Design Versus Actual Energy Performance **in Social Housing Buildings**

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ABSTRACT

The residential sector accounts for the third-largest share of energy used in Canada. As a result, the government and markets have prioritized the construction of energy-efficient and high-performance residential buildings to conserve energy and minimize carbon emissions. With this increased focus on energy performance, a research study was undertaken to verify how well buildings designed to high performance rating systems performed in practice.

This research initiative investigated ten LEED Gold certified social housing buildings in Victoria and Vancouver, British Columbia. The project aimed to examine the differences between how buildings performed in energy models compared to actual performance. Although some differences are expected due to fluctuations in weather and occupant behaviour, the aim was to analyze any performance gap, investigate its possible causes, seek practical solutions, and summarize recommendations for the building industry. The research involved collecting LEED energy models and over two years of energy utility data for each building. The performance gaps were analyzed by comparing predicted and actual energy consumption, examining the building characteristics, and consulting with their facility managers. Surveys with building operations staff and tenants provided additional information about each building's performance.

Of the 10 buildings, two had better actual performance then modelled (1.5% to 29.3% less energy), whereas the other eight consumed between 22.1% and 281.7% more energy than models predicted. The observed performance discrepancy is attributable to all the phases of the building life cycle, from conceptual design development to construction as well as commissioning to post-occupancy. However, a recurring issue related to lower than expected performance of air source heat pumps and differences between modelled and actual occupant behaviours.

Another potential challenge identified was the lack of awareness of the building operations staff on the buildings' performance goals. Only two buildings' operations staff were aware of their initial high-performance goals. The buildings operated without this knowledge showed higher energy consumption relative to their modelled predictions.

More accurate modelling of heat pumps and occupant behaviour, in addition to better equipment commissioning could help reduce differences between modelled and actual energy consumption.

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1 Introduction

The British Columbia (BC) government introduced the Step Code to help transition the BC Building Code (BCBC) from current energy requirements to near net-zero energy requirements by 2032. This target is in line with the federal government that is developing a "net-zero energy ready" model building code, with the goal that provinces and territories adopt it starting 2030. As shown in Figure 1.1, buildings account for around 17% of energy use in Canada of which space heating accounts for 62%. Improving energy efficiency in buildings is an essential part of governments' climate change mitigation strategies. With this increased focus on performance, a research study was undertaken to verify how well buildings designed to high performance rating systems in the past performed in practice.

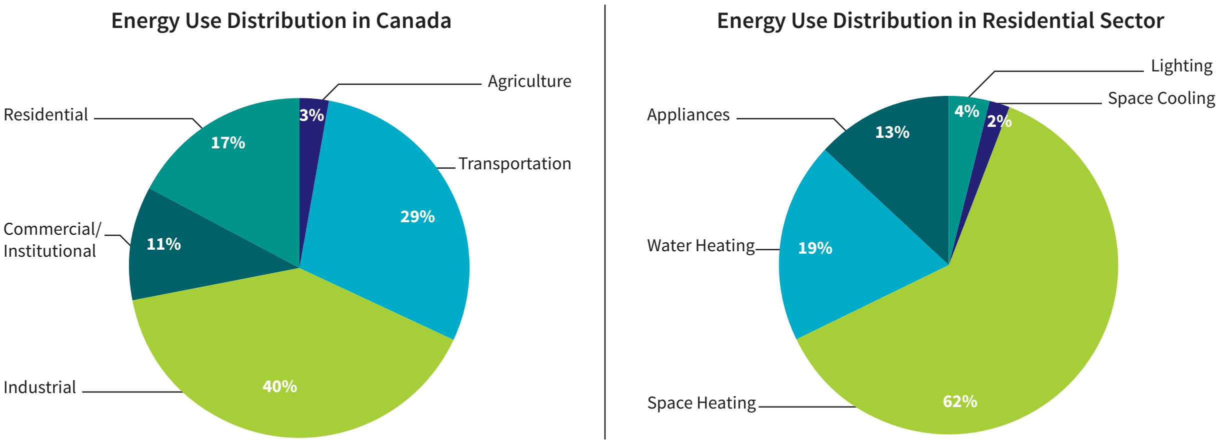


Figure 1.1: Breakdown of Overall Energy Use and Breakdown of Residential Sector Energy Use in Canada [1]

LEED (Leadership in Energy and Environmental Design) has been one of the most widely accepted and used green building rating systems that certify a building under seven main categories: sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation in design and regional priority (for example, local environment, social equity, public health priorities, etc.). Each category gives one or more prerequisites for designers to satisfy and receive the initial assessment qualification of LEED-certified buildings. Designers then have the right to select the most applicable and preferred points to earn for their projects under various credits. With total points adding up to 100, LEED v4 buildings can qualify for four levels of efficiency certification [3]:

- LEED Certified (40-49 points)
- LEED Silver (50-59 points)
- LEED Gold (60-79 points)
- LEED Platinum (80 or more points)

Passive House is another internationally recognized certification system for energy-efficient buildings that was initially developed in Germany. The modelled energy use intensity of Passive House certified buildings are often 60% lower than conventionally matched buildings, which is mostly attributable to the strict building envelope performance standards. The Passive House assessment requires a maximum 15kWh/m^2 heating energy consumption per year or 10 W/m^2 maximum heating load, a maximum of 120 kWh/m^2 total primary energy usage each year, and a maximum of 0.6 air changes per hour at 50 Pascals pressure (ACH50) [4].

