m^3/suite/day (40 US Gallons/suite/day) set by ASHRAE 90.1-2004 for multifamily buildings rather than the estimated values discussed in section 3.2.5 (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2004). Additionally, the usage schedule was taken from the Model National Energy Code for Buildings (MNECB), and can be found along with all of the other schedules used in Appendix C (National Research Council of Canada, 1999).

Table D-3: Initial Belmont model – domestic hot water loop properties

Property	Value	Notes
Water Loop Flow	Variable Flow	DesignBuilder default
Water Heater Tank Volume	Autosize	Calculated by DesignBuilder
Setpoint Temperature	DHW setpoint schedule – always 55°C	DesignBuilder default
Heating Fuel Source	Natural Gas	Known
Boiler Heating Capacity	178.7 kW (610 MBH)	From equipment boiler plate
Heating Thermal Efficiency	82.4%	From equipment boiler plate
Heater Part Load Factor Curve	Newer Style Moderate Temperature Boiler circa 1983	Selected from DesignBuilder templates based on year of construction
Pump Rated Power Consumption	Autosize	Calculated by DesignBuilder
Pump Speed	Variable	DesignBuilder default
Rated Pump Head	20 kPa (6.691 Ft H_2O)	DesignBuilder default
Pump Performance Curve	Constant Output (no variable speed)	DesignBuilder default
Pump Control Strategy	Intermittent	DesignBuilder default
DHW Demand	40 Gal/Day/Apartment	From ASHRAE 90.1-2004 User's Manual
DHW Suite Load	0.03031 Gal/ft^2/day	Based on ASHRAE 90.1 and the total apartment floor area within the model. This value is only applied to the suite floor area
DHW Demand Schedule	MNECB-1999 Multifamily DHW	Assumption See Appendix C
Water Heater Availability Schedule	Always On	Known

Baseboard Convectors were added to each suite as the heating system, powered by electricity using a heating coefficient of performance (COP) of 1.0. Note that DesignBuilder also offers baseboard radiators, but as the majority of heat transferred from modern electric baseboards is in the form of convection, baseboard convectors were selected instead. Additionally, while the heating setpoints are not known, a setpoint of 22°C (71°F) was taken based on the House Simulation Protocols produced by the US National Renewable Energy Laboratory (Wilson et al., 2014). Table D-4 list some of the key properties associated with the electric baseboards.

Table D-4: Initial Belmont model – electric baseboard properties

Property	Value	Notes
Typical Suite Capacity	Autosize	Calculated by DesignBuilder
Heating Fuel	Electricity	Known
Heating COP	1.0	Known
Heating Setpoint Temperature	22°C (71°F)	Assumption from NREL House Simulation Protocols
Heating Setback	None	Assumption from NREL House Simulation Protocols

D.1.4 Lighting, Gains and Occupancy

Internal gains from lighting, occupants, and miscellaneous equipment are crucial in determining the energy use of a building as they both use energy directly as well as offset the heating load which must be met by the HVAC system. The difficulty with these gains in the context of The Belmont specifically is that not very much information is available, and so one must rely on default values and generalized inputs from energy codes and modeling standards.

Lighting was broken down into three distinct areas: the parkade, the suites, and the corridors. Lighting intensities were taken from ASHRAE Standard 90.1-2007 using the building area method for multifamily buildings and parking garages, and the suites and parkades were therefore treated as one (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2007). The lighting schedules were taken from MNECB-1999, which can be found along with all other schedules used in Appendix C (National Research Council of Canada, 1999).

For MURBs, DesignBuilder defaults to include stepped lighting controls to mimic occupant control with respect to daylighting in the suites. This means that for a given time step, the illuminance of a space due to daylight is calculated and compared to the target illuminance. The discrete steps involved with stepped lighting control simulate turning specific fixtures on or off in order to meet the illuminance target, as opposed to simply turning all of the zone lighting on. In DesignBuilder, the default target illuminance of 300 Lux was used for all spaces.

Table D-5 displays some key inputs associated with the lighting properties in the three main areas of The Belmont model. Note that all other lighting parameters were left at the DesignBuilder default values, which are listed in Table 3-8.

Table D-5: Initial Belmont model – lighting properties

Property	Suites	Corridors	Parkade
Lighting Power Density	6.5 W/m^2 0.6 W/ft^2	6.5 W/m^2 0.6 W/ft^2	2.7 W/m^2 0.25 W/ft^2
Target Illuminance	300 Lux	300 Lux	300 Lux
Schedule	MNECB-1999 Multifamily Lighting	On	On
Lighting Controls	Stepped with 3 steps to mimic occupant behavior	N/A	N/A

In The Belmont, there are two main internal equipment gains: miscellaneous electrical equipment in suites, and natural gas fireplaces in suites on floors 9 through 13. To simplify the initial model, the fireplaces were not included. For the miscellaneous electrical equipment, a similar difficulty to the lighting exists in that not much information is available about the types of equipment and appliances present in each suite. As such, the MNECB-1999 value of 5 W/m^2 (0.4645 W/ft^2) was used along with the corresponding MURB miscellaneous electrical load schedule (National Research Council of Canada, 1999). No equipment electrical gain was included for the corridors or parkade in order to simplify the initial model, although some equipment is present there such as the elevators and parkade exhaust fans. Table D-6 lists some of the key properties associated with the equipment gains.

Table D-6: Initial Belmont model – miscellaneous equipment properties

Property	Value	Notes
Typical Suite Equipment Gain	5 W/m^2 ($0.4645\ W/ft^2$)	From MNECB-1999
Equipment Fuel	Electricity	Known
Equipment Schedule	MNECB-1999 Multifamily receptacle	From MNECB-1999
Radiant Fraction	0.2	DesignBuilder default

The Belmont, as previously discussed, is inhabited by individuals of at least 55 years or older. The majority of suites are 2 bedrooms, but are occupied by 1 or 2 individuals. The occupant density and metabolic considerations were based on DesignBuilder defaults for MURBs, however they are roughly correct based on what limited information is available about the occupants. The occupant schedule was based on MNECB-1999 as a starting point for the initial model, but as most occupants are retired the traditional workday assumptions inherent in residential schedules don't necessarily apply (National Research Council of Canada, 1999). Table D-7 displays some key properties associated with the occupancy. Note that these properties only apply to the suites, as the corridors and parkade are considered to be unoccupied.

Table D-7: Initial Belmont model – occupancy properties

Property	Value	Notes
Typical Suite Occupant Density	0.02 $People/m^2$ ($0.001858\ People/ft^2$)	DesignBuilder default
Occupancy Schedule	MNECB-1999 Multifamily occupancy	From MNECB-1999
Metabolic Activity Level	Typing	DesignBuilder default
Winter Clothing	1.0 clo	DesignBuilder default
Summer Clothing	0.5 clo	DesignBuilder default

D.1.5 Initial Modelled Energy Consumption

Given the inputs and assumptions described in Sections C.1.1 through C.1.4, the annual energy consumption of the Belmont initial model was calculated by DesignBuilder using EnergyPlus 8.4. Figure D-3 displays the modelled electricity consumption with respect to the metered consumption from BC Hydro in 2013. Note that as the typical meteorological year weather file was used in the models, an exact match was not expected from the initial model. However, some clear discrepancies are visible.

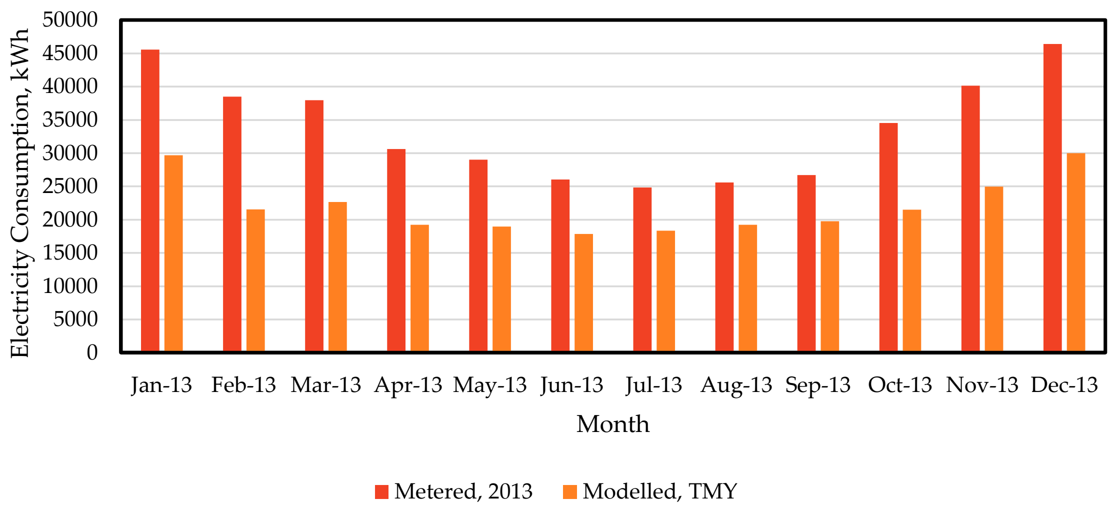


Figure D-3: Initial Belmont model – monthly electricity consumption

From Figure D-3, it is clear that the model is dramatically under predicting the electricity consumption. The under prediction of baseline consumption in the summer months indicates that the base lighting or electrical equipment gain needs to be increased. Additionally, the lack of seasonal variation with respect to the metered consumption indicates that the suite electric heating is not being fully captured.

Figure D-4 displays the modelled natural gas consumption with respect to the metered consumption from Fortis BC for 2013. The initial model is dramatically over predicting the natural gas consumption – particularly in the summer months where the modelled consumption is more than twice the metered consumption.

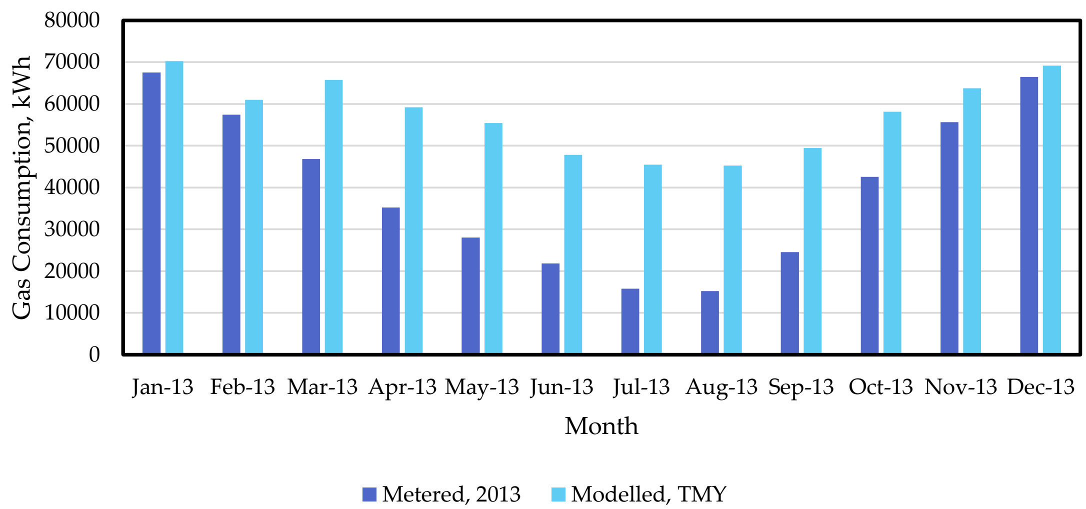


Figure D-4: Initial Belmont model – monthly natural gas consumption

A better understanding of how the model is calculating the energy consumption can be gleaned by analyzing the annual end-use consumption as seen in Figure D-5 in contrast with the estimated end-use consumption presented in Figure 3-17. To simplify the comparison, an annual summary by end use is presented in Figure D-6. Several of the end-uses are not being accurately simulated; The model is under predicting the baseboard heating electricity by approximately 75%. The domestic hot water is being under predicted by approximately 25%. As limited sub-metering was available in the metered energy analysis, it is difficult to ascertain whether or not the equipment and lighting loads are correct, but given the small values simulated for pumps and fans it is likely that those two specific equipment categories are not properly configured. Lastly, the make-up air unit gas consumption is almost 300% higher than the estimated consumption, indicating that one or more of the input assumptions associated with the air loop must be invalid.

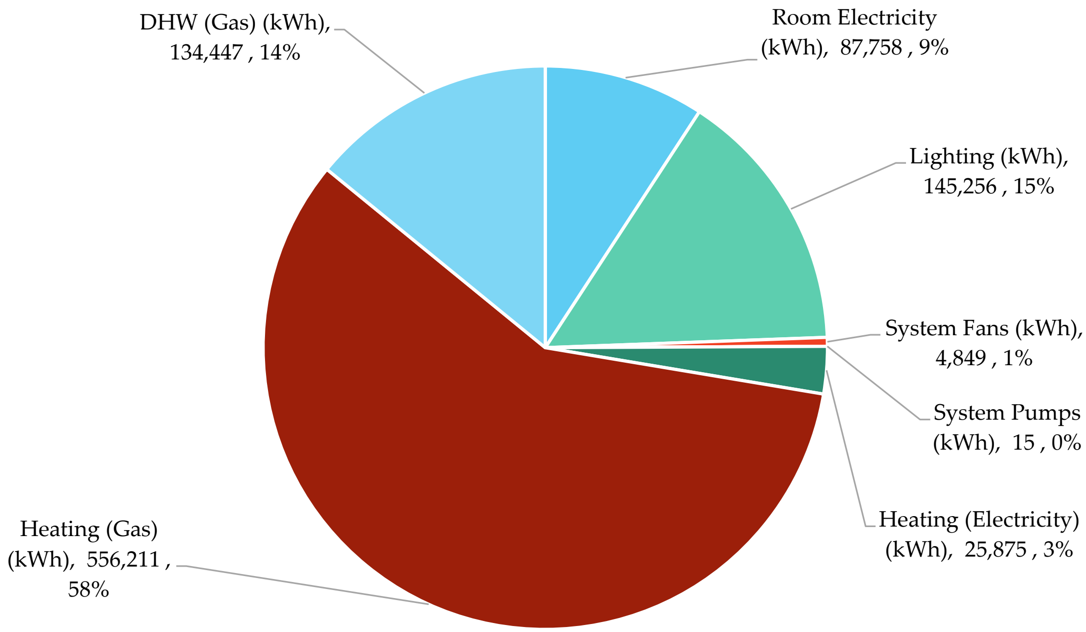


Figure D-5: Initial Belmont model – annual end-use consumption

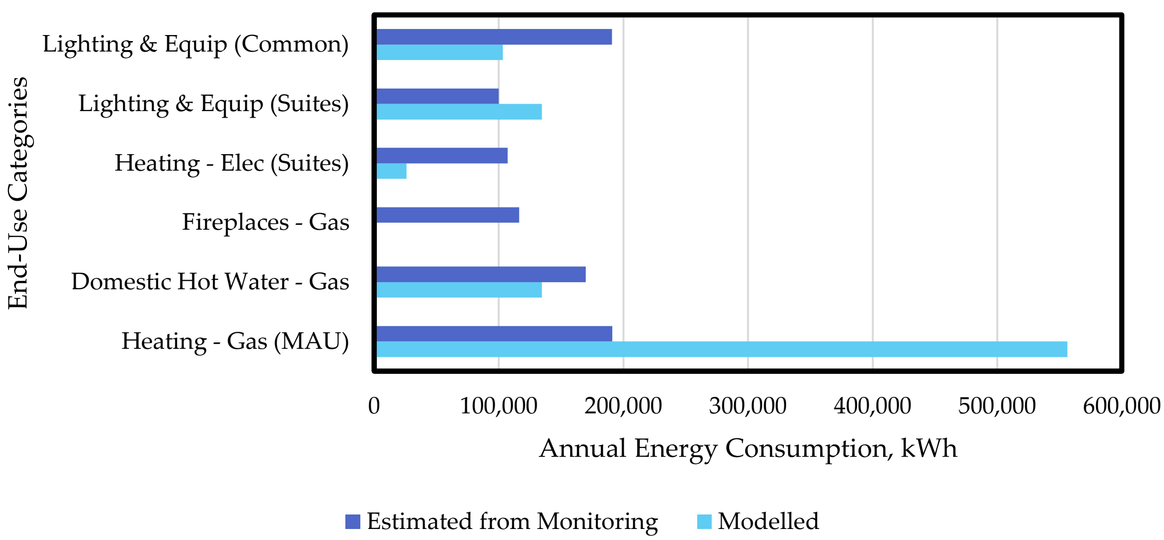


Figure D-6: Initial Belmont model – annual end-use consumption – modelled consumption vs estimates from monitoring data

Beyond the modeled energy consumption itself, an interesting observation can be made surrounding the calculated air change rate from natural ventilation, mechanical ventilation and infiltration. On average the simulation showed 0.58 air changes per hour for the whole building, with minimal variation throughout the entire year. This is not entirely consistent with the measured air change rate of 0.4-0.5 ac/h measured by RDH using tracer gas testing in April 2013 (Ricketts, 2014).

D.2 Second Pass Energy Model

While the initial model served as a first attempt at accurately simulating the Belmont, the results discussed in Section C.1.5 indicated several large discrepancies between the measured and modelled building performance. As such, the second pass model serves to address invalid initial assumptions and add additional detail to aspects of the model identified as potentially having significant contributions to the building energy use. The second pass model calibrations are based on additional known details and founded assumptions largely implemented to replace DesignBuilder default values and initial model simplifications.

D.2.1 Second Pass Model Calibrations

Calibrations to the initial Belmont model include changes to building geometry, mechanical systems, and internal gains. Table D-8 lists the calibrations in the order which they were applied. Note that in discussions of the energy impacts, each calibration is considered sequentially with discussed changes in energy consumption taken with respect to the previous model iteration.

Table D-8: List of second pass Belmont model calibrations in sequential order

Second Pass Iteration	Calibration
2.1	Modified internal layout to reflect actual floorplan
2.2	Adjusted DHW load to only apply to spaces containing hot water outlets
2.3	Adjusted the MAU delivery setpoint temperature
2.4	Added bathroom and kitchen mechanical ventilation
2.5	Added natural ventilation to account for open windows
2.6	Added fireplaces to the living rooms of suites on the top 5 floors

Second Pass Iteration	Calibration
2.7	Added parkade ventilation and elevator energy consumption
2.8	Changed domestic hot water pump settings to more realistic estimates
2.9	Changed the weather file to the 2013 Vancouver meteorological year

D.2.1.1 Calibration 2.1: Internal Layout

The first calibration involved subdividing the internal layout of each suite. Although not explicitly required, this was done in an attempt to add further resolution and accuracy to the model. Figure D-7 displays the new typical floor plan, which can be contrasted with Figure D-2 in Section D.1.1.