The Living Building Challenge (LBC) is another very stringent rating system. Similar to the LEED rating system, LBC buildings are evaluated based on specific categories, including location, water, energy, health and happiness, materials, equity and aesthetics. LBC encourages three different certifications – Living Building Certification, Petal Certification and Net Zero Energy Building Certification. A score is given based on a combination of achievements in seven different categories. Unlike other systems that rely on modelled energy performance, the LBC relies on actual energy consumption data from the first year of occupancy to demonstrate compliance to the net-zero energy performance criteria.

An analysis conducted by the National Research Council of Canada (NRC) [6] in 2009 concluded that LEED buildings, in general, saved 18-39% more energy compared with their typically matched buildings. The condition of an archetype is defined by this paper comparing buildings of similar age, activity type or usage, floor area, and climate zone. A study conducted by New Buildings Institute (NBI) [7] compared the median energy use intensity (EUI) of 100 LEED buildings to the mean EUI from the Commercial Buildings Energy Consumption Survey (CBECS) database. For these LEED buildings, the total EUI was obtained by adding up a year's worth of billing data. The results showed that the median EUI of LEED buildings was 33% lower than the mean EUI in the CBECS database.

There can be large discrepancies between the energy performance of green buildings because different standards target different energy performance levels. A presentation at the 20th International Passive House Conference in 2016 reported that an average of 85% reduction in energy use for heating and cooling per square meter can be expected for buildings certified by the Passive House standard, which is mostly attributable to the strict certification criteria of the Passive House benchmark [8]. Also, buildings designated by the Living Building Challenge (LBC) present satisfactory results due to the LBC's reliance on actual performance data for certification.

This study was inspired by a series of research projects that reported the performance gaps between designed versus actual energy consumption in green buildings that used different rating systems. The differences in the rating systems, evaluation of building performance, investigation of possible causes, and hidden issues related to green buildings were used as the foundation of this thesis.

Ten LEED Gold buildings constructed for BC Housing during a span of the past five to ten years are the subjects for analysis in this study. Performance assessment for these buildings was conducted post-occupation to verify if the primary design goals were realized. The examination of each building was conducted to explore reasons for the performance discrepancy and to summarize solutions for overcoming some of the observed obstacles. Surveys with tenants and building operations staff were conducted to identify issues unique to each building and to provide guidance for future building development.

2 Literature Review

2.1 2.1 Comparison of Different Green Rating Systems

2.1.1 LEED 2009 vs LEED v4

LEED v4 is the successor to the LEED 2009 version of the LEED building rating system and took almost four years to develop. LEED v4 combines the ten different rating systems of LEED 2009 into five ratings, namely:

- LEED for Building Design and Construction (BD+C)
- LEED for Interior Design and Construction (ID+C)
- LEED for Building Operations and Maintenance (O+M)
- LEED for Neighborhood Development (ND)
- LEED for Homes Design and Construction

Multi-family buildings with four or more stories can use LEED BD+C for certification. However, in the next version, LEED v4.1, multi-family homes of any number of stories need to use LEED v4.1 Residential.

One of the main objectives of LEED v4 is to improve the use-transparency in material and resources such as material sourcing, impacts on environment and health among other metrics. Although some LEED-certified buildings meet the energy-saving criteria, material selection was not always "green." Three new credits have been added to the Building Product Disclosure and Optimization certification to track sources of raw materials, material ingredients and product life-cycle impacts. Additionally, a new prerequisite for LEED v4 is the specification of waste treatment and recycling rates.

Another valuable development of LEED v4 involves the importance of water and energy metering. In some past LEED projects, the lack of post-occupancy metering impacted performance. The new strict prerequisites ensure better building performance in energy and water efficiency. The commissioning process has been given a higher significance in LEED v4 with comprehensive prerequisites and credit specifications as well as the need for a mandatory review of the building envelope design [9].

2.1.2 Passive House vs. LEED vs. Living Building Challenge

Both LEED and the Living Building Challenge standards are based on assessments for different categories. In addition to energy performance ratings, items that can have a significant impact on the certification authorization such as site and material selection, need to be evaluated and ranked. In contrast, the Passive House standard primarily focuses on the total energy consumption, heating load and airtightness level. Table 2.1 shows the comparison between the three standards.

Table 2.1: General Comparison between LEED, Passive House and Living Building Challenge

Categories	LEED	Passive House	Living Building Challenge
Average Energy Saving vs Baseline Models	25-30%	60-70%	100% (net-zero energy use requirement)
Energy Assessment	% reduction in energy use compared modelled reference building (35/100 points)	Predicted energy consumption meets the certification criteria	Twelve-month post-occupancy metered data to prove net-zero energy use
Water Assessment	% reduction in water use compared modelled reference (10/100 points)	Boundary conditions or calculation rules applied at the design stage	Net-zero water use
Site	Pollution control and public transit service (26/100 points)	N/A	Construction, protection and storability
Material	Materials reuse and recycle (14/100 points)	High-performance air barrier materials required	Red list materials free, net positive waste
Indoor Environment	Indoor Air Quality Performance test at the design stage (15/100 points)	Boundary conditions or calculation rules applied at the design stage	A nine-month post-occupancy Indoor Air Quality test

2.2 Comparison of Modelled versus Actual Energy Consumption

This section summarises several past studies that examined differences between modelled and actual energy performance.

Canada Mortgage and Housing Corporation (CMHC) performed a study to review the performance of a six-storey, multi-unit residential building [10]. They examined the energy consumption, indoor environmental quality and environmental impacts. The design objective was to reduce energy use by 35% based on the Canadian Model National Energy Code for Buildings and simultaneously demonstrate a higher level of occupant satisfaction. A refined heat recovery HVAC system and building insulation strategy was used with a separate subsystem metering to capture the secondary end-use and natural gas data.

According to the collected data, the building saved around 29.7% of the energy compared to the Model National Energy Code value and 54.3% energy savings compared to a functionally equivalent reference buildings. Additionally, the apartment performed much better than conventional buildings in terms of water saving, HVAC system efficiency and saw an overall reduction in thermal bridging.

International Initiative for a Sustainable Built Environment (iiSBE) investigated the differences between the modelled and actual performance of key performance indicators (KPI) of nine green buildings in Canada [11]. The assessment of energy consumption in this research examined a minimum of two years of energy billing data. Along with interviews with building stakeholders such as designers and managers, the occupants were also provided with an overall understanding of building performance targets. The number of occupants assumed in the energy model at the design phase did not always represent reality, which can be one of the key elements that influenced the results.

In the iiSBE study, the energy use intensity for five of the green buildings exceeded the modelled value and one of them used approximately 2.3% more energy than the conventionally matched buildings. This report pointed out that buildings with poor performance records were more likely to receive lower resident satisfaction ratings in areas such as acoustic, lighting and thermal comfort.

K. Mahapatra and S. Olsson [12] investigated two Passive House certified residential apartment buildings in Sweden. The research suggested a concept of "specific energy use" that was used in the Building Code of Sweden to describe the actual energy consumption for building operations without household end uses. About 90% of the building owners or tenants were satisfied with the building's performance that included good indoor environmental quality and low energy costs. Compared to the modelled energy, the actual specific energy use was 10.4% higher due to increased energy consumption for space heating. Nonetheless, the two green apartments saved around 3.7 kWh/m^2 of energy (total energy use including household end-uses) and performed better than the Passive House benchmark as well as the typical reference buildings.

A survey was conducted by C. Turner [13] to study LEED building performance for the Cascadia Region Green Building Council. Eleven buildings that were in operation for more than a year were included in this study. Seven of them were non-residential buildings and four were multi-family residential buildings. Most of the occupants reported a high level of satisfaction related to the overall quality of the indoor environment despite some noise issues. Six of the buildings had lower actual EUI (Energy Use Intensity) than modelled out of which three buildings were residential. On average, residential buildings in this study used 86% more energy compared to their modelled values. The study also compared these LEED buildings through EUI and Energy Star standard benchmarks. All but two buildings were below or within the range of the Energy Star benchmark. Additionally, six out of seven building's actual water consumption exceeded their modelled value by an average of 133%.

Research organized by the U.S. Green Building Council (USGBC) and related institutions in 2006 explored the energy performance of 21 buildings certified by LEED between 2001 to 2005 [14]. Although these 21 samples only accounted for 7% of 300 LEED buildings certified since 2006, they were representative of the major buildings types. Most buildings reported three years of utility billing data. The performance of these buildings varied, eleven out of eighteen demonstrated an average of 27.4% energy saving compared to their modelled values. Four of these eleven buildings were eligible for Energy Star certification. In this study, the federal buildings in operation performed better than non-federal buildings. The federal buildings saved 22% of their energy consumption compared to modelled values, in contrast, the non-federal (excluding four laboratory buildings) exceeded 2% EUI.

In 2013, a study [15] featured eQuest simulation software and real weather data to investigate the discrepancy between the actual and modelled performance of a five-storey university building. The weather file and metering data included electricity and gas use from 2011 to 2013. The simulation was run on both an annual and monthly basis to ensure an accurate comparison. The actual electricity use illustrated savings of 6.4%, 0.7%, and 19.5% respectively each year (the assessment for 2013 was conducted from January to April). In contrast, the actual gas consumption showed an increase in energy use of 33%, 4.5% and 21.7%, respectively. On this basis, the overall actual energy consumption was 3.9% lower compared to eQuest modelled values. Concerning monthly data, most of the predictions were highly accurate except for a noticeable performance gap of 51.6% in May 2011 reporting less energy use. One of the reasons for the difference between electricity and gas consumption was the occupancy load (number of people living in the building). Observations from 2012 data suggested that the occupancy load was only 55% of the load specified in the simulation. Twenty-one out of 38 buildings achieved their modelled results with an overall range in differences of 200% to +80%.

The improvement of occupant satisfaction with IEQ (Indoor Environmental Quality) is another crucial factor in the success of green buildings. In a questionnaire survey [16] conducted by the University of California, 15 LEED buildings, along with 200 conventional buildings, had their IEQ assessed with four categories: thermal comfort, indoor air quality, lighting and acoustics. Answers were classified into seven levels of satisfaction with 3 points for very satisfied and -3 for very dissatisfied.

The results of the survey suggested that in terms of overall building comfort, satisfaction and indoor air quality, LEED buildings performed better in comparison to conventional buildings under 15 years old and received higher satisfaction ratings. However, the performance of lighting and acoustics in LEED buildings was not superior to conventional buildings. The same results were found in another study consisting of 12 green buildings and 12 conventional [17] where the buildings were paired according to similar properties such as use, size, age and climate zone. The study was based on online surveys, interviews with operators, and measurements of a few physical elements, such as airspeed, temperature and small particles using the NICE Cart.