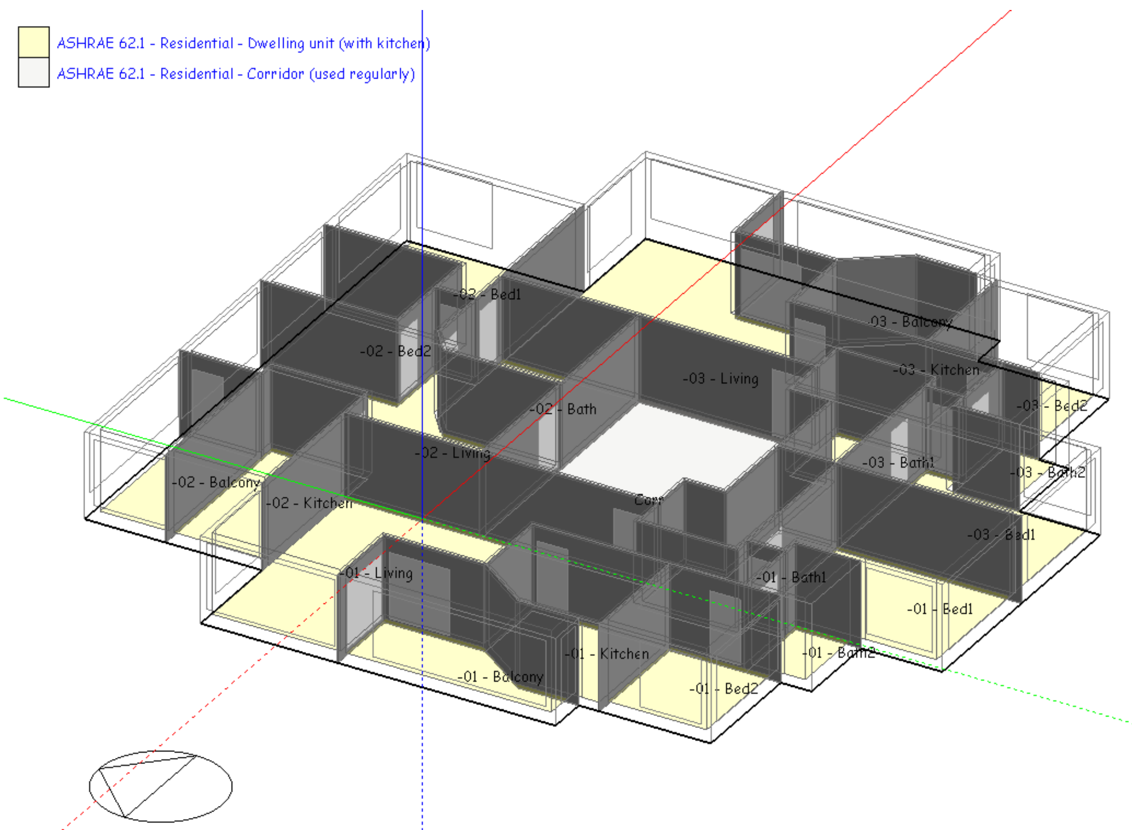


Figure D-7: Second Pass Belmont model typical floorplan

As part of changing the internal layout, some of the window locations needed to be adjusted slightly such that there was no overlap between the fenestration location and interior wall to exterior wall connections. Otherwise, all of the other inputs were left the same as the initial model.

In comparison to the initial model results, there were several slight variations in end-use consumption with the subdivided internal layout. Firstly, the miscellaneous electrical load decreased by around 4200 kWh or 5% annually. This can be attributed to the fact that equipment loads are defined in power per unit floor area, and as the internal partition walls have finite dimensions, the effective floor area of each unit decreased slightly. A similar result was observed with respect to the domestic hot water, which is also defined per unit area and decreased by about 7000 kWh or 5% annually. Conversely, the lighting energy increased slightly by around 2000 kWh or 1% annually. This is likely due to the fact that the lighting controls in the suites account for daylighting, and with the internal partition walls numerous spaces see little or no daylight – requiring more lighting energy. Overall, the total change with respect to the initial model was around 8000 kWh or a 0.8% decrease annually. While this is non-trivial, it is fairly insignificant and was therefore deemed acceptable.

D.2.1.2 Calibration 2.2: Domestic Hot Water

With the internal layout of each suite divided into specific rooms, it is possible to redefine the domestic hot water load to reflect only the spaces which contain hot water outlets. This is also necessary as the initial DHW input of 0.03031 Gal/ft^2/day discussed in Table D-3 was based on the initial model suite floor areas, and the new suite floor areas are slightly smaller.

In keeping with the original assumption of 40 gallons per day per apartment from ASHRAE 90.1-2004, a new load of 0.1354 Gal/ft^2/day was assigned based on the new floor areas of only the bathrooms and kitchens with the intent of replicating the initial domestic hot water use observed in Section D.1.5 (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2004).

On an annual basis, the domestic hot water load increased by around 6300 kWh or 5% as compared the previous model iteration, resulting in an annual domestic hot water energy use of around 134,000 kWh. This annual consumption, while an increase from the previous model iteration, is very similar to the initial domestic hot water consumption discussed in Section D.1.5 and the insignificant differences can be attributed to rounding error.

D.2.1.3 Calibration 2.3: Makeup-Air Unit Setpoint Temperature

One of the most visible inaccuracies of the initial model annual energy consumption results had to do with the makeup air unit natural gas consumption. This excessive consumption can be attributed to the fact that the setpoint temperature was left at the air loop heating default value of 35°C. In reality, the corridor ventilation air is only conditioned to 18-20°C, and this extra 15°C of conditioning at all times resulted in a substantial amount of energy given that the MAU constantly provides 1557 l/s (3300 cfm) of fresh air.

Changing the setpoint temperature to 18°C resulted in a 358,000 kWh decrease in annual ventilation heating energy used by the MAU. This 64% decrease in gas heating energy resulted in a 32,000 kWh increase in space heating energy to account for the fact that less heating energy was entering the suites from the corridors. Overall, the total annual energy consumption of the building decreased by 327,000 kWh or 34%.

D.2.1.4 Calibration 2.4: Kitchen and Bathroom Mechanical Ventilation

With the added resolution provided by the subdivided internal layout, it was possible to include previously overlooked mechanical equipment – in this case, the kitchen and bathroom exhaust ventilation fans.

In each suite, there are two bathrooms each containing a 33 l/s (70 cfm) exhaust fan which is operated only when activated by occupants as a form of point exhaust for pollutant control. As such, exhaust fans were added, but with a capacity of 24 l/s (50 cfm) at 125 Pa static pressure due to the fact that installed fans typically observe lower than rated airflow due to inadequate rated static pressures to overcome friction losses in ductwork (Canadian Mortgage and Housing Corporation, 2003). Additionally, the fan flow rates in a number of units were measured using a balometer, and while the flow rates varied significantly, 24 l/s is generally representative of current performance (Ricketts, 2014). Based on the average bathroom volume of 22 m^3 (760 ft^3), this results in 3.94 ac/h for the bathrooms when the fans are operating.

In terms of a bathroom fan operating schedule, little guidance is available through standards. The NREL House Simulation Protocols assume that bathroom fans, when operating as point exhaust, are only on for an hour per day which can be simulated between 7 and 8am (Wilson et al., 2014). While not intended for use in high-rise MURBs, this assumption is still valid and was therefore implemented in the Belmont model.

For the kitchen exhaust, no information about fan capacity was provided through site visits or mechanical drawings. As such, the DesignBuilder default value of 100 l/s (211 cfm) at 125 Pa static pressure was retained as this is a reasonable capacity for a kitchen exhaust hood. Based on the average kitchen volume of 31 m^3 (1100 ft^3), a flow rate of 11.5 ac/h is achieved when the fan is operating. As with the bathrooms, no information was available to dictate the kitchen operating schedule, but the NREL guidelines recommend modelling the kitchen fans as operating for one hour a day between 6-7pm (Wilson et al., 2014).

On an annual basis, these additional fans increased the building fan energy consumption by 9400 kWh, which is a 193% increase from previous model iterations. This is to be expected as all of these fans were previously unaccounted for. This increased consumption corresponds to a 1.5% increase in total annual energy consumption.

D.2.1.5 Calibration 2.5: Natural Ventilation

One of the unique characteristics of high-rise multi-unit residential buildings which sets them apart from other high-rise construction is the abundance of operable windows and doors for natural ventilation. This was not included in the initial model, but it seemed a necessary inclusion for improved model accuracy.

As with the bathroom and kitchen exhaust ventilation, little guidance was available with how to model natural ventilation explicitly, so assumptions were needed. It was assumed that when the indoor temperature is above 22°C (72°F), the occupants would open the windows resulting in 3 ac/h of outdoor ventilation air. While the 3 ac/h was a DesignBuilder default value, the indoor temperature setpoint was taken from the NREL house simulation protocols (Wilson et al., 2014).

The addition of natural ventilation had a notable impact on electric baseboard heating energy, increasing it by 12,000 kWh or 20% annually. Proper implementation of natural ventilation would stipulate that the indoor minimum temperature setpoint should be raised to avoid windows being open when heating is required, but as some occupants will likely have their windows open during these periods regardless, the result was deemed acceptable. In addition to the change in energy consumption, the whole building air change rate increased. Previously, the modelled air change rate was around 0.38-0.4 ac/h on average throughout the year, the building air change rates increased up to 1.4 ac/h during the summer months.

D.2.1.6 Calibration 2.6: Fireplaces

The natural gas fireplaces were omitted from the initial model as they are only present in the living rooms of suites on the top 5 floors, and they are intended to be used as a luxury item as opposed to a space heating device. However, as identified in the measured energy consumption analysis, the fireplaces constitute a considerable amount of the annual building energy consumption and therefore should be accounted for in the model.

The typical fireplace unit installed in The Belmont suites has a capacity of 8.8 kW (30,000 Btu/h) as discussed in section 3.1.3. Based on the average living room area of the suites on the top 5 floors, this results in a space gain of 1.4 W/m^2 (15 W/ft^2) to the living rooms when the fireplaces are operating. As gas fireplaces tend to transmit most of their heat as radiation, and typically only achieve efficiencies of 50-70%, the radiant fraction of the gain was set to 0.6. The fraction lost set to 0.4 in order to account for the energy lost through the flue.

Determining the fireplace usage schedule was difficult as the fuel consumption was not measured, but rather the temperature of the baseplate adjacent to the pilot light. A number of assumptions were inherent in determining the times during which the units were on as discussed in Section 3.2.3. The fireplace scheduled monthly hour of operation from all units can be seen in Figure D-8 along with the estimated hours of operation from the monitoring data. Note that in order to simplify the creation of daily and weekly schedules, the hours of operation were only approximated.

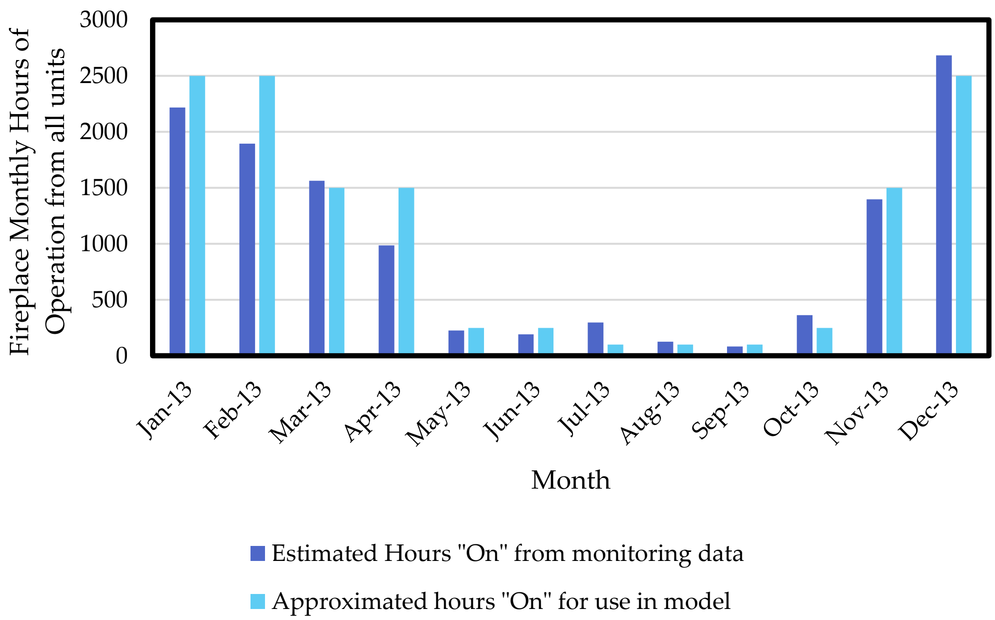


Figure D-8: Second pass Belmont model fireplace monthly hours of operation vs. estimated monthly hours of operation from monitoring data. Values represent the total for all fireplace units in The Belmont

The actual fireplace schedule implemented in DesignBuilder needed to have a higher resolution than presented in Figure D-8. Based on the monthly hours of operation, weekly and daily schedules were created in order to capture the approximate total number of hours on while also applying the loads at realistic times during the day. Table D-9 displays the daily scheduled hours of operation, which were chosen to coincide with periods of occupancy.

Table D-9: Second pass Belmont model – fireplace schedule

Month	Weekdays	Weekends	Monthly Hours "On" per Fireplace
January	5pm – 10pm	12pm – 8pm	179
February	5pm – 10pm	12pm – 8pm	164
March	7pm – 10pm	4pm – 8pm	103
April	7pm – 10pm	4pm – 8pm	98
May	9pm – 10pm	N/A	23
June	9pm – 10pm	N/A	20
July	N/A	9pm – 10pm	8
August	N/A	9pm – 10pm	9
September	N/A	9pm – 10pm	9
October	9pm – 10pm	N/A	23
November	7pm – 10pm	4pm – 8pm	99
December	5pm – 10pm	12pm – 8pm	182

As no room gas load previously existed in the model, adding the fireplaces represented a significant increase of around 103,000 kWh per year. All of this additional heat did correspond in space heating gains however, and as such the suite electrical heating energy consumption decreased by around 15,700 kWh or 22%. This decrease is larger than expected, but the suite heating energy is still under modelled which is resulting in a disproportionately large percentage decrease. On an annual basis, the total building energy consumption increased by around 86,000 kWh or 13%.

D.2.1.7 Calibration 2.7: Parkade and Elevator Loads

The initial model did not include any equipment loads for the parkade or the elevator machine room, despite the fact that the parkade contains large exhaust fans and the elevator machine room contains the elevator motors. As these are both electrical equipment loads, and the initial model under predicted the baseline electrical consumption, the parkade and elevator mechanical equipment gains seemed a necessary addition.

The parkade contains two 4800 l/s (10,200 cfm) exhaust fans which operate with an external static pressure of 31 Pa (1/8″ water column). Based on the volume of the parkade, the space receives a ventilation rate of 5.4 ac/h with the fans fully operational. As the parkade exhaust fan schedule is unknown but ventilation is likely always required, the fans were simply set to operate at all times.

For the elevator machine room, determining the equipment load was difficult given the lack of information. DesignBuilder has a default template for elevator machine rooms, but the 16 W/m^2 lighting intensity and the 4000 W/m^2 equipment gains seemed unrealistic for this application. The lighting was left off as the space is very small and typically unoccupied. The equipment load was estimated to fall somewhere between an infrequently operated low-rise elevator of 1900 kWh/year and a frequently operated high-rise elevator at 15,000 kWh/year (Sachs, 2005). It was assumed that the Belmont consumption falls in between these two extremes at around 8500 kWh/year. This load was divided by the area of the elevator machine room and the hours of the year to get a load of 21.5 W/m^2 (2 W/ft^2). While the true hours of operation are unknown, it is unlikely that the elevator is ever deactivated aside for maintenance, and so the constant application of the load is acceptable.

The additional parkade ventilation resulted in a 4400 kWh increase in annual fan energy – 31% more than modelled in the previous iteration. The added elevator machine room equipment load increased the miscellaneous electric load by 8500 kWh or 10% annually, but this added head decreased the space heating electricity slightly by 1200 kWh or 2%. The total annual building energy consumption therefore increased by 11,600 kWh or 1.6%.

D.2.1.8 Calibration 2.8: Domestic Hot Water Pump Specifications

All previous simulations modelled pump power consumption of only 16 kWh annually. This consumption corresponds to the only pump in the model which is associated with the domestic hot water loop. The true consumption of the pump is not known, but the minimal value suggests that the input assumptions are not valid despite the fact that all pump specifications were left at DesignBuilder defaults. Three invalid assumptions were identified and addressed individually: the pump speed, the control strategy, and the pump head pressure.

The domestic hot water loop flow type and pump speed are tied together in DesignBuilder, and can either be set to constant flow with a constant speed pump or variable flow with a variable speed pump. The default values involve variable flow and speed, but given the vintage of the Belmont, the pump is most likely constant speed. The flow and pump speed were therefore changed to constant, and rather than utilizing an autosized flow rate, the maximum flow rate was set to the known design value of 0.63 l/s (10 gpm).

The default pump control strategy is intermittent which implies that the pump cycles on and off depending on demand. This is also unlikely given the vintage of the Belmont, and was therefore changed to constant operation.

The domestic hot water recirculation pump serves to circulate the water throughout the building, and to facilitate flow to the mechanical penthouse where the boiler and water heaters are located. As this is an open loop, the pump must overcome a physical change in height, meaning that the default head pressure of 20 kPa (6.7 ft H_2O) is dramatically insufficient. From the original Belmont drawings, the pump head is 75 kPa (25 ft H_2O), and so the model inputs were changed accordingly. Additionally, the pump input power was changed from autosize to the known value of 250 W (1/3 hp).

The new pump configuration increased annual pumping energy by 2160 kWh or 14,270%. While this new estimate still gives pumping the smallest end-use consumption, it is likely closer to the real consumption than previously modelled. The new control strategy did however decrease the domestic hot water energy consumption slightly by 3270 kWh, resulting in an overall decrease in annual energy consumption of 1100 kWh or 0.1%.

D.2.1.9 Calibration 2.9: Vancouver 2013 Meteorological Weather Data

Up to this point, all model iterations have been completed using the Vancouver International Airport CWEC historically averaged weather file. While this weather data is statistically representative, it does not reflect the actual weather which was occurring during the measured consumption period of 2013. To address this, RDH provided the 2013 actual meteorological year weather file from the Vancouver International Airport for use with EnergyPlus.