Results similar to [16] and [17] were demonstrated in other studies. The green residential high-rise building analyzed in a study by Xiong et. al. [18] received positive feedback in terms of thermal comfort and indoor air quality. Moreover, the review study by Birt and Newsham [19] concluded that positive feedback was mostly given for thermal comfort and indoor air quality in green buildings, but not to lighting and acoustics.

2.3 General Reasons for Performance Differences

Narrowing the gaps between field performance and modelling outputs is a fundamental long-term goal of the construction industry. Addressing the gaps can reduce cost, maintenance, and improve the long-term durability of each facility. The differences pertain to various issues and they can be classified into four main phases: design, construction, commissioning, and operation.

2.3.1 Design

The first challenge with the design phase can be the diverse number of ideas from designers, consultants and owners of the building, as they pertain to the construction and operation of the facility [20]. W. Shen [21] introduced a user simulation activity and evaluation method (UASEM), that offered a more effective way for engineers and occupants to communicate. This pre-occupancy evaluation tool can optimize the performance of green buildings to some extent. However, other issues exist in the design process including an insufficient estimate of the number of occupants, plug-loads, and passive heating and cooling [22].

The design itself can frequently result in the under-performance of buildings. The green building industry tends to use sophisticated control systems to achieve higher energy efficiency, which are not always well understood and operated once the building is occupied [22].

The Zero Carbon Hub study [23] demonstrated a holistic process that assigns separate parts of the design process to different directors. For example, the initial exterior enclosure design that meets both artistic and construction requirements may lead to trouble during subsequent detailed design stages, such as thermal bridge minimization and airtightness optimization. Thus, an iterative communication process between members of the team at different design stages is recommended to ensure an effective performance model.

Another point that must be kept in mind is the limitation of the energy simulation software. The accurate modelling of certain items like weather data [25] and airflow [26] is hard to realize with today's technology. Moreover, a typical simulation is performed with very detailed boundary conditions, which might not be consistent with the actual data [27]. The discrepancy between theoretical and simulated values may lead both designers and owners to have higher expectations at the design stage.

Without the post-occupancy building operation data, the input parameters that were applied in the original energy model at the design stage are more likely to deliver an inaccurate energy performance prediction. For instance, the research conducted by iiSBE [11] pointed out that the miscalculation of occupancy numbers, occupancy behaviour, and operation practices contributed significantly to the identified performance gaps. Uncertainties related to lighting control, plug loads, HVAC system operation, temperature setpoints and operable window control, were all contributing factors to the increased actual energy use of the building [28].

Underestimating the amount of structural timber, inadequate accounting of thermal bridges/bypasses and poor quality control issues can also lead to significant (≈70%) underestimation of energy use [29]. The unexpected occupancy densities and behaviours are very likely to cause the inaccurate modelling of heating systems and ultimately create performance gaps [30]. It is recommended that more effort be taken to calibrate the initial models using actual performance data, and thus provide a way to establish better models for future designs [27], [28].

2.3.2 Construction

A common challenge at the construction phase is determining whether a building can be constructed as originally designed. Significant performance discrepancies may result from small changes from the original design [20]. An unplanned cost-cutting decision at the construction phase may lead to a decrease in construction quality, such as less effective insulation or airtightness system [22]; issues that affect the energy performance of a building.

The Zero Carbon Hub report [23] emphasizes the importance of maintaining control of the resources used in actual construction, and transparency related to potential changes to the performance that may occur as a result of replacing products and materials specified in the original design.

An example of this is shown in the Elm Tree Mews research [29], where switching to a different window supplier increased heat losses by 21% as compared to the original modelled values. Also, with more and more complicated control systems being used, there are more challenges with how things are installed. In the Elm Tree Mews research, difficulties installing the passive solar systems commonly resulted in leaks and positioning errors.

Performance gaps may also be related to a common defect in the construction process. The Zero Carbon Hub report [23] summarized a series of issues that required careful inspection during a typical construction process. These included understanding the fundamental principles of sustainable buildings and effective as-built performance assessments. A flexible production control during construction can be advantageous for resource management but is not conducive to robust and repeatable performance. It can negatively impact energy performance and sustainability. Accordingly, the development of more detailed construction sequencing is recommended to ensure the construction process leads to high performance and is cost-effective. The inspection process can also be simplified and made more efficient with advanced standardization.

Finally, as a critical part of a construction process, the as-constructed performance evaluation needs to be more accountable. For instance, if the relatively simple and clear process of testing airtightness is implemented superficially, it will create barriers for operators to properly evaluate the installation work. If appropriate support is available to help with the measurement process, the quality of construction and improvement of the design can be assured.

2.3.3 Commissioning

There may be opportunities to narrow the performance gap at the building commissioning phase. Building commissioning is defined as a process whereby a professional conducts a review of the building systems such as the mechanical, electrical and renewable energy systems, along with their sub-systems. The professional confirms the completion and effectiveness of these systems in comparison to the initial design targets [31].

From an analysis [32] of 643 buildings, commissioning was proven to be a cost-effective method to achieve better energy performance. However, this paper notes that most of the improvements through commissioning were not noticeable immediately, and as a result, owners were not willing to pay for the process.