The 2013 weather file differed only slightly from the CWEC historically averaged file, but the changes were enough to make non-trivial changes to the space conditioning and lighting energy. The most significant changes were to the ventilation energy, which decreased by 11,300 kWh or 6% as well as the electric baseboard heating electricity which decreased by 9,900 kWh or 18%. There were however slight increases to the fireplace and lighting energy consumption. Overall, the total annual energy consumption decreased by 20,200 kWh or 2.7%.

D.2.2 Summary of Second Pass Calibrations

Table D-10 displays the impact of all the sequential calibrations discussed in Section D.2.1 in terms of the impact each calibration had on the annual total building energy consumption.

Table D-10: Summary of second pass Belmont model calibrations and their effect on annual energy consumption

Second Pass Iteration	Calibration	Annual Energy Consumption kWh	Change from Previous Model Iteration	
			kWh	%
2.1	Internal Layout	946,371	-8,039	-0.8%
2.2	DHW load	952,715	6,343	0.7%
2.3	MAU Setpoint	626,110	-326,605	-34.3%
2.4	Bath and Kitchen Ventilation	635,490	9,380	1.5%
2.5	Natural Ventilation	643,969	8,480	1.0%
2.6	Fireplaces	729,577	85,607	13.3%

Second Pass Iteration	Calibration	Annual Energy Consumption kWh	Change from Previous Model Iteration	
			kWh	%
2.7	Parkade and Elevator Gains	741,152	11,575	1.6%
2.8	DHW pump	740,047	-1,105	-0.1%
2.9	2013 Weather File	719,803	-20,243	-2.7%

D.2.3 Second Pass Modelled Energy Consumption

Combining all of the sequential model calibrations, the final second pass Belmont energy model provides much more detail with respect to the model representation of available information about the building. Despite this, the modelled energy consumption still is not completely consistent with the metered electricity consumption for 2013.

Figure D-9 displays the modelled and metered electricity consumption for 2013 as recorded by BC Hydro and simulated by the second pass model. As with the initial model, the baseline electrical consumption is being under modelled in the summer months, and the seasonal variation from electric baseboard heating and lighting energy is not being fully captured.

Figure D-10 displays the modelled and metered natural gas consumption as recorded by Fortis BC and as simulated by the second pass model. Unlike the electricity, the natural gas now seems to be much closer to the metered consumption – although some months such as October and November are still under modelled.

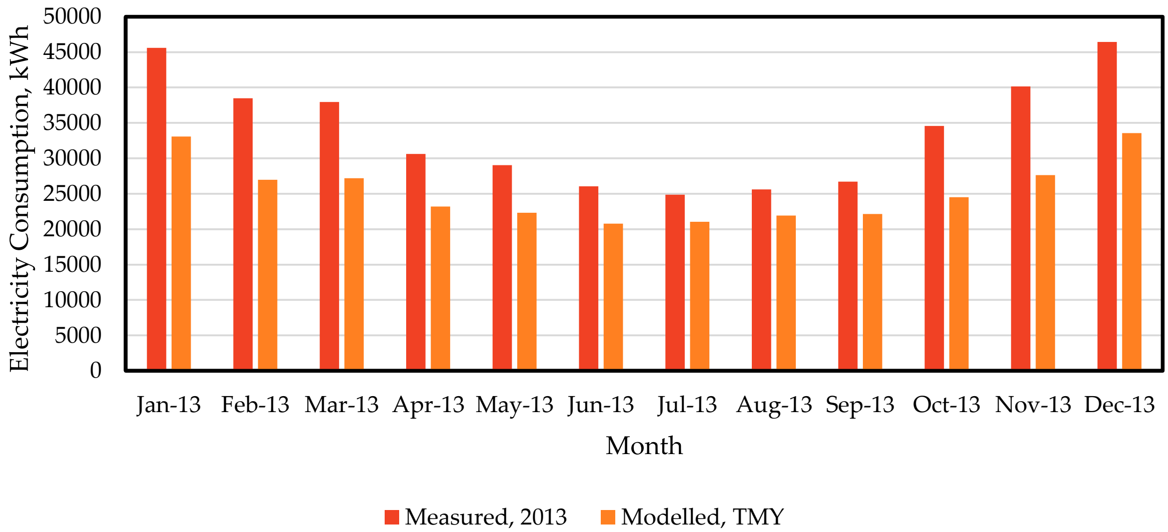


Figure D-9: Second pass Belmont model – monthly electricity consumption for 2013

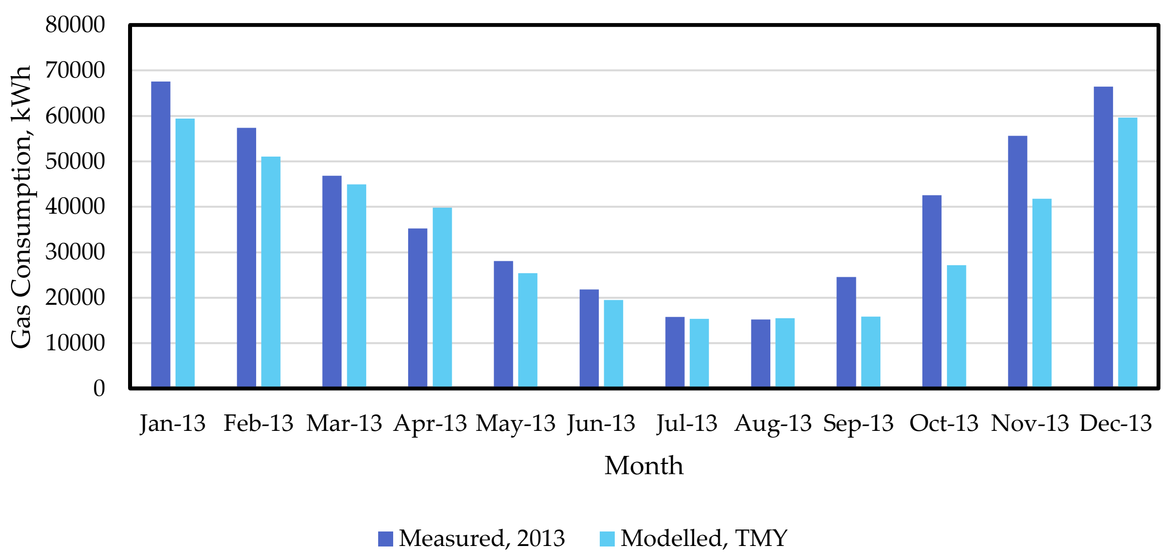


Figure D-10: Second pass Belmont model – monthly natural gas consumption for 2013

Figure D-11 displays the second pass model annual end-use splits. Note that in comparison to the initial model, the calibrations have improved the model accuracy in a number of ways. For example, the ventilation energy, DHW, and fireplace energy (displayed as Room Gas) are all now in the right order of magnitude. However, the heating electricity is still being under estimated by the model.

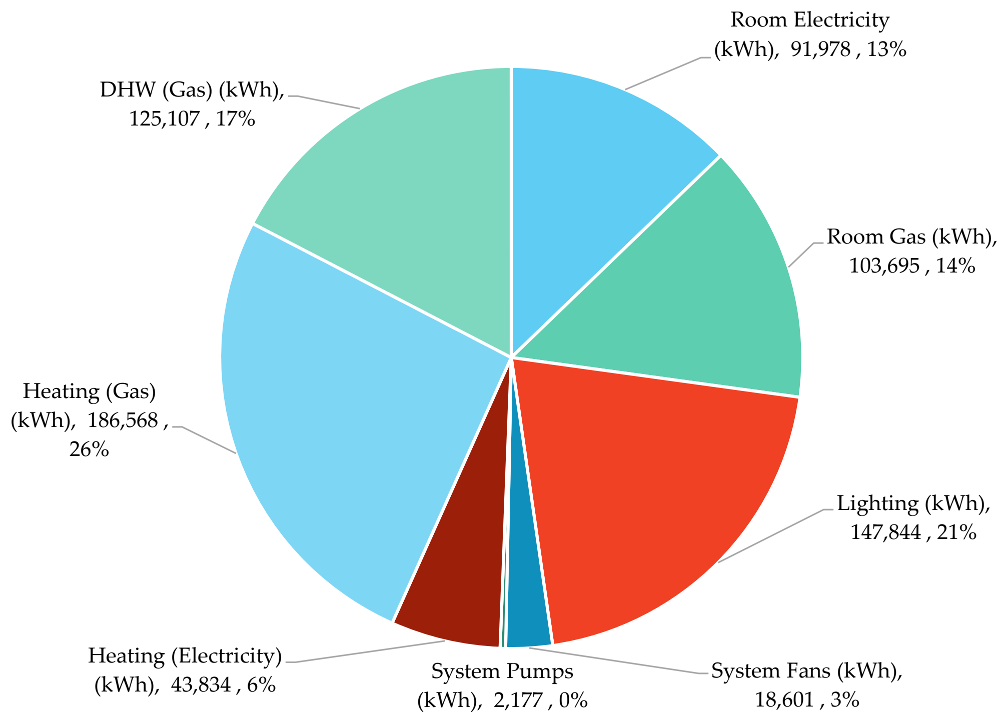


Figure D-11: Second pass Belmont model – annual end-use consumption for 2013

Figure D-12 displays the second pass modelled end-use consumption against the estimated consumption from monitoring data. While most of the end uses are now closer to the previously discussed estimates, it is clear that some large discrepancies remain. The common lighting and equipment is still significantly under predicted while the suite lighting and equipment is slightly over estimated. The suite heating is still insufficient, but the domestic hot water loads are fairly accurate with the exception of the domestic hot water load which still needs to be increased.

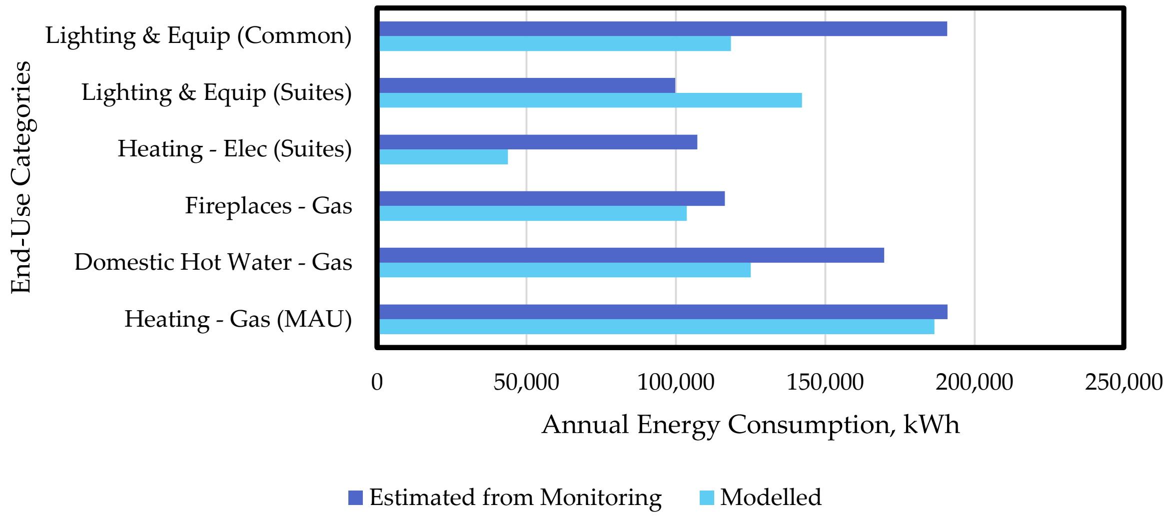


Figure D-12: Second pass Belmont model – annual end-use consumption – modelled consumption vs. estimates from monitoring data

With respect to the modelled air change rate, the second pass simulations are much more representative of the measured 0.4-0.5 ac/h measured in April of 2013 (Ricketts, 2014). A whole building air change rate of 0.45-0.5 ac/h was simulated during the winter and spring, with much higher air change rates of up to 1.5 ac/h simulated during the summer due to natural ventilation.

D.3 Third Pass Energy Model

The second pass energy model of the Belmont represented the best attempt at replicating the measured energy consumption based on known details and founded assumptions. The simulated consumption still differed significantly from the measured consumption, and as such a third pass of calibrations is required. Unlike the previous iteration, these calibrations are founded on logical arguments and engineering judgement in an attempt to achieve agreement between the modelled and measured energy consumption.

D.3.1 Third Pass Model Calibrations

The third pass calibrations to the Belmont model are focused on addressing the specific deficiencies identified in the second pass result comparison to estimated end-use consumption.

Specifically, calibrations are focused on suite electricity, common electricity, domestic hot water consumption, and fireplace consumption. The complete list of third pass calibrations can be seen below in Table D-11. Note that as previously discussed, the calibrations were preformed and are discussed in sequential order.

Table D-11: List of third pass Belmont model calibrations in sequential order

Third Pass Iteration	Calibration
3.1	Modified suite electrical loads
3.2	Added common miscellaneous electrical loads (MELs)
3.3	Adjusted domestic hot water demand
3.4	Adjusted fireplace base load and operation schedule
3.5	Adjusted temperature setpoints and enclosure airtightness to increase the baseboard electrical heating load

D.3.1.1 Calibration 3.1: Suite Electrical Loads

As identified in Figure D-12, the modelled suite lighting and equipment loads exceed the estimated consumption based on utility data; the modelled consumption amounted to 142,000 kWh/year, whereas the estimated consumption from metering was only 100,000 kWh/year. This indicates that between the suite lighting, miscellaneous electrical loads (MELs), and suite exhaust fans, one or more of the model inputs is too large. As such, all three inputs need to be re-evaluated individually.

The bathroom and kitchen exhaust fans were simulated to consume 9300 kWh/year collectively between the 37 suites. This consumption is based on 50 cfm bathroom fans and 210 cfm kitchen fans operating for one hour per day (Wilson et al., 2014). As this amounts to 250 kWh per suite annually, the modelled consumption is within reasonable expectations and is not the root cause of the excessive simulated energy consumption. The suite exhaust fan inputs were therefore unmodified.

The suite miscellaneous electrical loads are assumed to be 5 W/m^2 (0.4645 W/ft^2) from MNECB-1999, which based on an average modelled suite floor area of 116 m^2 (1250 ft^2) amounts to approximately 580 W of installed miscellaneous equipment per apartment (National Research Council of Canada, 1999). While this resulted in a total annual consumption of 83,000 kWh, 580 W per apartment is fairly realistic given the power demands of modern appliances. However, this means that of the 100,000 kWh of annual suite lighting and equipment consumption estimated from metering, 83% is assumed to be equipment related. As this is a relatively high percentage, the MELs were dropped to the equivalent of 500 W of installed capacity per suite, or 4.3 W/m^2 (0.4 W/ft^2).

Assuming that the MELs are correct, the suite lighting consumption must be reduced from 50,000 kWh/year to 17,000 kWh/year in order to achieve agreement between the modelled and estimated consumption. The original input was 6.5 W/m^2 (0.6 W/ft^2) from ASHRAE Standard 90.1-2007, which based on an the aforementioned average suite floor area results in 750 W of installed and task lighting within each suite (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2007). While this power draw would be conceivable if the majority of the fixtures were incandescent, modern compact fluorescent (CFL) and light emitting diode (LED) fixtures require substantially less power – often achieving efficacies over four times that of incandescent lamps (Mather, 2014). As such, the reduction in suite lighting energy is plausible. In order to achieve the 33,000 kWh/year reduction in energy consumption, the suite lighting power density was lowered to 2.24 W/m^2 (0.21 W/ft^2).

Implementing these changes had a fairly substantial impact on electrical loads. Room electricity decreased by 11,600 kWh or 13% annually while baseboard electric heating increased by 12,100 kWh. Additionally, the lighting energy decreased by 32,100 kWh or 32% annually. Overall, the annual total energy consumption decreased 31,400 kWh or 4.4%, which achieved the intent of decreasing the suite energy consumption.

D.3.1.2 Calibration 3.2: Common Electrical Loads

The common electricity consumption represented the single largest discrepancy between the measured and modelled energy consumption with the model under predicting consumption by 72,300 kWh annually. As with the suites, the electrical model inputs associated with the common electricity consumption need to be re-evaluated in order to determine the source of the discrepancy. End-uses contributing to the common electrical consumption consist of the DHW pump, MAU and parkade fans, corridor lighting, and parkade lighting.

The DHW pump and MAU fan are modelled to consume a combined 6500 kWh annually. While this is a relatively small value, it has already been increased within reasonable limits and likely isn't responsibly for a substantial portion of the missing 72,300 kWh. As such, the inputs surrounding the modelled performance of these systems was left unchanged.

The corridor and parkade lighting power densities were assumed to be 6.5 W/m^2 (0.6 W/ft^2) and 2.7 W/m^2 (0.25 W/ft^2) respectively based on ASHRAE Standard 90.1-2007 (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2007). As these are already conservative values, it is unlikely that the missing common electrical consumption is due to inadequate modelling of the common lighting. As such, the lighting power densities were unchanged.

It is evident that the source of the missing electrical consumption has not yet been identified. It could be the result of transformers in the parkade, electrical/telephone closets in the corridors, and other as-of-yet unaccounted for MELs. However, as no clear source was identified, it was instead necessary to implement distributed electrical loads in order to match the metered consumption. The selections were somewhat arbitrary, but the new MELs were split between the corridors and the parkade. Equipment loads of 4.75 W/m^2 (0.4413 W/ft^2) and 2 W/m^2 (0.1858 W/ft^2) were applied to the corridors and parkade respectively.

The added common MELs increased the annual room electricity consumption by 72,800 kWh or 91%, with a minimal decrease in suite baseboard electrical consumption of

5,300 kWh or 9%. The total annual energy consumption increased by 67,400 kWh or 10%, which is in accordance with the intent to increase common electricity.

D.3.1.3 Calibration 3.3: Domestic Hot Water Demand

The domestic hot water natural gas consumption simulated was 44,600 kWh/year less than the estimated consumption from monitoring data. The domestic hot water heater was configured based on the known equipment specifications, so the main assumption associated with the system is the daily hot water demand per apartment. This was previously modelled to be 40 Gallons/day/apartment based on ASHRAE Standard 90.1-2004 (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2004). In order to achieve agreement between the metered and modelled consumption, the demand was increased to 53 Gallons/day/apartment, which is consistent with the estimated consumption calculated in section 3.2.5.

The new domestic hot water demand increased DHW natural gas consumption by 41,000 kWh/year or 33%. This increase, while not the precise value desired, is close enough to be acceptable, and the small variation of 3000 kWh can be attributed to rounding error in the input value.

D.3.1.4 Calibration 3.4: Fireplace Consumption

The fireplace consumption also differed from the estimated consumption from monitoring, but in this case there are many more assumptions – particularly with respect to the fireplace operating schedule – that need to be re-evaluated.

Firstly, the natural gas consumption of each fireplace was modelled based on the known value of 8.8 kW (30,000 Btu/h) as previously discussed. This is unlikely to be incorrect, however the fireplaces do implement a standing pilot light which in many suites is likely left on for substantial portions of the year. This is could be a possible cause for the discrepancy in modelled in metered fireplace natural gas consumption of 12,000 kWh/year. In order to address this, an additional process load of 1.8 W/m² (0.17 W/ft²) was added to the living rooms with fireplaces.

The fireplace schedule is the result of numerous assumptions as discussed during the natural gas monitoring data analysis in section 3.2.3. Rather than re-evaluating all of the core assumptions and developing a new schedule, the existing schedule was reshaped to match the trends in consumption observed in the natural gas data. Figure D-13 displays the new fireplace operating schedule as compared to the previous revision. The total number of hours of operation were roughly retained for consistency between the second and third pass models. Note that it was assumed that the MAU and DHW loads are correct, and the remaining inconsistencies in the natural gas comparison are related to the operation of the fireplaces.

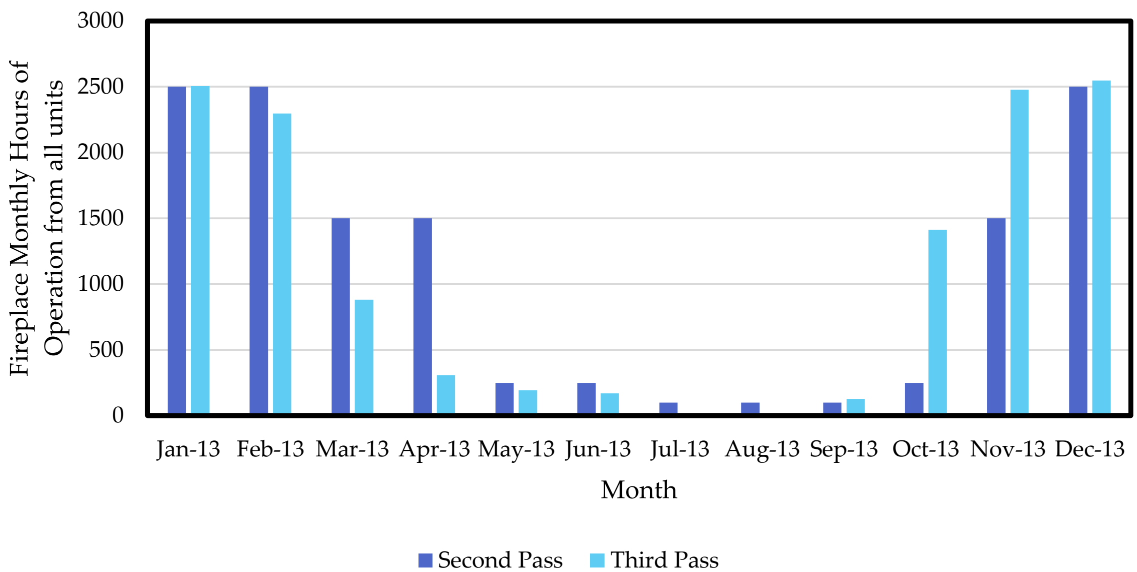


Figure D-13: Second pass vs. third pass fireplace schedule hours of operation for all units

The changes to the fireplace schedule and pilot light baseload resulted in an increase of 12,000 kWh/year of natural gas consumption. This increase was the targeted amount, and confirms that the approximate number of fireplace operating hours was conserved between the second and third pass models of the schedule. There was a slight decrease of baseboard heating energy of 900 kWh, resulting in an overall increase in energy consumption of 11,100 kWh/year.

D.3.1.5 Calibration 3.5: Baseboard Electric Heating

The previously discussed calibrations involved manipulating input assumptions associated directly with a specifically identified end-use. In the case of the baseboard electric heating, however, the consumption has less to do with the equipment itself and more to do with the space loads simulated within the suites. As such, the heating setpoints, natural ventilation controls, and infiltration were re-evaluated to achieve agreement between the metered and modelled consumption data. Note that the building enclosure insulation level and window characteristics also impact the space load, but as RDH performed the rehabilitation, these values are well understood and should not be the source of the discrepancy.

The heating setpoints at the Belmont vary from suite to suite, but for the model a value of 22°C (71°F) was chosen based on literature (Wilson et al., 2014). A significant increase in setpoint temperature would be difficult to justify, so only a modest increase to 22.2°C (72°F) was applied.

Natural ventilation in DesignBuilder is controlled by a set air change rate, modified by an indoor temperature setpoint. In the previous model iterations, a rate of 3 ac/h was applied at an indoor temperature exceeding 22°C (71°F). NREL recommends that the natural ventilation setpoint always exceed the heating setpoint by 1°F to prevent simultaneous heating and cooling during shoulder seasons (Wilson et al., 2014). As such, in accordance with the revised heating setpoint, the natural ventilation indoor temperature control needed to be increased. However, some simultaneous heating and cooling is likely to occur in the Belmont, and may be a likely contribution to the missing electric baseboard consumption observed in previous model iterations. Therefore, the natural ventilation setpoint was increased by only 0.5°F above the heating setpoint to a value of 22.5°C (72.5°F).

Infiltration is a function of many input properties including the building enclosure's air permeability, wind forces, stack effect, and mechanical pressures. In DesignBuilder, the user can input an airtightness value which is converted to an air leakage flow rate as discussed in Section 3.3.2. The value used in previous model iterations was 1.4 ac/h @ 50 Pa based on airtightness testing performed at the Belmont (Ricketts, 2014). However, despite all of the calibrations thus far, the baseboard electricity is greatly under predicted by the model – particularly during the heating season. This indicates that the heat loss from the space is still too low. As such, the airtightness value was increased until the baseboard consumption modelled was in adherence with the value estimated from metering. This value was substantially higher than the measured airtightness at 3.5 ac/h @ 50 Pa. While this may seem excessive, it is possible that due to the inaccuracy inherent with the process through which DesignBuilder estimates air leakage from airtightness values, a higher than measured input is required for realistic results.

The discussed calibrations resulted in an increase in suite heating energy consumption of 60,000 kWh or 120% annually. While this is substantial within the specific end-use, the overall annual consumption increased by only 7.5%.

D.3.2 Summary of Third Pass Calibrations

Table D-12 displays the impact of all the sequential calibrations discussed in Section D.3.1 in terms of the impact each calibration had on the annual total building energy consumption.

Table D-12: Summary of third pass Belmont model calibrations and their effect on annual energy consumption

Third Pass Iteration	Calibration	Annual Energy Consumption kWh	Change from Previous Model Iteration	
			kWh	%
3.1	Suite electrical loads	688,404	-31,399	-4.4%
3.2	Common equipment loads	755,792	67,388	9.8%
3.3	DHW demand	796,722	40,930	5.4%
3.4	Fireplace load and schedule	807,849	11,127	1.4%
3.5	Electric Baseboards	868,100	60,251	7.5%

D.3.3 Third Pass Modelled Energy Consumption

Combining all of the previously discussed third pass calibrations, the new iteration of the Belmont model now represents the best possible attempt at simulating the observed real world energy consumption based on available data, founded assumptions, and engineering judgement.

Figure D-14 displays the third pass model monthly electricity consumption for 2013 as compared to the metered consumption from BC Hydro. Note that the largest discrepancy now lies in October with the modelled consumption falling 11% below the metered consumption. All other months were within 7% of the target value.

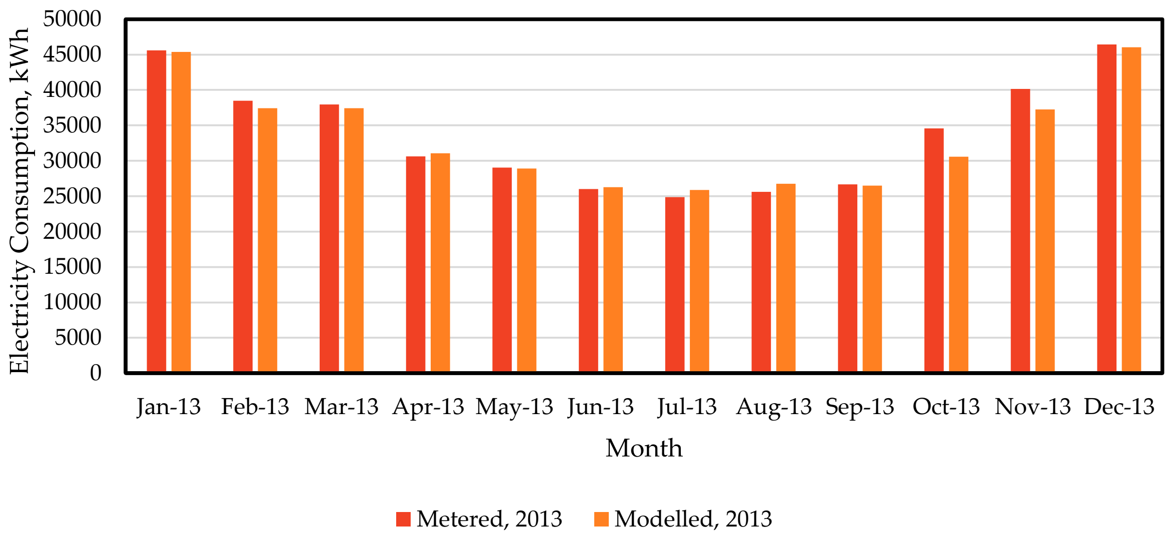


Figure D-14: Third pass Belmont model – monthly electricity consumption for 2013

Figure D-15 displays the third pass model monthly natural gas consumption for 2013 as compared to the metered data from Fortis BC. Unlike the electrical data, there are still several months that fall outside the desired level of agreement, with August reaching 22% above the measured consumption. However, while this is a large percentage, the finite value of the difference is only 3,300 kWh which represents 0.7% of the annual natural gas percentage. Furthermore, the discrepancy is likely due to varying seasonal domestic hot water demands which are not captured in the model given the limited resolution of the DHW schedule.

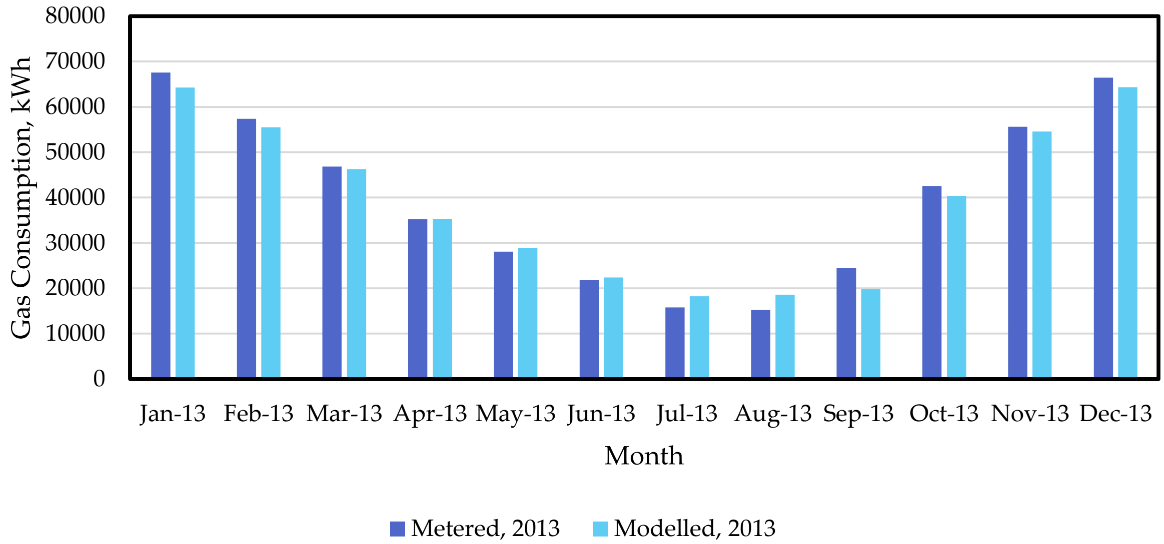


Figure D-15: Third pass Belmont model – monthly natural gas consumption for 2013

On an annual basis, the end-use splits from both electrical and natural gas demands can be summarized as shown in Figure D-16. Unlike in previous model iterations where the lighting dominated electrical consumption and the MAU heating coil dominated the natural gas consumption, the end-use splits are within norms.

Figure D-17 demonstrates the comparison between the third pass modelled end-use consumption and the end-use estimates from monitoring data developed in Section 3.2.4. All modelled end-uses are now within 3% of the estimated consumption, with the common lighting and equipment almost registering an exact match.

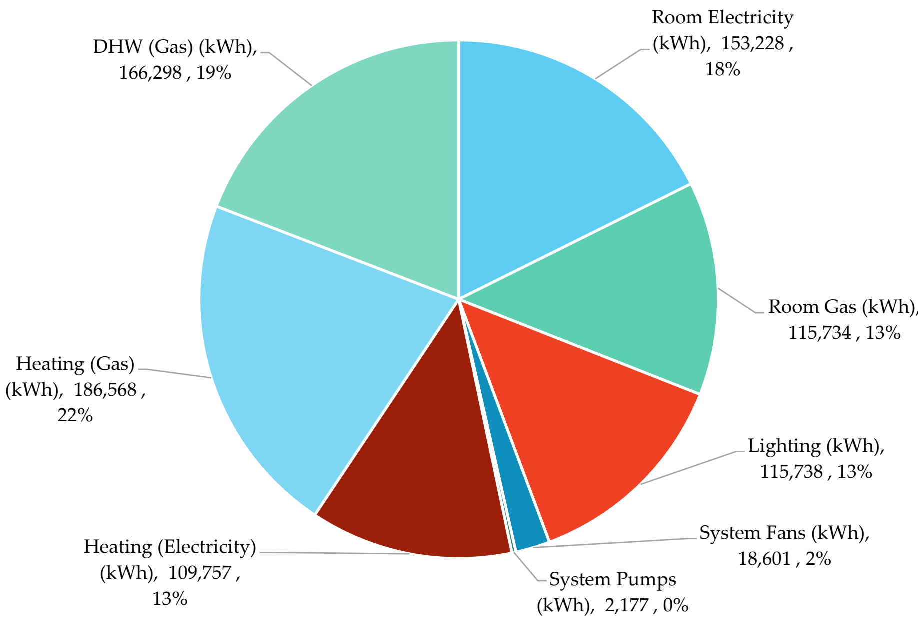


Figure D-16: Third pass Belmont model – 2013 annual end-use splits

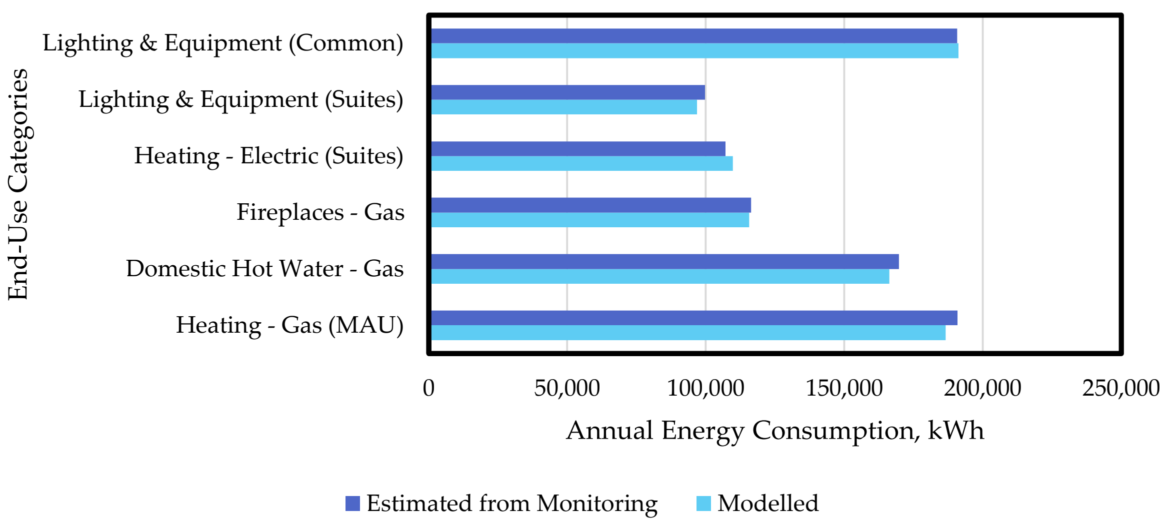


Figure D-17: Third pass Belmont model – annual end-use consumption – modelled consumption vs. estimates from monitoring data

Figure D-18 and Figure D-19 display the monthly simulated end-use consumption throughout the 2013 meteorological year. On the electrical side, it is visible that the room electricity and lighting comprise the majority of the baseload and remain constant throughout the year, while all of the seasonal fluctuations are largely the result of electric baseboard space heating. With respect to the natural gas consumption, it is evident that the fireplace and MAU consumption vary seasonal significantly while the DHW consumption only varies slightly due to fluctuations in the water mains temperature.