A typical challenge in building commissioning is to ensure adequate verification of building systems and their associated sub-systems. However, as Bordass [33] mentioned, many energy-saving devices do not perform as they were originally designed due to incomplete commissioning applications.

A similar situation was also revealed in ARUP's study [22]. It showed that not testing sub-metering systems adequately during commissioning likely results in worthless operation data. Retro-commissioning is introduced as a solution for this. One example showed that after a retro-commissioning of the cooling system, a 25% reduction in cooling loads were achieved [34].

A large number of inadequate commissionings may be a result of insufficient time to complete the process. According to a study [32], only about 25% of buildings started commissioning at the design phase, and approximately 30% started during construction.

Natural Resources Canada recommends lifecycle commissioning rather than one-time commissioning [35]. They suggest that even if commissioning is completed to meet the Owner's Project Requirements, performance gaps may still exist during continued operation.

The IFMA Foundation demonstrated that even buildings that had commissioned, well-maintained systems usually had a 10-15% performance reduction after several years of operation [36]. Seasonal commissioning was suggested by Arup [22] and Carbon Trust [37] to mitigate the impact of weather changes on a building's performance. For instance, to verify the operation of the heating system at its peak season, Bideford College re-commissioned the systems in winter to ensure the optimal performance of the building.

Re-commissioning was also suggested by Lewis et. al. [38] whenever there are ageing equipment, drifting sensors and other factors that might change the building's function. In this case, continuous commissioning is essential to keep the building operating at high efficiency [39]. A framework of continuous commissioning or 'Soft Landings' mandates a graduated handover of a building, and designer and contractor involvement beyond the handover period to ensure desired performance and better sustainability [37], [40].

2.3.4 Operation

One of the most significant factors that can lead to problems in building performance is the imprecise control of building systems. The lack of appropriate metering limits the accuracy of performance data for building operators or managers. For them, understanding the operation of the building appears to be more important, making it almost impossible to adjust the control systems for higher efficiency. It has been shown [41] that buildings with energy consumption metering systems installed have an average performance improvement of 10% as compared to the 4% improvement shown for those without metering.

In Arup's case study [22], with the adjusted operation of control systems according to sufficient metering data, the building showed significant savings within two years, in both electrical and gas use; a 13% and 48% reduction respectively. However, they suggest that once the monitoring system is installed, it should be checked for possible metering errors to ensure the data can be used effectively [40]. A study [42] introduced an approach that combined smart meters with disaggregation algorithms to ensure accurate access to performance data.

The effective operation of green buildings usually requires professional knowledge of technical controls due to the complexity of the systems. As mentioned in the study [41], experienced operators, as opposed to new green building operators, are capable of finding optimal control strategies related to the monitoring data, and to improve the building performance to the maximum extent. An insufficient understanding of the building system from both managers and inhabitants' point of view, may give rise to the underperformance of the building [20], [22], [29], [33]. For example, the inappropriate control of HVAC and lighting systems brought about a 200% increase in energy use over what was modelled in one study [13]. Consequently, developing the professional skills of operators has great potential to save the actual energy expenditure of buildings.

There is increasing evidence to show that occupant behaviour has an enormous impact on the deviations seen in building performance. Occupant preference for building system controls such as temperature set points and operable windows are one of the most significant operational factors that affect heating and cooling energy consumption of a residential building [30], [43]. A study [44] pointed out that voluntarily controlled operational hours of heating systems have a higher contribution to energy usage than automated temperature set points. For non-domestic buildings, where occupants cannot control heating and cooling systems directly, the opening and closing of windows is the likely cause of wasted energy [45] - [47]. Furthermore, the uncertainty of how many people occupy a building can influence the energy expenditure significantly [22], [33].

2.4 Other Potential Performance Challenges

2.4.1 Green Roofs

Green roofs are used to reduce rain runoff, mitigate the urban heat island effect, and save energy by keeping the buildings cool in the summer [48]. They can be categorized into two types based on different soil media depth, and plant species – extensive and intensive roofs [49]. Issues related to these categories have been questioned and studied in an attempt to optimize the performance of green roofs.

One of the most significant challenges is selecting a proper weight for the growing medium. Intensive green roofs are usually very heavy and may place a burden on a building's structure and thus are rarely used [50]. A CMHC research study [51], found that a 75mm depth of growing medium performed as well as a 150mm, for both rainwater management and thermal effectiveness.

Using a heavier weight green roofing system may cause structural problems, and lead to higher maintenance costs [52].

There are also some questions whether green roofs may lead to more space heating consumption in winter [53]. When covered with vegetation and growing medium, it can be more challenging to detect leaks in drainage, insulation and membrane layers [54]. Also, the materials used for drainage, filtration, protection and membrane layers are typically polymers that can result in extra energy consumption and pollution as a result of the fabrication process [53], [55]. While this is a concern, some pollution can be offset by the long-term use of green roofs. Greener construction materials are recommended to achieve real sustainability [56].

2.4.2 Materials

The ultimate purpose of green buildings is to construct in an environmentally conscious way, to operate sustainably, and to function at maximum efficiency. To mitigate pollution generated by conventional materials, the use of renewable materials has become a trend and an obligation according to suggestions made by green building rating systems [9]. However, the lack of awareness about newly available materials can lead to the inappropriate selection of materials. This also introduces potential risks to building durability and performance [57]. As an example, the new OSB-core resin door is formaldehyde-free but can be easily damaged by compression which makes it a short-lived and a potentially non-green product [58]. Also, some of these doors were only partially tested in the laboratory to ensure the basic properties of compliance, such as thermal and acoustics qualities and as a result, they may be defective in other areas of performance [59].