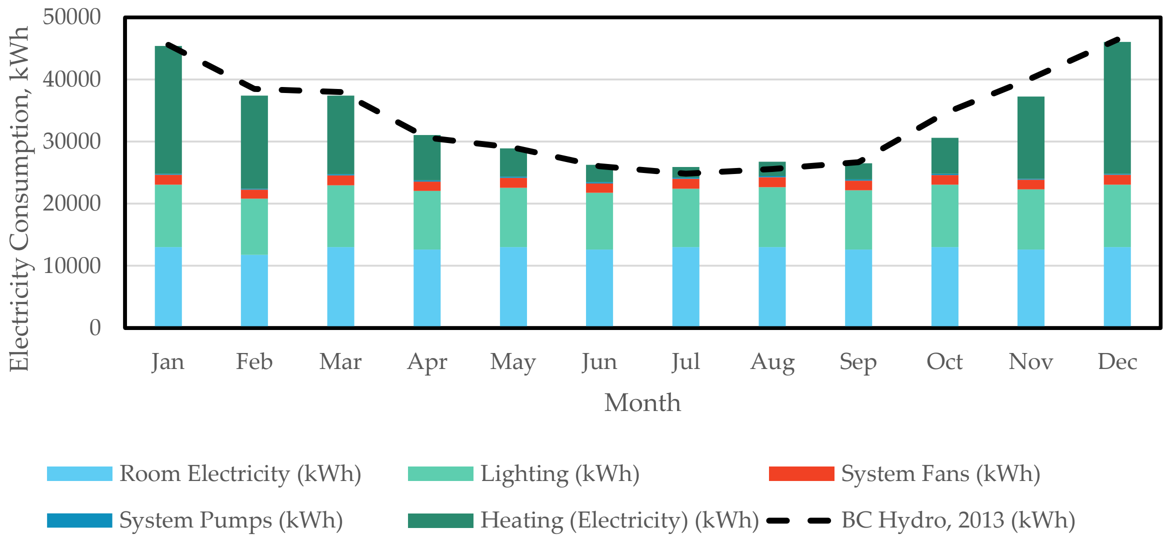


Figure D-18: Third pass Belmont model – monthly electrical end-use consumption

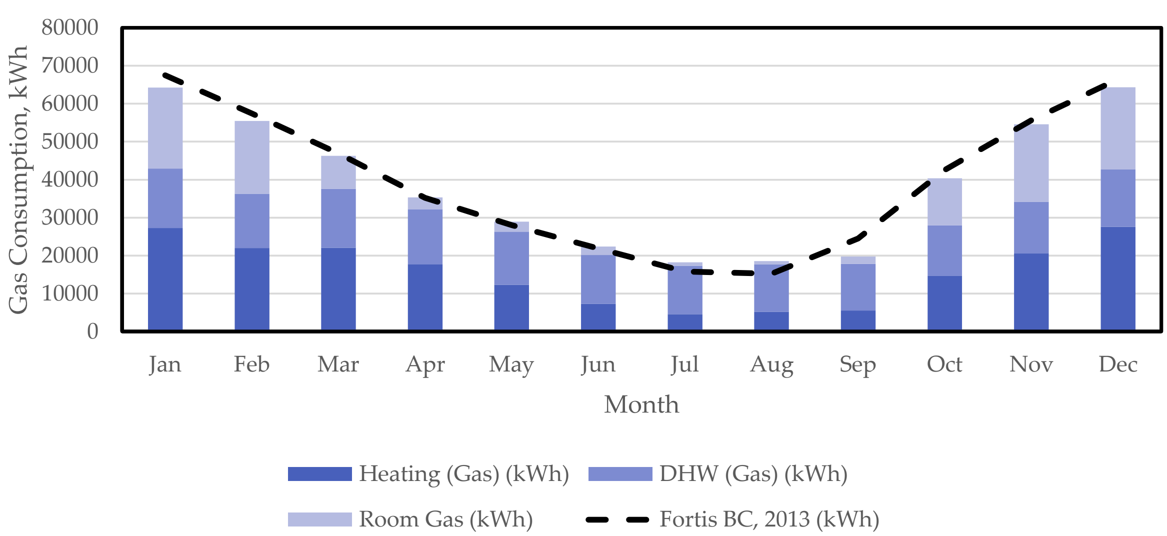


Figure D-19: Third pass Belmont model – monthly natural gas end-use consumption

D.4 Heat Flow Analysis

With the Belmont model's compliance with the utility and monitoring data confirmed, the heat balance performed by the EnergyPlus solver at each hourly time step can be aggregated and assessed on an annual scale. This involves assessing the total thermal energy transferred annually through different means both in and out of the whole building. In this case, the energy values are less important than the percentage splits between different heat transfer paths and mechanisms.

Figure D-20 displays the annual heat gains to the Belmont as a whole. It is useful to note that the baseboard electric heaters only account for 18% of the total heat gain, while miscellaneous equipment represent the largest source of heat gain at 36%.

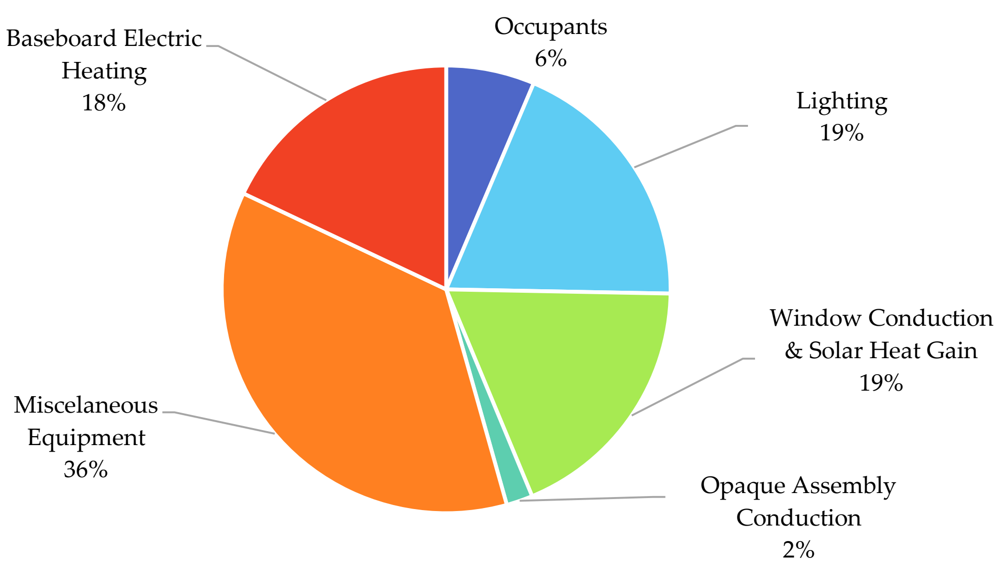


Figure D-20: Third pass Belmont model – annual heat gains by source

Figure D-21 displays the annual heat losses from the Belmont as a whole. Note that the corridor ventilation shows up as cooling, while the make-up air unit itself only contains a heating coil. This is the result of two factors: first, the MAU serves the corridors, which are located in the center of the building, and therefore do not experience the same magnitude of thermal exchange with the exterior that spaces adjacent to the building enclosure undergo. Secondly, the ventilation air heating setpoint is 18°C, despite most surrounding suites being conditioned to 22.2°C. These two factors combine to result in the ventilation air effectively cooling the corridors during the heating season.

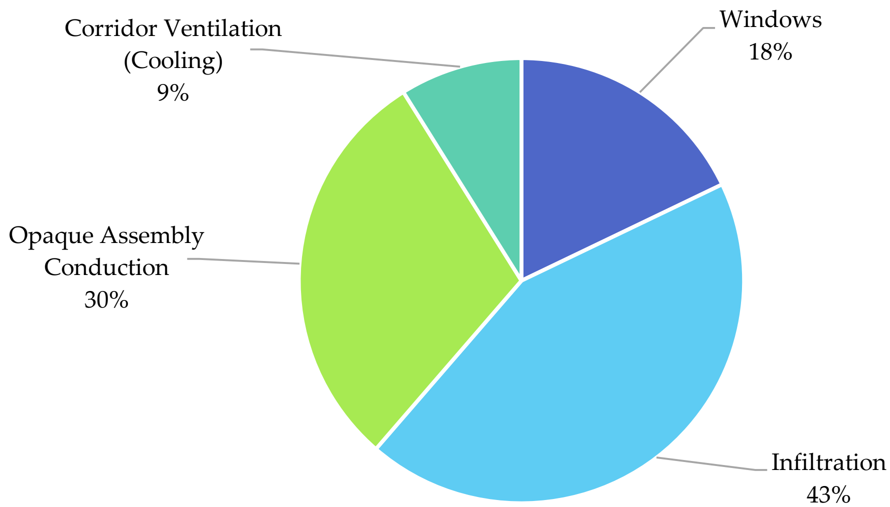


Figure D-21: Third pass Belmont model – annual heat losses by source

The opaque assembly conduction – representing conduction through walls, floors, and roofs – only accounts for 30% of the thermal losses, which can likely be attributed to the high insulation levels. However, the largest amount of heat loss is attributed to infiltration, despite the high level of airtightness achieved by the building enclosure. In calibrating the model however, the airtightness level was increased slightly, which is likely the reason behind the large influence infiltration is exhibiting over the whole building thermal losses.

The annual heat loss analysis identified the major sources of heat losses and gains from the building. Most heat losses are due to infiltration and conduction through opaque assemblies despite the 51% window-wall ratio. The largest source of heat gain is miscellaneous equipment, however lighting, window conductive and radiative gains, and baseboard heating all contributed a considerable amount.

D.5 Sensitivity Analysis of Building Characteristics

With the Belmont energy model built, calibrated, and verified, further analyses can be conducted in order to determine the relative impact of different building characteristics on annual energy consumption, with extrapolations to other high-rise MURBs where possible. Of particular interest are the building characteristics indirectly related to the HVAC and DHW systems such as the building enclosure, fireplaces, and location.

D.5.1 Fenestration Properties

The window properties used in the development of the Belmont model represent fairly high performance values given currently available technologies and price points. This is because RDH conducted a building enclosure retrofit in 2012 which included a window upgrade to a high performance glazing system. Nevertheless, alternative window properties can be modelled to explore the relationship between fenestrations and energy use for this specific building. Fenestration properties of a given building are typically described by four variables: window-to-wall ratio (WWR), U-value, solar heat gain coefficient (SHGC), and visible light transmittance (VLT or VT).

The modelled windows are triple glazed, fiberglass framed units with low-emissivity coatings and argon gas fill. As discussed in section 3.3.2, the window properties are as follows: an overall USI-value of 0.97 W/m^2 K (U-value of 0.171 $Btu/ft^2 \cdot {}^{\circ}F \cdot hr$), a solar heat gain coefficient of 0.2, and a visible light transmittance of 0.7. Note that glazing properties can be calculated with centre-of-glass values or overall values which include the frame effects. All values discussed in this section incorporate the effects of the frame.

D.5.1.1 Window-to-Wall Ratio

The Window-to-wall ratio (WWR) describes the amount of window area with respect to the total wall area, where the total wall area encompasses both window area and opaque wall area. Including window frames and dividers in the window area, the Belmont WWR is approximately 64% as built and modelled. Historically high-rise MURBs have been built in Canada with a wide range of WWRs, but recent trends and architectural styles have led to higher typical WWRs than in previous periods of construction.

Figure D-22 displays the sensitivity analysis conducted on the window-to-wall ratio. Specifically, the correlation between energy consumption and WWR is displayed. Note that there is only minimal correlation with electricity – all of which is related to the baseboard heating – and no substantial trend is visible in the natural gas consumption.

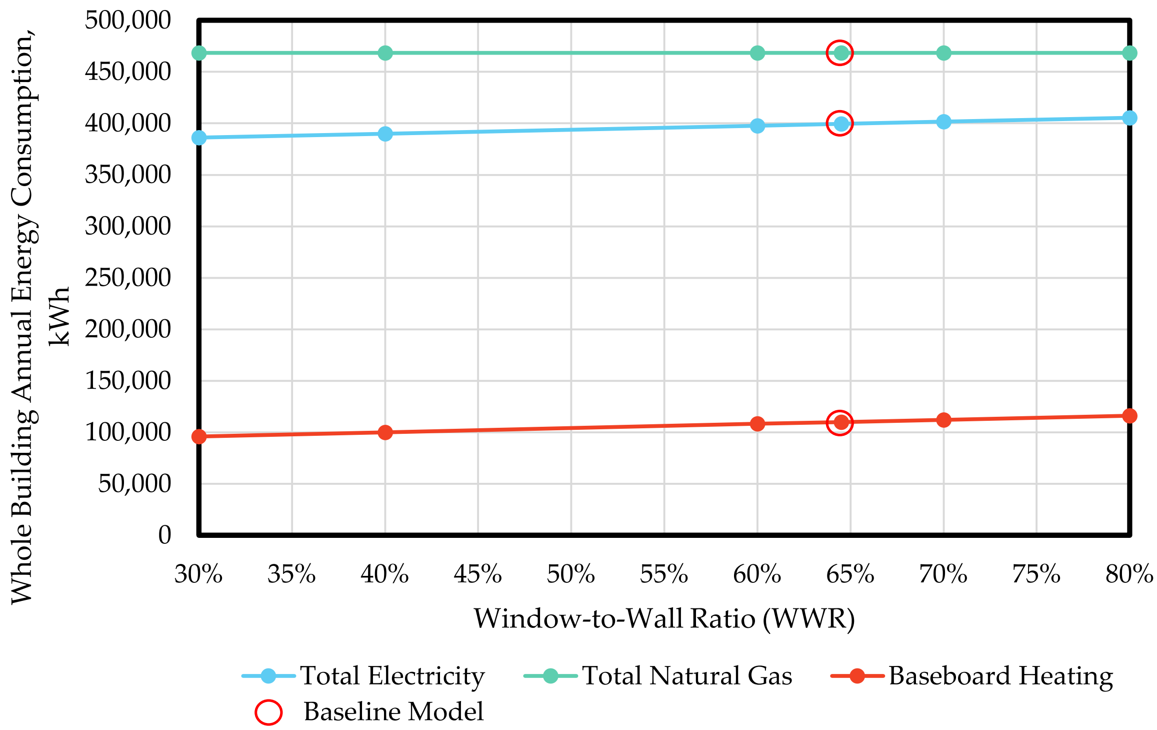


Figure D-22: Sensitivity analysis – window-to-wall ratio

For The Belmont specifically, with its post-retrofit high performance assemblies, it appears that varying WWR has minimal impact on annual energy consumption. Furthermore, what little correlation there is between WWR and electricity only relates to the baseboard heaters. This is likely due to the fact that the Belmont windows perform far beyond that required by the BC Building Code or the Vancouver Building Bylaw, and more correlation might be visible with lower performance fenestrations.

D.5.1.2 Window Assembly U-value

The U-value is the universal heat transfer coefficient of the window assembly, and describes the rate of heat transfer per unit window area and temperature difference. The baseline modelled USI-value of 0.97 W/m^2 K (U-value of 0.171 Btu/ft^2·°F·hr) is quite low compared to typical glazing systems implemented in high-rise MURBs which can approach values as high as 3 W/m^2 K in existing buildings. As such, it is necessary to consider the implications of lower performance windows on the building energy consumption.

Figure D-23 displays the sensitivity analysis conducted on the window U-value with respect to energy consumption. There is a visible trend between U-value and electricity, but as with the WWR, this only applies to the baseboard heating.

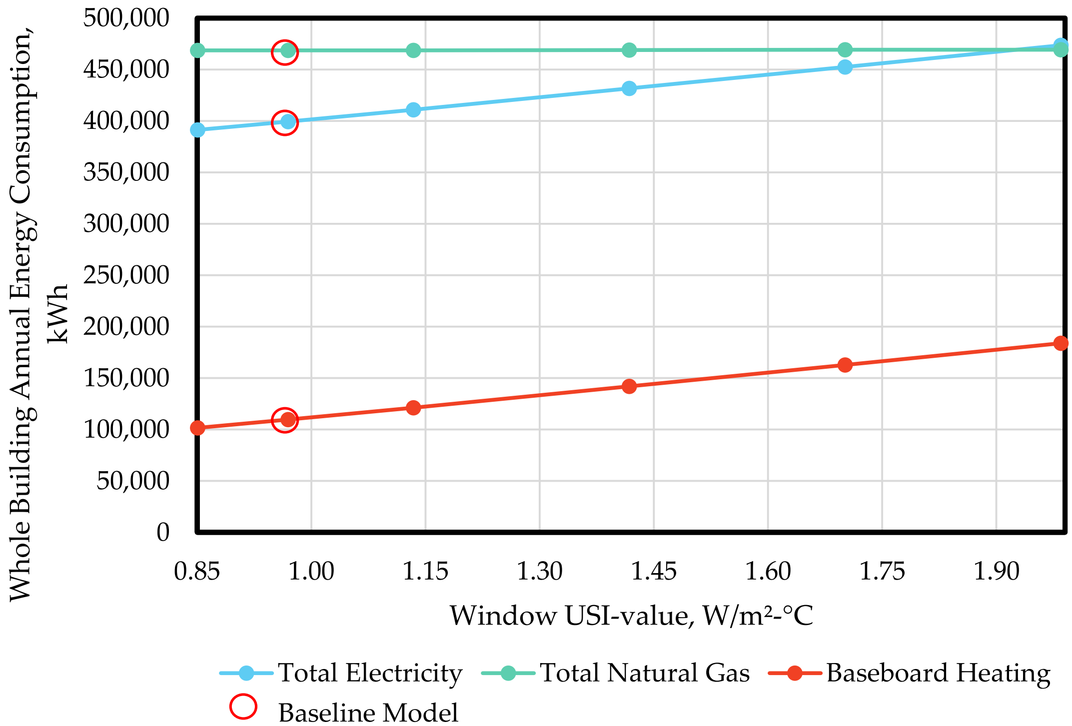


Figure D-23: Sensitivity analysis – window U-value

The window U-value clearly does correlate with electricity, but as only the baseboard heating is affected, the overall change in annual energy consumption is still limited. An increase from the baseline value of USI 0.97 W/m^2 K (U-value of 0.171 Btu/ft^2·°F·hr) to the maximum value modelled of 1.98 W/m^2 K (U-value of 0.35 Btu/ft^2·°F·hr) increased the baseboard heating energy by 68%, but this corresponds to an increase in total electricity of 19%, and an increase in total energy of 9%.

D.5.1.3 Solar Heat Gain Coefficient

The SHGC refers to the percentage of solar energy incident on the window area which passes through to the interior, and is often discussed at normal incidence although it can be calculated at any incidence angle. The Belmont windows have an as-built and modelled SHGC of 0.2, which is very low. Typical values very by window type and manufacturer and are improving with time. That being said, accepted example values range from 0.45 for triple glazed windows with low-e coatings to 0.75 for single glazed windows with no coatings (McQuiston et al., 2005).

Figure D-24 displays the sensitivity analysis conducted on the SHGC, with values ranging from 0.1 to 0.6. Unlike the previously discussed fenestration properties, the SHGC shows a negative correlation with energy consumption, which again is tied to the baseboard heating.

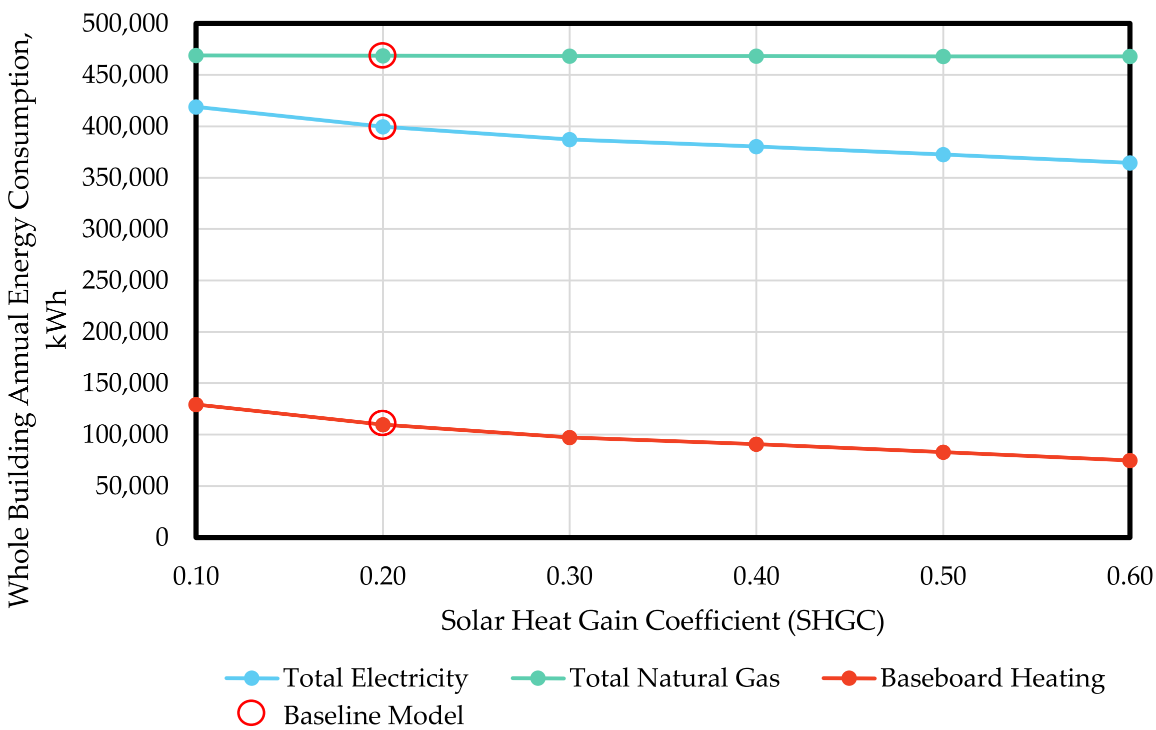


Figure D-24: Sensitivity analysis – solar heat gain coefficient

The correlation between SHGC and electricity consumption is slight, but definitively negative. On the surface, this appears contradictory, as higher SHGC values correspond to cheaper, lower performance windows. However, the decrease in heating electricity is due to added solar heating, which in turn also increases cooling loads. The Belmont does not have any active cooling equipment, and therefore the increased solar gains do not appear in the energy data, but increases are apparent in the temperature and airflow data.

Figure D-25 displays the monthly average operative temperature across all interior spaces for varying SHGC values. The operative temperature represents the average between the air and mean radiant temperature within the interior spaces, and is a common metric used to discuss thermal comfort. ASHRAE Standard 55 provides guidance for thermal comfort, which is a very complex subject area, but it can generally be observed that while the modelled temperatures are within acceptable limits, the increasing operative temperature would likely lead to an increasing number of instances of discomfort among occupants (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2009). It should also be noted that as the operative temperature increases with SHGC, so does the disparity between the mean radiant temperature and the air temperature – a trend that could also lead to thermal comfort concerns.

Figure D-26 displays a similar trend in increasing air change rates with increasing SHGC. This is due to the natural ventilation operation scheme implemented in the model which simulates the opening of windows when the interior temperature exceeds 22°C (72°F). Combined with the previous plot of operative temperature however it is clear that for SHGC of 0.5 or higher, there are periods when natural ventilation provides inadequate cooling, and some form of active cooling would likely be required to ensure thermal comfort.

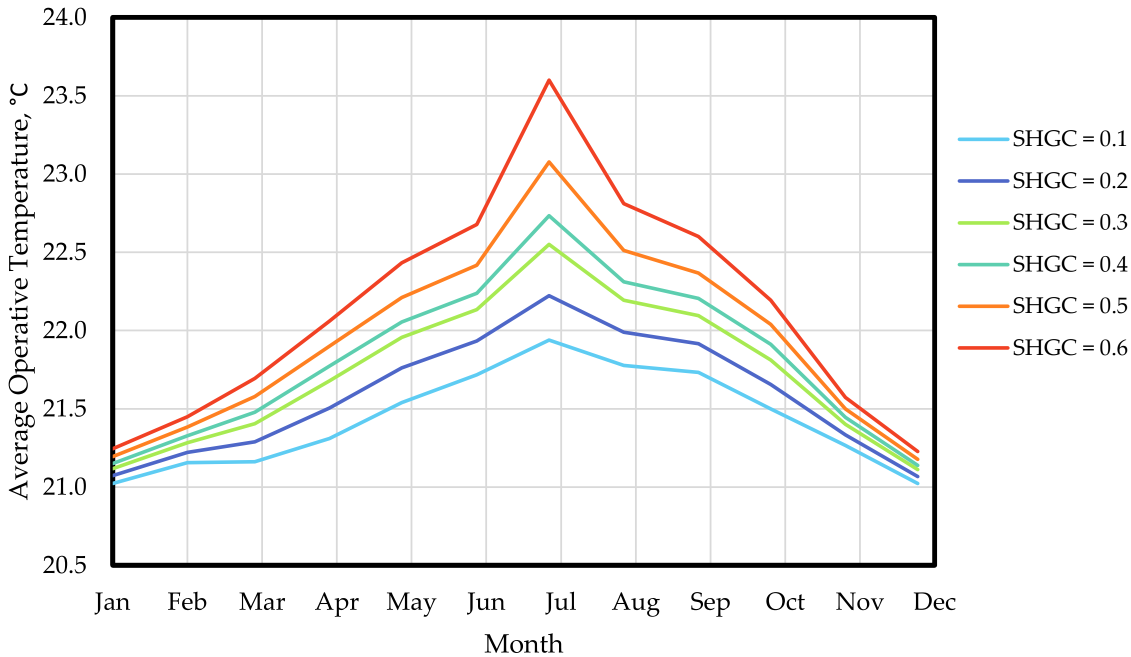


Figure D-25: Sensitivity analysis – solar heat gain coefficient – average monthly operative temperatures

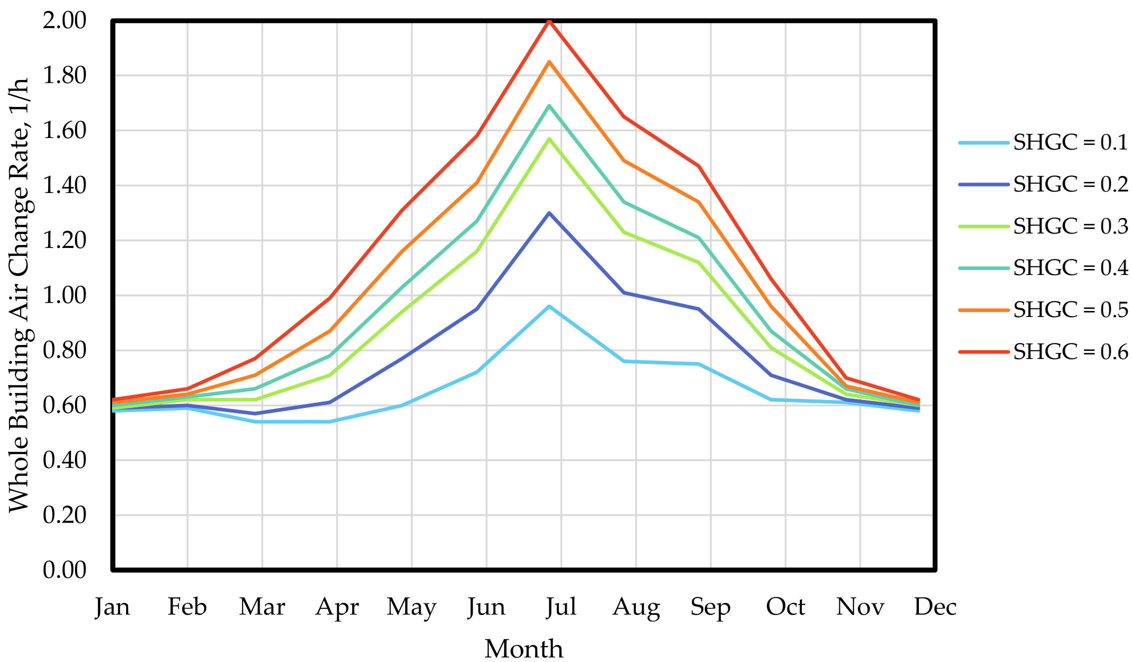


Figure D-26: Sensitivity analysis – solar heat gain coefficient – average monthly air change rates

Overall there was a slight negative correlation between energy consumption and SHGC. Transitioning form the baseline value of 0.2 to the highest value modelled of 0.6, the baseboard heating decreased by 32% which corresponds to a decreases of 9% in total electricity and 4% in total energy. While this correlation is modest, it is clear that at higher SHGC values, thermal comfort would become an issue and some form of cooling would likely become necessary.

D.5.2 Opaque Wall Insulation

The opaque wall insulation refers to the insulation value of the vertical surfaces not associated with the fenestrations assemblies on the exterior walls of the building. While the specific materials used in the wall assembly matter from a building science perspective, in this case the only relevant parameter is the insulation value which is quantified by the assembly effective R-value. In the baseline model and as-built building, The Belmont post-retrofit wall assemblies have an effective RSI-value of 2.82 m^2·K/W (R-value of 16.06 ft^2·°F·hr/Btu). This exceeds the BC Building Code and Vancouver Building Bylaw minimum, but is not as insulating as assemblies used in low energy building construction such as Passive House (Canadian Passive House Institute, 2016). As such, it is useful is examine effective R-values both greater than and less than the baseline case.

Figure D-27 displays the sensitivity analysis conducted on the opaque wall RSI-value. As with the SHGC, a slight negative trend is visible, but this is to be expected based on Fourier's Law. Note that within the model, internal areas are calculated based on the perimeter area less the exterior wall thickness, and so the total wall thickness had to remain constant throughout all parametric runs in order to avoid inadvertent modification of internal loads which are applied on a per unit floor area basis. As such, modifications were made to material types and non-critical material thicknesses, but the thermal mass elements such as the structural concrete were retained at the baseline values.

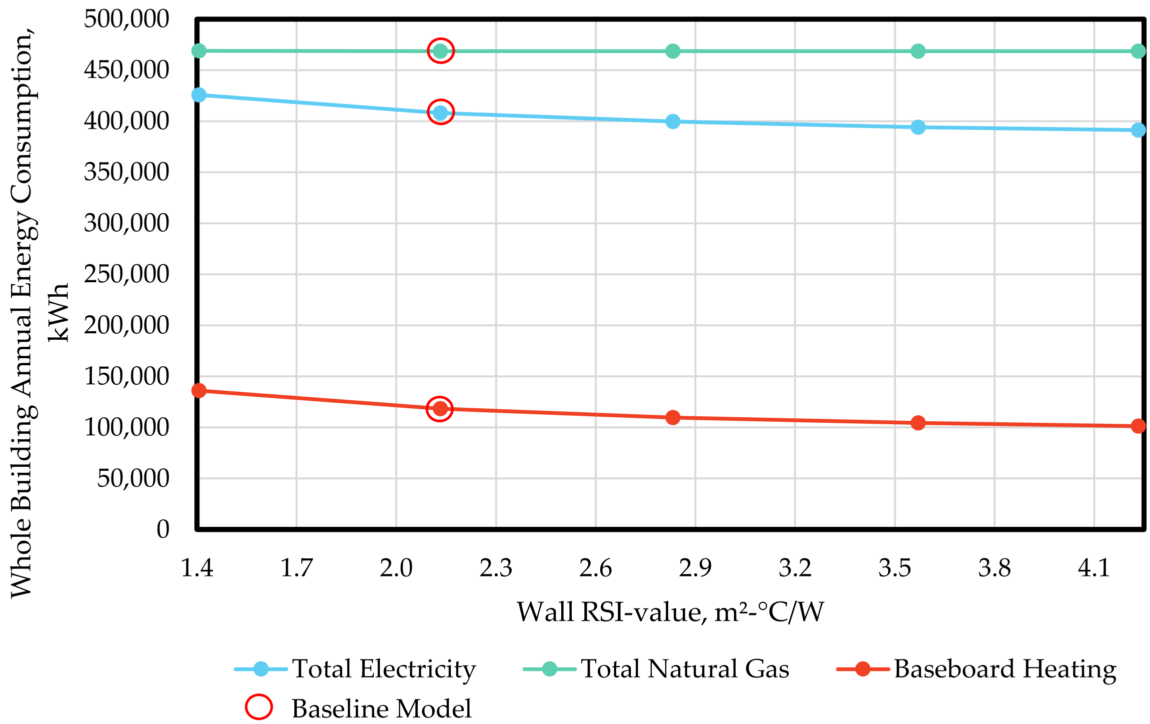


Figure D-27: Sensitivity analysis – opaque wall RSI-value

It is clear that while a negative correlation is visible between effective R-value and energy consumption, it is still fairly minimal. A change from the baseline effective RSI-value of 2.82 m^2·K/W (R-value of 16.06 ft^2·°F·hr/Btu) to the maximum value modelled of 4.21 m^2·K/W (R-value of 23.86 ft^2·°F·hr/Btu) resulted in a decrease of 14% in annual baseboard heating. This equates to a decrease in total electricity of 4%, and a decrease in total energy of 2%.

D.5.3 Roof Insulation

The roof insulation, as with the opaque wall insulation, is concerned with the effective R-value of the roof assembly. In the baseline model and as-built construction, The Belmont roof has an RSI-value of 3.5 m^2·K/W (R-value of 19.9 ft2·°F·hr/Btu). Unlike the wall assemblies, the nature of inverted roof assemblies results in minimal thermal bridging, and therefore the nominal R-value is usually a valid input when modelling.

Figure D-28 displays the sensitivity analysis conducted on the roof RSI-value. Only a slight correlation is visible, but as with the wall insulation, the trend is negative.

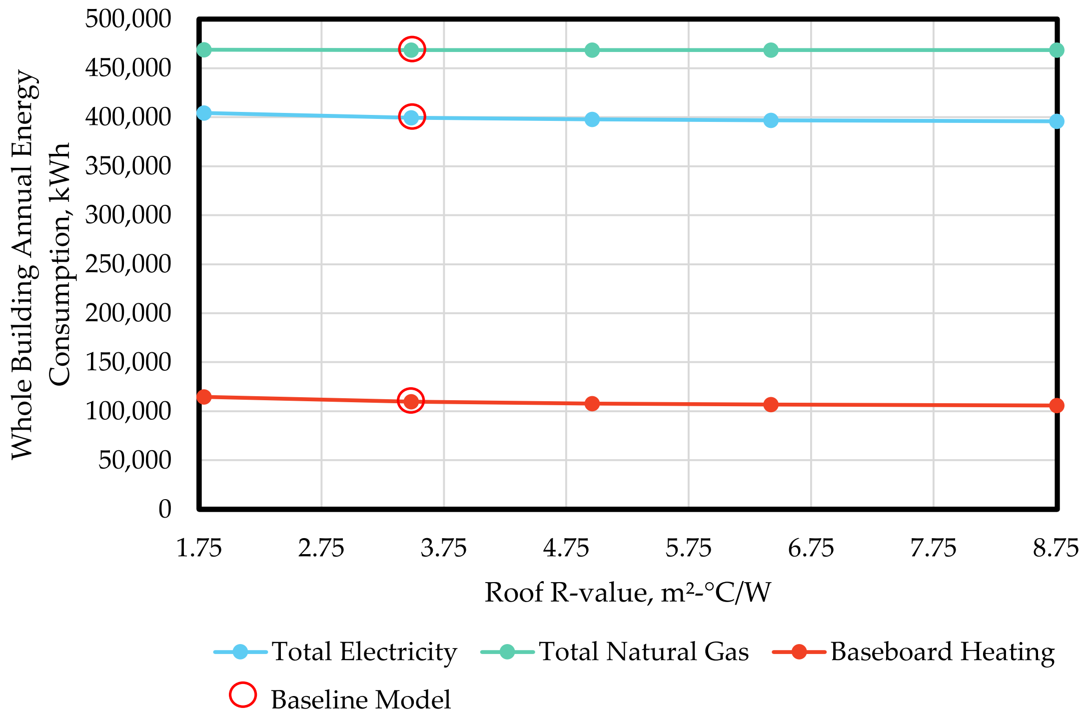


Figure D-28: Sensitivity analysis – roof RSI-value

Only a minimal correlation is visible between the roof insulation level and building energy consumption, with a maximum variation from the baseline electricity consumption of only ±1% across all values modelled. This minimal variation is likely due to the form factor of the building, and the fact that only 5 of the 37 suites have any contact with the roof assembly.

D.5.4 Airtightness

Airtightness is a building enclosure performance metric, and describes the amount of air that can pass through an assembly at a given differential pressure. In application, whole building airtightness testing is often conducted to in order to quantify the performance of the air barrier systems. As previously discussed in Section 3.3.2, The Belmont was tested by RDH and was found to have an overall airtightness of 1.4 Ac/h at 50 Pa.

In the context of energy modelling, air leakage is an important input as it determines the amount of air exchange simulated across the building enclosure at each time step of the simulation. Infiltration is distinctly different from airtightness however as infiltration occurs at much lower differential pressures, and therefore converting between the two represents an engineering challenge.

In The Belmont model, the infiltration was input in the form of an airtightness value, and DesignBuilder converted this value to an infiltration rate by means of equation D-1 as described in BS EN12831 (European committee for Standardization, 2003).

$$V_{Inf,i} = 2 \cdot V_i \cdot n_{50} \cdot e_i \cdot i \qquad \text{Eq. D-1}$$

where: $V_{Inf,i}$ = infiltration air flow rate for zone i, $[m^3/h]$

V_i = volume of a given interior zone, $[m^3]$

n_{50} = measured air change rate at 50 Pa, [Ac/h]

e_i = shielding coefficient $(0.03 - 0.05$ for tall buildings in windy areas)

i = height correction factor $(1 - 1.5$ depending on the height of the zone)

While equation D-1 does include a correction factor in an attempt to account for differences in wind pressure resulting from building height, it makes no attempt to account for varying building pressures, and therefore represents a fairly simplistic method of converting airtightness to infiltration.

In the development of the Belmont model, the measured airtightness value of 1.4 Ac/h at 50 Pa was calibrated to 3.5 Ac/h at 50 Pa in order to get realistic predictions of space heating loads. This likely indicates that equation D-1 under predicts infiltration, and so more conservative inputs are required.

Figure D-29 displays the sensitivity analysis conducted on the building enclosure airtightness value. Note that the airtightness values represent the inputs as entered into DesignBuilder, and the corresponding real-world airtightness values are likely lower based on the case of The Belmont specifically.