A review of renewable insulation materials identified that the study of unconventional materials is often limited [60]. Materials may perform well when tested for thermal performance or off-gassing but may not be adequately tested for durability, mould growth and other variables. It has been shown [61] that microbial growth can be found in various building materials and some are even generated during the production process [62]. Very little research data is available on the relationship between green materials and fungal growth [63]. Testing of these materials over the long term is essential but is yet to be conducted [64].

Although green building rating systems suggest using low emitting Volatile Organic Compounds (VOCs) materials, some of the recycled materials present in furniture show high levels of VOCs that are detrimental to human health [65].

2.4.3 Water

The design of water systems in green buildings are generally targeted to have a minimum of 20% less usage than conventional designs [66]. However, this specification indirectly leads to a longer period of water storage which may impact water quality and ultimately an occupant's health [67].

According to a fact sheet [68], the longer the time water is stored, the more likely it is to damage plumbing. A resulting increase in corrosion can promote the growth of microorganisms that may impact human health. This was confirmed in a study [66], where three green water systems were compared to a conventional system. The results demonstrated that water in green plumbing systems can be preserved for 2.7 days to 6.7 months, whereas water a conventional system is stored for only one day. Consequently, the level of pathogenic microorganism was found to be much higher in green building systems than conventional systems.

2.5 EnergyPlus as the LEED Building Modelling Software

CaGBC (Canadian Green Building Council) has approved several energy-modelling software to predict the performance of buildings pursuing LEED certification. EnergyPlus is a widely used and accepted simulation tool for this purpose. It was developed based on BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 programs. Each version of EnergyPlus is tested both analytically (HVAC and building fabric tests based on ASHRAE Research Project) and comparatively (such as ANSI/ASHRAE Standard and IEA-SHC BESTest) [69].

A benchmark of 400 residential buildings in Brunei, Darussalam was set up using EnergyPlus [70]. Information about the building geometry, such as the building envelope and materials were collected using surveys and interviews with individuals involved with the project. Also, the climate data provided by the local Meteorological Department was used in the energy modelling process. Detailed schedules of operation were also identified. The predicted energy consumption stayed approximately the same as the actual utility bills, despite some small fluctuations related to occupant behaviour. The energy models were successfully calibrated to benchmark the residential buildings in this area.

Boyano et al. [71] used EnergyPlus to build energy models for assessing itemized energy consumption and recognizing possible energy saving methods in European office buildings. All relevant parameters of both the building operation (plug-loads, scheduling, HVAC systems and water systems) and the building itself (orientation, envelope, surrounding and geometry) were provided by EnergyPlus. Three different locations representing different climate zones (cold, medium, warm) were selected and 42 simulations were applied to each location. The simulated results were approved by comparing them with actual measurements. In this study, lighting was identified as an area of potential saving. It is stipulated that the building orientation and insulation factors may have contributed to reducing energy use in relatively cold areas.

Fumo et al. [72] proposed a simplified method to analyze how and where the energy of a building is used by creating hourly energy consumption profiles using EnergyPlus Benchmark Models. The simulation process used predetermined coefficients that were derived from running various EnergyPlus Benchmark Models with detailed weather data. The results were validated through a comparison with several hypothetical buildings and errors were within a 10% margin. The method was further improved by introducing modified EnergyPlus benchmark building energy consumption profiles. These used monthly electrical and fuel bills to scale a given benchmark building energy profile to approximate the real building energy profile [73].

Another research project used EnergyPlus to study the primary energy consumption of an office building's cooling, heating, and power (CHP) systems on an hourly basis [74]. The baseline model simulated in EnergyPlus was modified by applying appropriate CHP systems with a variety of related parameters such as a power generation unit (PGU) and a heat exchanger. The results indicated a significant reduction in primary energy use when adjusting CHP elements. They demonstrated that EnergyPlus is an effective energy modelling system for buildings.

EnergyPlus is a highly useful tool to examine numerous specific components of buildings, from envelopes to complex operation systems, thanks to its open-source hallmark. For example, Hong et al. [75] started an analysis of new variable refrigerant flow (VRF) systems with more editable elements in EnergyPlus. The new system was assumed to have advanced controls and more accurate simulation results compared to conventional VRF models. These expectations were strongly validated once the building was operational. Another example by Zhao et al. [76] used three EnergyPlus models (baseline, typical and mixed-mode active HVAC predictive control systems) to investigate the energy consumption and thermal comfort based on occupant preferences. The thermal and energy study of buildings with double skin facades were also simulated using EnergyPlus in [77] [78] [79] [80] [81].

2.6 Research Objectives

Through a review of research papers on green building performance and an examination of the causes of performance differences, several findings can be concluded:

- Most energy-efficient buildings, except those with serious operational or design issues, performed better than their conventional peer buildings. However, around half of the green buildings did not achieve their energy performance targets.
- In general, occupants of green buildings felt satisfied with their Indoor Environment Quality (IEQ), yet acoustics performance was similar to those of conventional buildings.
- The performance gaps may be narrowed if tenant and operator feedback is used to calibrate design models.
- Precise control of the construction and commissioning processes are necessary to reach high-performance targets. The advanced commissioning process – continuous commissioning – is an effective approach to optimizing building operating systems year-round.
- Proper energy metering contributes significantly to energy efficiency improvements.
- An effective way to actualize energy savings is to invest in professional operating system training for building operators.