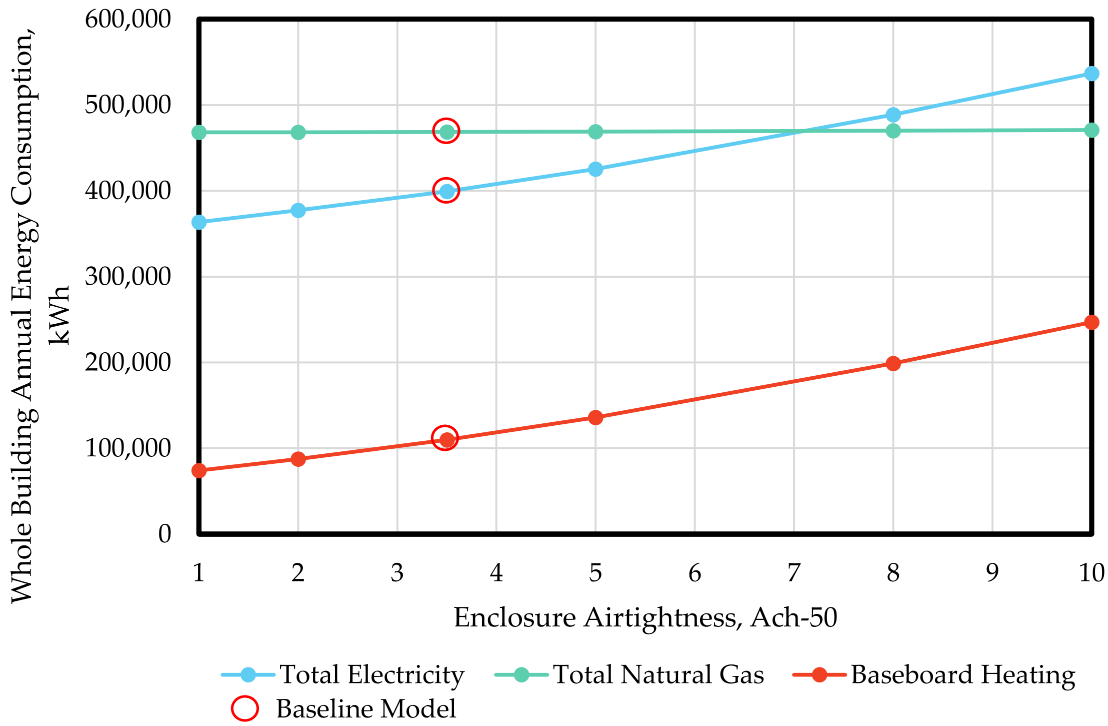


Figure D-29: Sensitivity analysis – airtightness value as entered into DesignBuilder

It is clear that airtightness is strongly correlated with electricity use, despite the only end-use associated with the correlation being baseboard heating. A variation from the already exaggerated value of 3.5 Ac/h at 50 Pa in the baseline model to the maximum value simulated of 10 Ac/h at 50 Pa resulted in an increase in baseboard heating energy consumption of 182%. This increase corresponds to an increase in electricity consumption of 42%, and an overall increase in energy consumption of 19%. From these numbers it is clear that proper input of the airtightness value is crucial to the accurate simulation of whole building energy consumption, even in a climate as mild as Vancouver.

D.5.5 Fireplaces

The Belmont has natural gas fireplaces in the living rooms of the suites on the top 5 floors, which corresponds to 13% of the total building annual energy consumption. The presence of these fireplaces, however, is atypical of new construction high-rise MURBs. As such, it is necessary to also consider how the presence of the fireplaces shifts the distribution of energy consumption between the remaining end-uses.

Figure D-30 displays the annual energy consumption of the major end-uses in The Belmont model both for the baseline case with fireplaces as well as the alternative case involving no fireplaces. Aside from the variation in fireplace consumption, removing the fireplaces increased the baseboard heating energy by 20% or 22,000 kWh/year.

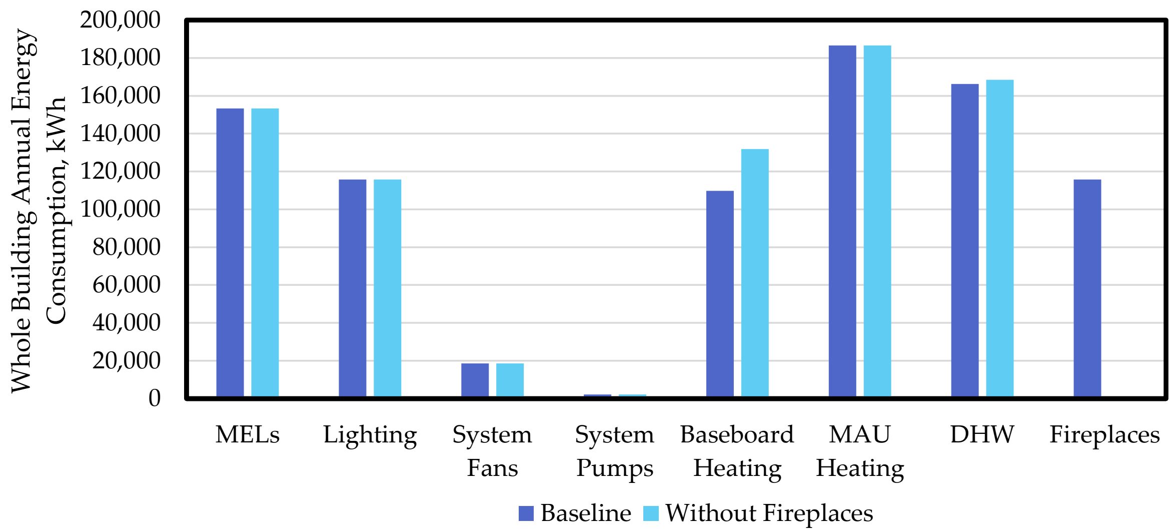


Figure D-30: Sensitivity analysis – The Belmont model with and without fireplaces

Removing the fireplaces results in a decrease of 116,000 kWh of natural gas consumption, which combined with the increase in electric baseboard consumption of 22,000 kWh leads to a total decrease in consumption of 94,000 kWh. This substantial decrease shifts the percentage breakdown between the remaining end-uses, which can be seen in Figure D-31. With the new configuration, the mechanical systems – including the DHW, MAU, baseboard heaters, system pumps and fans – comprise 65% of the annual energy consumption.

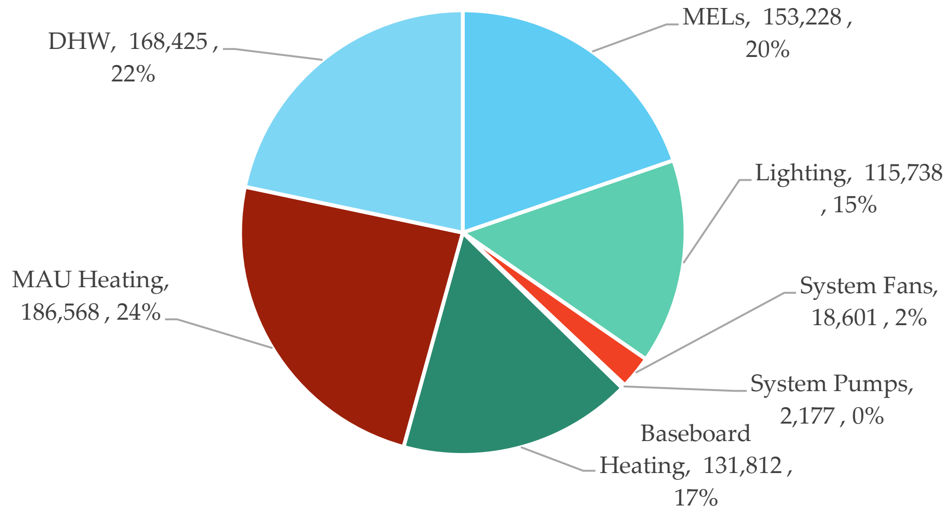


Figure D-31: Sensitivity analysis – end-use breakdown of The Belmont model annual consumption without fireplaces

The change in space heating energy of 22,000 kWh despite the decrease in fireplace energy of 116,000 kWh indicates that the majority of the energy consumed by the fireplaces was not effectively contributing to the building space heating needs. This is likely due to the relatively low efficiency of the fireplaces, which were modelled as having an efficiency of 60%, all of which acted as radiant heat gains. Additionally, as fireplaces were only present in the living rooms of the suites on the top 5 floors, they only influenced a small percentage of the total conditioned floor area. Overall, the fireplaces consumed a large percentage of the total building energy use despite not contributing significantly to the space heating loads.

D.5.6 Enclosed Balconies

In addition to the fireplaces, another atypical building characteristic of The Belmont is the presence of enclosed balconies. These zones represent spaces within the outer building enclosure that are additionally separated from conditioned interior space, and have no active conditioning equipment installed.

Within the energy model of the Belmont, the enclosed balconies were modified in order to treat the zones differently. The easiest change to implement involved simply changing the designation of these spaces such that they were also conditioned with baseboard electric heating in order to be consistent with the rest of the suite conditioned floor area. This addition of 316 m^2 (3,400 ft^2) of conditioned floor area caused an increase in baseboard electricity consumption of 11% annually. While not a substantial change in this end-use, the additional energy does change the end-use splits as depicted in Figure D-32.

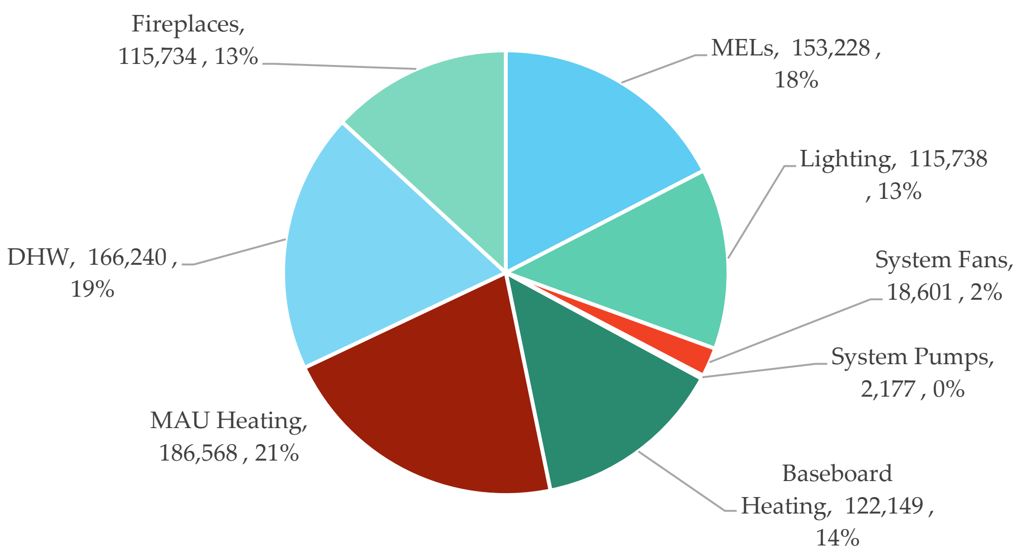


Figure D-32: Sensitivity analysis – end-use breakdown of The Belmont model annual consumption without enclosed balconies

Modifying the model to include the enclosed balconies as conditioned interior space did increase the space heating load slightly, but had a minimal increase on overall energy consumption of 1%. A slight improvement was also visible in the mean operative temperature during winter months. Overall the change had minimal impact on the whole building consumption values.

D.5.7 Location

The building location determines the loads experienced by the space conditioning systems, and by extension has a large influence over the whole building energy use. Construction practices and system selections can be regionally specific for a wide variety of reasons, include local building codes and material availability. Furthermore, it would be unlikely for a building with all of The Belmont's characteristics to be constructed in a colder climate zone than Vancouver, but it is useful to evaluate the impact varying climate types would have on the annual energy use.

Figure D-33 displays the end-use energy consumption of the Belmont for a variety of different weather files. Note that the baseline used the Vancouver International Airport 2013 actual meteorological year (AMY), while the other weather files are based on typical meteorological year (TMY) data from the CWEC database.

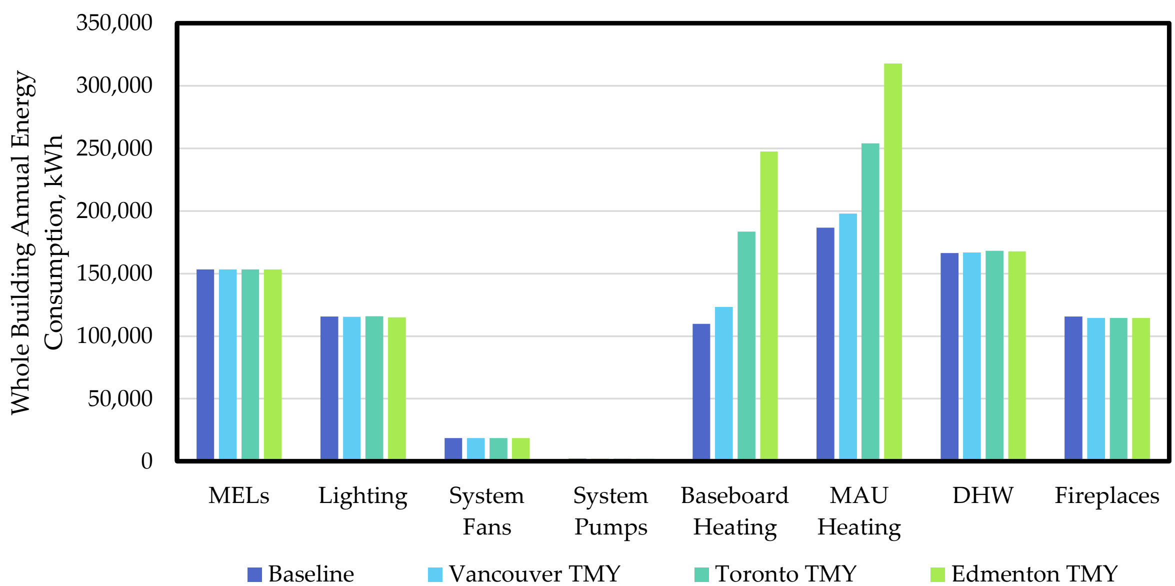


Figure D-33: Sensitivity analysis – location

The only end-uses correlated with location are baseboard heating and MAU heating, but the variation from Vancouver to Edmonton was substantial; baseboard heating energy increased by 126%, and make-up air heating energy increased by 70%. Figure D-34 displays the end-use consumption splits based on the Edmonton typical meteorological year weather file.

The increase in space conditioning loads in Edmonton results in a shift in end-use consumption such that HVAC and DHW systems now constitute 67% of the total annual energy consumption as opposed to 55% in the baseline scenario. While the specific systems and equipment may be different based on typical practices under the Alberta Building Code, it is evident that there is a substantial variation in space conditioning energy consumption between the locations. The increase in ventilation energy is artificially high as heat recovery of ventilation air is required in Edmonton under the 2011 NECB.

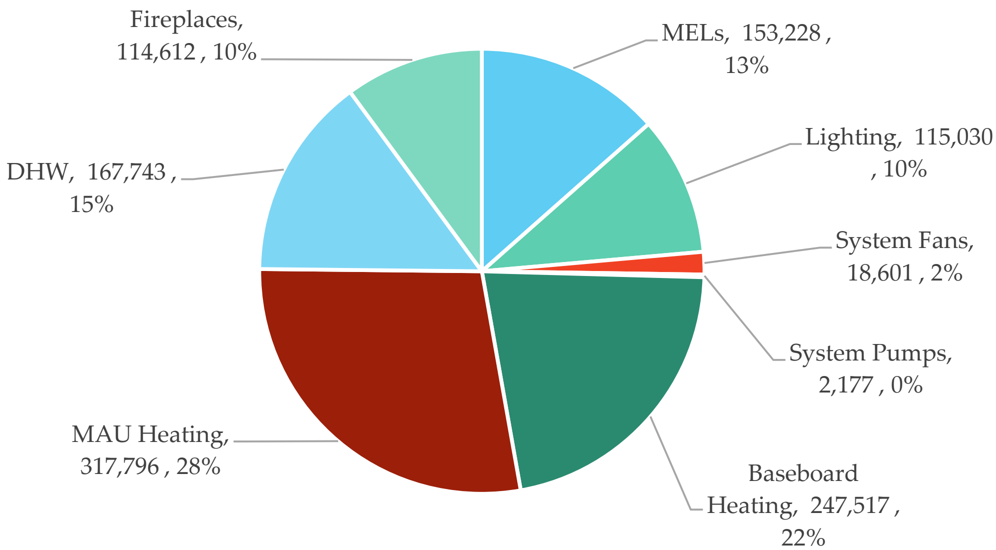


Figure D-34: Sensitivity analysis – End-use breakdown for the Belmont model based on the Edmonton TMY weather file

Appendix E: Mechanical System Model Inputs

In this section, the modelling inputs required to configure each of the independent mechanical systems identified in the main body of the thesis are listed. Figure E-1 displays the different system type numbers, as discussed in Chapter 2. Table E-1 summarizes the different system types as classified for this analysis. Table E-2 provides relevant information and explanations of acronyms and abbreviations used throughout this appendix. Table E-3 describes each system, with subsequent tables denoting the specific modelling inputs associated with each system.

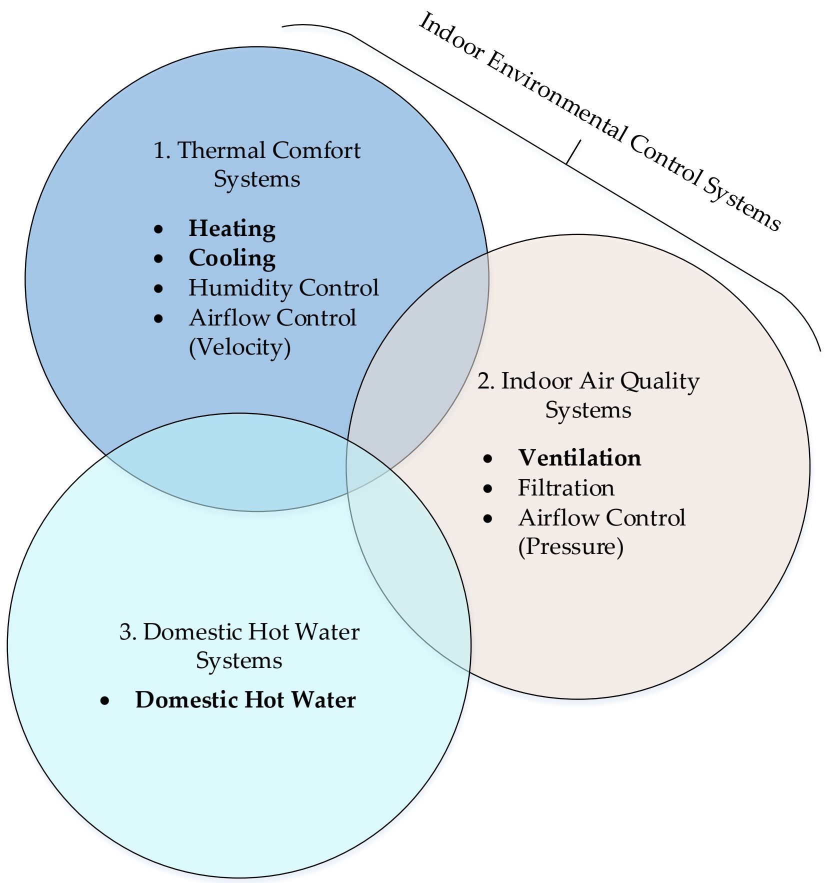


Figure E-1: Residential mechanical system types 1-3 as defined for the purposes of this body of work. This figure is repeated from Section 2.5 for convenience

Table E-1: Residential mechanical system types – as classified based on their primary functions served

System Type	Primary Functions Served	Notes
1a	• Heating	May also provide filtration, humidity, airflow control
1b	• Cooling	May also provide filtration, humidity, airflow control
1c	• Heating • Cooling	May also provide filtration, humidity, airflow control
2a	• Suite Ventilation	May also provide filtration, humidity, airflow control
2b	• Corridor Ventilation	May also provide filtration, humidity, airflow control
2c	• Suite Ventilation • Corridor Ventilation	May also provide filtration, humidity, airflow control
3	• Domestic Hot Water	

Table E-2: Acronyms and abbreviations used throughout this appendix

Term	Meaning	Description
S/S	Suite by suite layout	Refers to systems which have all energy production/rejection components located within individual suites
F/F	Floor by floor layout	Refers to systems which have all energy production/rejection components located on each floor in common space
C/	Centralized	Refers to systems which have all energy production/rejection components located in one central area of the building
V	Vancouver	Used to abbreviate location modelled
T	Toronto	Used to abbreviate location modelled
E	Edmonton	Used to abbreviate location modelled

Table E-3: Mechanical system descriptions

System Number	System Type	Primary Fuel	Layout	Distribution Medium	Description	Locations Modelled
1	1a	Elec	S/S	N/A	Electric resistance, convective heating	V, T, E
2	1a	Elec	S/S	Air	In-suite AHU with forced air electric furnace	V, E
3	1a	Gas	S/S	Air	In-suite AHU with forced air natural gas furnace	V, E
4	1a	Gas	C/	Water	Radiant floor with centralized natural gas boiler	V, T, E
5	1a	Gas	C/	Water	2-pipe FCUs with centralized natural gas boiler	V, E
6	1a	Gas	C/	Water	Hydronic convectors with central natural gas boiler	V, T, E
7	1b	Elec	S/S	N/A	PTAC, no heating	T
8	1b	Elec	C/	Water	Chilled ceilings with central chiller, cooling tower	T
9	1c	Elec	S/S	N/A	PTAC, electric heating coil	V, T, E
10	1c	Elec	S/S	N/A	PTHP, electric backup heating coil	V, T, E
11	1c	Elec	S/S	Air	In-suite AHU, electric furnace, dx cooling	T
12	1c	Elec/Gas	S/S	Air	In-suite AHU, natural gas furnace, dx cooling	T
13	1c	Elec	S/S	Refrigerant	Central VRF system, air source heat pump	V, T, E
14	1c	Elec	S/S	Refrigerant	Central VRF system, ground source heat pump	V, T, E
15	1c	Elec/Gas	C/	Water	4-pipe FCUs, central natural gas boiler, chiller, cooling tower	T
16	1c	Elec/Gas	C/	Air/Water	In-suite WSHP, central natural gas boiler, cooling tower	T
17	2a	Elec	S/S	Air	In-suite Heat Recovery Ventilator (HRV)	V, T, E

System Number	System Type	Primary Fuel	Layout	Distribution Medium	Description	Locations Modelled
18	2a	Elec	S/S	Air	In-suite Energy Recovery Ventilator (ERV)	V, T, E
19	2b	Elec	F/F	Air	Floor AHU, DOAS serving corridors, heat recovery	V, T, E
20	2b	Elec	F/F	Air	Floor AHU, DOAS serving corridors, enthalpy recovery	V, T, E
21	2b	Elec	C/	Air	Central AHU, DOAS serving corridors, heat recovery	V, T, E
22	2b	Elec	C/	Air	Central AHU, DOAS serving corridors, enthalpy recovery	V, T, E
23	2c	Elec	F/F	Air	Floor AHU, DOAS serving suites + corridors, heat recovery	V, T, E
24	2c	Elec	F/F	Air	Floor AHU, DOAS serving suites + corridors, enthalpy recovery	V, T, E
25	2c	Elec	C/	Air	Central AHU, DOAS serving suites + corridors, heat recovery	V, T, E
26	2c	Elec	C/	Air	Central AHU, DOAS serving suites + corridors, enthalpy recovery	V, T, E
27	2c	Elec/Gas	C/	Air	Central MAU, corridor pressurization, natural gas heat	V, T, E
28	3	Elec	S/S	Water	In-suite electric storage tank water heater	V, T, E
29	3	Gas	S/S	Water	In-suite natural gas storage tank water heater	V, T, E
30	3	Elec	S/S	Water	In-suite electric tankless water heater	V, T, E
31	3	Gas	S/S	Water	In-suite natural gas tankless water heater	V, T, E
32	3	Elec	F/F	Water	Floor electric storage tank water heater	V, T, E
33	3	Gas	F/F	Water	Floor natural gas storage tank water heater	V, T, E
34	3	Elec	C/	Water	Central electric boiler with storage tanks	V, T, E
35	3	Gas	C/	Water	Central natural gas boiler with storage tanks	V, T, E

System Number	System Type	Primary Fuel	Layout	Distribution Medium	Description	Locations Modelled
36	3	Elec	C/	Water	Central solar thermal hot water system, electric boiler	V, T, E
37	3	Gas	C/	Water	Central solar thermal hot water system, natural gas boiler	V, T, E
38	1a+2a	Elec	S/S	Air	In-suite AHU w/ OA heat recovery, electric furnace	V, E
39	1a+2a	Gas	S/S	Air	In-suite AHU w/ OA heat recovery, natural gas furnace	V, E
40	1a+2a	Elec	S/S	Air	In-suite AHU w/ OA enthalpy recovery, electric furnace	V, E
41	1a+2a	Gas	S/S	Air	In-suite AHU w/ OA enthalpy recovery, natural gas furnace	V, E
42	1a+2a	Gas	C/	Water	2-pipe FCUs w/ OA intake, centralized natural gas boiler	V, E
43	1c+2a	Elec	S/S	N/A	PTAC, electric heating coil, OA intake, point exhaust	V, T, E
44	1c+2a	Elec	S/S	N/A	PTHP, OA intake, point exhaust	V, T, E
45	1c+2a	Elec	S/S	Air	In-suite AHU w/ OA heat recovery, electric furnace, dx cooling	T
46	1c+2a	Elec/Gas	S/S	Air	In-suite AHU w/ OA heat recovery, natural gas furnace, dx cooling	T
47	1c+2a	Elec	S/S	Air	In-suite AHU w/ OA enthalpy recovery, electric furnace, dx cooling	T
48	1c+2a	Elec/Gas	S/S	Air	In-suite AHU w/ OA enthalpy recovery, natural gas furnace, dx cooling	T
49	1c+2a	Elec/Gas	C/	Water	4-pipe FCUs w/ OA intake, central natural gas boiler, chiller, cooling tower	T
50	1c+2a	Elec/Gas	C/	Air/Water	In-suite WSHP w/OA enthalpy recovery, central natural gas boiler, cooling tower	T

System Number	System Type	Primary Fuel	Layout	Distribution Medium	Description	Locations Modelled
51	1c+2a	Elec/Gas	C/	Air/Water	In-suite WSHP w/ OA heat recovery, central natural gas boiler, cooling tower	T
52	1a+3	Gas	S/S	Water	Radiant floor, in-suite gas tank water heater	V, E
53	1a+3	Gas	S/S	Water	Hydronic convectors, in-suite gas tank water heater	V, E
54	1a+3	Gas	S/S	Air/Water	In-suite AHU w/ HW coil, in-suite gas tank water heater	V, E
55	1a+3	Gas	S/S	Air/Water	In-suite AHU w/ HW coil, in-suite gas tankless water heater	V, E
56	1a+3	Gas	C/	Water	Radiant floor, central gas boiler, providing DHW	V, E
57	1a+3	Gas	C/	Water	2-pipe FCUs, central gas boiler, providing DHW	V, E
58	1a+3	Gas	C/	Air/Water	In-suite AHU w/ HW coil, central gas boiler, providing DHW	V, E
59	1a+3	Gas	C/	Water	Hydronic convectors, central gas boiler, providing DHW	V, E
60	1c+3	Elec/Gas	S/S	Air/Water	In-suite Ducted FCU, dx cooling, in-suite natural gas storage tank water heater	T
61	1c+3	Elec/Gas	S/S	Air/Water	In-suite Ducted FCU, dx cooling, in-suite natural gas tankless water heater	T
62	1c+3	Elec/Gas	C/	Water	4-pipe FCUs, central natural gas boiler with storage tanks, chiller, cooling tower, providing DHW	T
63	1c+3	Elec/Gas	C/	Air/Water	In-suite WSHP, central natural gas boiler with storage tanks, cooling tower, providing DHW	T

Table E-4: Modelling inputs – energy production/rejection components

Equipment	Model Inputs
Condensing Gas Boiler	• 90% full load thermal efficiency (higher values result in part load/ low return temp efficiencies >100%) • DesignBuilder default condensing boiler part load curves • 25 W parasitic exhaust fan load as DesignBuilder default • 25 ft H_2O pump head, 90% full load efficiency with variable flow, intermittent control except for radiant floors • Boiler LWTs depend on system. • Design supply/return delta of 10-15°C
Non-Condensing Gas Boiler	• This only applies to hydronic systems with high water temperatures, such as hydronic convectors • 82% full load thermal efficiency (Charbonneau, 2011) • DesignBuilder default non-condensing boiler part load curves • 25 W parasitic exhaust fan load as DesignBuilder default • 25 ft H_2O pump head, 90% full load efficiency with variable flow, intermittent control except for radiant floors • Boiler LWTs depend on system. • Design supply/return delta of 10°C
Chiller	• Water cooled reciprocating chiller • COP of 5.0, about 0.7 kW/Ton (Natural Resources Canada, 2002) • DOE-2 Reciprocating chiller part load curves • Default DesignBuilder reference temperatures • 25 ft H_2O pump head, 90% full load efficiency with variable flow, intermittent control except for chilled ceilings • Design LWTs depend on system • Design supply/return delta of 4°C
Cooling Tower	• Single speed, fan cycling • Blowdown concentration ratio of 3.0 • Condenser loop temperature set to follow outdoor air dry bulb temperature, min/max of 10°C/50°C
Ground Exchange Loop	• Ground temperature of 13°C (56°F) from DesignBuilder default • Vertical U-tube borehole field, 76m (250 ft) deep, 240 boreholes • Borehole properties left at DesignBuilder defaults: 2.5" borehole radius, 1" pipe outer diameter, 1" U-tube distance • Default G-function data for ground exchange calculations • Supply water temperature set to follow ground temperature

Appendix E: Mechanical System Model Inputs

Equipment	Model Inputs
Central MAU	• Gas heating coil efficiency of 90% • DX cooling SEER of 11 • Supply ductwork only • Supply fan static pressure of 1″ H_2O, fan efficiency of 45%, motor efficiency of 90% • Delivery effectiveness of 1.0
Central AHU	• Gas heating coil efficiency of 95% (if heating included) • DX cooling SEER of 17 (if cooling included) • Supply and return ductwork • Heat recovery/ enthalpy recovery as below • Supply fan static pressure of 1″ H_2O + 0.5″ for heat recovery, 0.5″ if ducted to suites • Fan efficiency of 45%, motor efficiency of 90% • Delivery effectiveness of 1.0 to corridors, 0.8 to suites
In-suite AHU	• 95% gas furnace thermal efficiency, fully modulating, variable capacity (Charbonneau, 2011) • DX cooling SEER of 17 (Natural Resources Canada, 2015) • Fan static pressure of 0.5″ H_2O + 0.5″ for heat recover, 45% fan efficiency, 70% motor efficiency (Canadian Mortgage and Housing Corporation, 2015; Kohta Ueno, 2010b) • Delivery effectiveness of 0.8 if supplying outdoor air
HRV/ ERV	• Sensible effectiveness: 0.8 at 75% heating flow, 0.8 at 75% cooling flow, 0.7 at 100 % heating flow, 0.7 at 100% cooling flow • Delivery effectiveness of 0.5 without ductwork, 0.8 with ductwork delivering hot air at high level • Defrost strategy for floor/central systems involves electric preheat coil with 5°C setpoint, only necessary in Edmonton • HRVs use a plate heat exchanger, ERVs use a rotary wheel
Storage Tank Domestic Hot Water Heaters	• Gas water heater energy factor of 0.7 (Natural Resources Canada, 2012) • 10% improvement on energy factor if providing space heating, resulting in an energy factor of 0.8 (Clinton, 1999) • In-suite pumps with 1/3 hp motor, 5 ft H_2O head, 70% motor efficiency
Instantaneous Domestic Hot Water Heaters	• Gas instantaneous water heater energy factor of 0.98 (Natural Resources Canada, 2012) • Internal storage of 1 US gallon • In-suite pumps with 1/3 hp motor, 70% motor efficiency

Equipment	Model Inputs
Solar Thermal Domestic Hot Water Heater	• Veissman SV1 flat plate collector selected as solar thermal array from 86 pre-loaded templates found in DesignBuilder based on previous experience with this collector • Collector array located on the southern side of the roof, facing south at a 45° angle • Each collector is 27 ft^2 of total area, with a total of 12 collectors (this is the maximum number that can be connected to one loop according to the manufacturer) • Approximately one collector per floor • One solar loop storage tank • Backup heating provided by electric or natural gas boiler connected to storage tanks. See condensing natural gas boiler for assumptions • Solar loop and hot water loop pumps selected as 1/3 hp with 10 ft H_2O head and a motor efficiency of 90%
VRF Outdoor Unit	• VRF outdoor units are defined by 26 part load curves in DesignBuilder • Accurate modelling of a general case system is difficult. • Used LG VRF predefined systems, up to 36 tons' capacity per system depending on building demand • Natural ventilation interior maximum temperature setpoint of 75.5°F • For Edmonton, minimum compressor operation temperature lowered from -25°C to -35°C

Table E-5: Modelling inputs – Terminal Units

Equipment	Model Inputs
Electric Baseboards	• Zone equipment: electric convectors
Hydronic Baseboards	• Zone equipment: water convector • Supply water temperature of 70°C from boiler loop, 10°C loop delta T

Equipment	Model Inputs
Fan Coil Units	• Zone equipment: 4-pipe FCU (no option for 2-pipe, so chilled water loop included but not enabled for heating only systems) • Supply water temperature of 65°C from boiler loop, 15°C loop delta T • Fan static pressure of 0.5″ H_2O, 45% fan efficiency, 70% motor efficiency (Canadian Mortgage and Housing Corporation, 2007; Kohta Ueno, 2010b) • When cooling provided, natural ventilation interior maximum temperature setpoint of 75.5°F
Radiant Floors	• Zone Equipment: heated floor • Internal floor construction consisting of 6″ concrete, 1″ EPS, 1.5″ cement screed, 0.3″ ceramic tile • Internal source (hydronic piping) placed above EPS layer, with 2D option enabled and at a spacing of 8″ • Interior heating setpoint changed to 70.5°F code, 71.5°F low-energy, with operative temperature control instead of air temperature control • Supply water temperature varied from 30 to 50°C based on outdoor air reset between -8 and 22°C
Chilled Ceilings	• Zone Equipment: chilled ceiling • Internal ceiling construction consisting of the reverse of the that used for radiant floors (6″ concrete, 1″ EPS, 1.5″ cement screed, 0.3″ ceramic tile) • Internal source (hydronic piping) placed below EPS layer, with 2D option enabled and at a spacing of 8″ • Operative temperature control instead of air temperature control • Supply water temperature of 13°C
Packaged Terminal Air Conditioner (PTAC)	• Zone equipment: PTAC • Heating provided by electric resistance coil, COP=1 • Target SEER-17 (COP-5.0) (Natural Resources Canada, 2015) • Fan static pressure of 0.5″ H_2O, 45% fan efficiency, 70% motor efficiency (Canadian Mortgage and Housing Corporation, 2007; Kohta Ueno, 2010b) • Natural ventilation interior maximum temperature setpoint of 75.5°F
VRF Indoor Units	• Zone equipment: VRF indoor unit

Equipment	Model Inputs
Vertical Stacked Water Source Heat Pump (WSHP)	• Zone equipment: water-to-air heat pump • Heating COP of 5, cooling COP of 4.4 (Daikin Applied, 2015; Trane, 2015) • Part load performance left at DesignBuilder default based on equation fit method • Fan controlled by cycling, static pressure of 0.5” H_2O, 45% fan efficiency, 70% motor efficiency (Canadian Mortgage and Housing Corporation, 2007; Kohta Ueno, 2010b) • Natural ventilation interior maximum temperature setpoint of 75.5°F
Packaged Terminal Heat Pump (PTHP)	• Zone equipment: PTHP • Backup heating provided by electric resistance coil, COP=1 • Target HSPF-8.6 (COP-2.5), SEER-17 (COP-5.0) (Natural Resources Canada, 2015) • Minimum temperature for compressor = -10°C • Maximum temperature for resistance heating = 21°C • Defrost strategy: reverse cycle, max temperature of 5°C for running defrost cycle • Fan static pressure of 0.5” H_2O, 45% fan efficiency, 70% motor efficiency (Canadian Mortgage and Housing Corporation, 2007; Kohta Ueno, 2010b) • Natural ventilation interior maximum temperature setpoint of 75.5°F

Appendix F: Emission Factors and Utility Prices

In order to convert the energy consumption data generated through building simulation to annual greenhouse gas emissions and operating costs, conversion factors are necessary. Table F-1 displays the conversion factors used to generate the results presented in Chapter 4.

Table F-1: Greenhouse gas emission factors and blended average energy costs for conversion between energy consumption and GHG emissions, operating costs (BC Ministry of Environment, 2014; Canadian Mortgage and Housing Corporation, 2015)

Location	Utility	Emission Factor Kg eCO_2 per kWh (Kg eCO_2 per GJ)	Energy Cost CAD per kWh (CAD per m^3)
Vancouver	Electricity	0.0101 (2.8)	$0.116
	Natural Gas	0.1791 (49.75)	$0.0322 ($0.34)
Toronto	Electricity	0.1044 (29)	$0.12
	Natural Gas	0.1791 (49.75)	$0.0265 ($0.28)
Edmonton	Electricity	0.8100 (225)	$0.11
	Natural Gas	0.1791 (49.75)	$0.0104 ($0.11)