The fact that some green buildings don't perform as designed, led BC Housing to explore performance gaps between the modelled and actual performance of ten BC Housing, multi-unit, green residential buildings. Based on lessons learned from the literature review, the objectives for this study are outlined as follows:

- Examine if the buildings included in this study perform as modelled,
- Investigate the cause for gaps in their performance, and summarize the factors that contribute to this variation,
- Explore the cost-effectiveness of various methods to achieve better performance, and
- Explore general parameters that can be modified according to the actual building performance to help better predict energy use in social housing buildings.

3 Methodology

Ten LEED-Gold certified social housing buildings constructed within the past eight years were selected for the evaluation and analysis of their energy performance. A comparative analysis between their actual and modelled performance objectives was performed. Furthermore, the buildings were compared to their baseline models and conventional benchmarks to examine their energy efficiency. By studying individual buildings, issues in each building were documented to identify any commonalities. Recommendations to improve energy efficiency in social housing are suggested.

3.1 Data Collection

A comparison between actual and predicted energy performance of the buildings was accomplished by collecting monthly utility bills over two years and energy modelling information of baseline and proposed models. Monthly bills of electricity and natural gas for 2016 and 2017 for each building, were collected from either building management organizations or utility providers, including BC Hydro, Fortis BC and/or the City of New Westminster. While it is typical to have gaps in data and estimates in these types of studies, in the case of these buildings, there were no gaps or estimates over the 24 months. LEED Canada NC v1.1 compliance energy model information for the proposed cases was gathered.

Building locations, envelopes, service features, materials, mechanical systems and occupants demographics were gathered from building management societies and energy modellers. Both baseline and proposed energy models for all buildings were established based on the MNECB standards and compiled as per the MNECB Code Supplement except in one case, for Building H. Building H used ASHRAE 90.1-1999 for the primary building code requirements. All buildings were modelled using EE4 software version 1.7 except for Building H that used eQuest V3.64. The table below summarizes the level of detail that was available for the energy modelling data.

Table 3.1: Energy Modelling Data-Monthly/Annually

Building	Energy Modelling Results	Building	Energy Modelling Results
A	Monthly	F	Annually
B	Monthly	G	Annually
C	Monthly	H	Monthly
D	Annually	I	Monthly
E	Monthly	J	Annually

The annual electricity and natural gas energy consumption of the buildings was first compared in terms of eMWh/yr. Building performance in terms of EUI in eKWh/m^2/yr was then compared with buildings from the Building Energy Performance Index (BEPI). The data source for benchmarking originated from NRCan's Comprehensive Energy Use Database, which was last updated in 2015.

The social housing buildings in this research operate similarly to hotels and care homes and yet have a residential component. Taking this into consideration, they cannot be directly compared with residential apartments. NRCan compiles a database of average performance for different building uses that are available for such comparisons. A total of three types of benchmark buildings – Multi-unit Residential Buildings (MURBs), Health Care and Social Assistance (HCSA), Accommodation and Food Service (AFS) – were selected from NRCan's database to encapsulate the characteristics of each building examined in this report.

Table 3.2: Benchmark Buildings Data Extracted from NRCan's Database [1]

Building Type	Electricity *(eKWh/m²/yr)*	Natural Gas *(eKWh/m²/yr)*
MURB	52.8	66.7
HCSA	172.2	183.8
AFS	175	177.8

3.2 Simulation Process

Building A was selected to perform a simulation using OpenStudio and EnergyPlus. All the required information was gathered from shop drawings and LEED energy models that had been previously submitted. The building geometry, including roofs, doors and windows were modelled in SketchUp. The neighbouring properties and trees were simplified to show only surfaces that might cause shading. The OpenStudio plug-in available in SketchUp made it possible to save the model in OpenStudio at the same time. Thermal zones were identified and included at the geometry generation stage as well. The specification of the building envelope was entered using the "material" and "construction" function in OpenStudio.

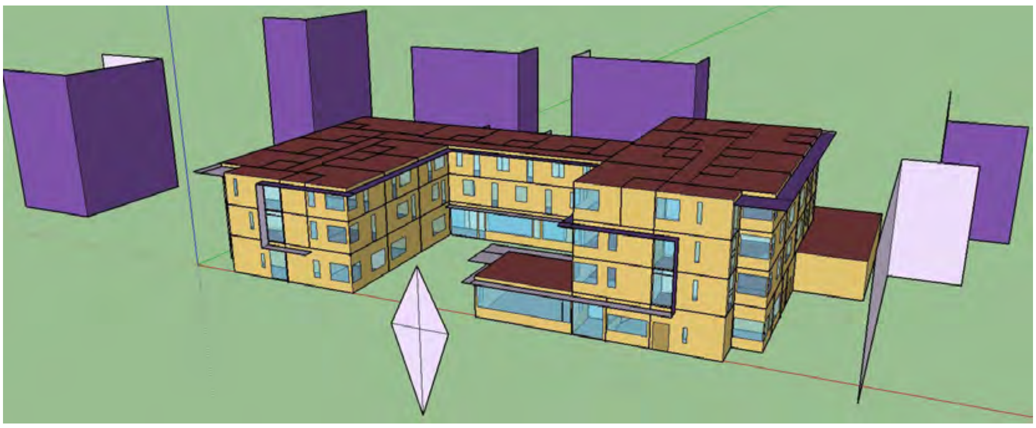


Figure 3.1: Geometry and Shading of Building A

After creating the geometry model, detailed information on internal gains (interior lighting, electrical equipment and the number of people) for each zone was specified using the LEED energy model. The end-use loads were calculated according to the scheduling of internal load items. The total load for each category in each zone was user-defined. “Fraction” was used as the schedule type of lighting, equipment and occupancy to describe the percentage use or vacancy rate for each item during a specific time of the day.

The heating and cooling schedules and setpoints for each zone were set up according to the LEED energy model except for the heating thermostat set-point for residential suites. Based on the occupancy survey, interviews and DDC system records, heating set-points for units were adjusted to 23°C instead of 21.1°C.

The modelling of the mechanical system was based on the proposed LEED energy model and parameters were obtained from shop drawings. The only difference from the drawings was that the air source heat pump was removed and only a boiler was kept in the heating loop. This change was made to determine if the performance gap was related to the inefficiency of the air source heat pump at low outdoor temperatures. Detailed information and modelling parameters of the mechanical system for Building A can be seen in Section 4.1.

3.3 Exploration of Possible Causes

3.3.1 Effect of Weather

The weather file used for the energy model had 30-year average weather data based on the Canadian Weather for Energy Calculations (CWEC) weather file. The actual weather conditions for the year 2016 and 2017 may be different from the weather data applied during the simulation process. The Measurement and Verification process of LEED buildings usually considers the influence of heating degree days (HDD) and calibrates the energy model according to the comparison results. Accordingly, the effect of weather on performance gaps needs to be reviewed to verify if it has the potential to cause discrepancies.

Heating degree days (HDD) and cooling degree days (CDD) are assessment tools to estimate the amount of energy required for heating or cooling a building to achieve thermal comfort [2]. The value of HDD and CDD specifies the number of degrees required to heat or cool a building to the temperature boundary point over a particular period using a balance point temperature of 18°C for heating and cooling.

If the HDD is equal to or less than zero, then the average temperature for this particular day is at or higher than 18°C and the HDD value for this day would be zero. If the HDD result is greater than zero, taking 18 as an example, then the average outdoor air dry bulb temperature for this day would be 0°C. The HDD for the whole month is calculated by adding up all the HDD values. The result is the total degrees required for heating for a particular month.

Figure 3.2 and Figure 3.3 show the HDD comparison between the monitored year and 30-year average weather data used in the energy model [3]. The monitored year’s weather file and the LEED energy model use the same geographical location of Vancouver International Airport. Space cooling only accounted for around 1.5% of the total energy consumption on average of the modelled energy breakdown included in this study. Since the building site is at a heating-dominated location and the impact of the performance gap in cooling degree days is much less than heating degree days, the effects of cooling degree days are negligible.

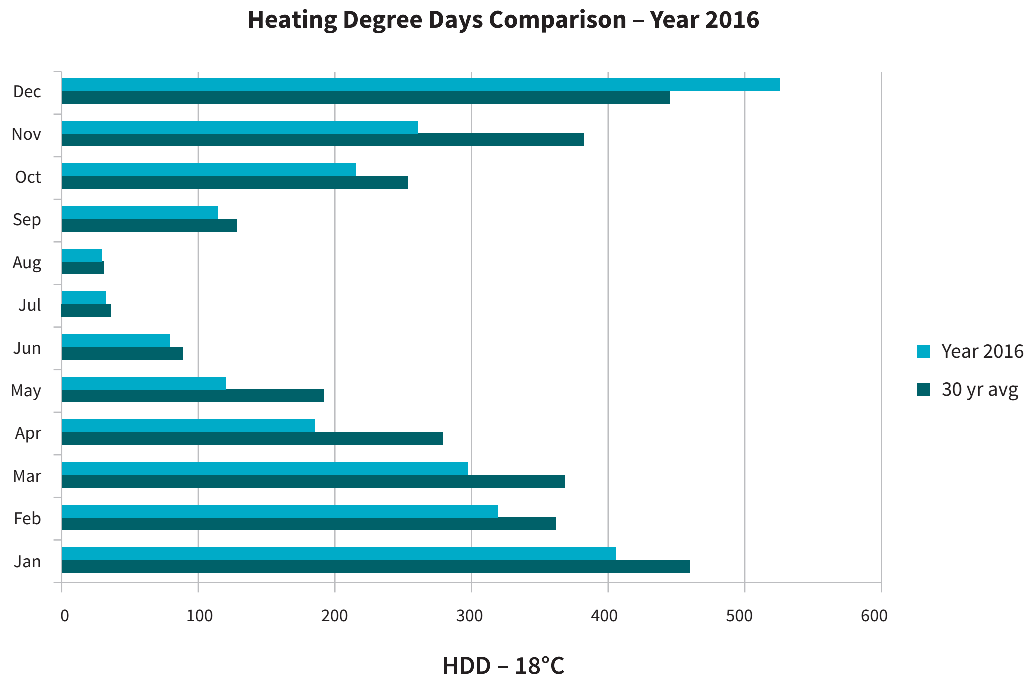


Figure 3.2: 30-year Average HDD vs 2016 HDD

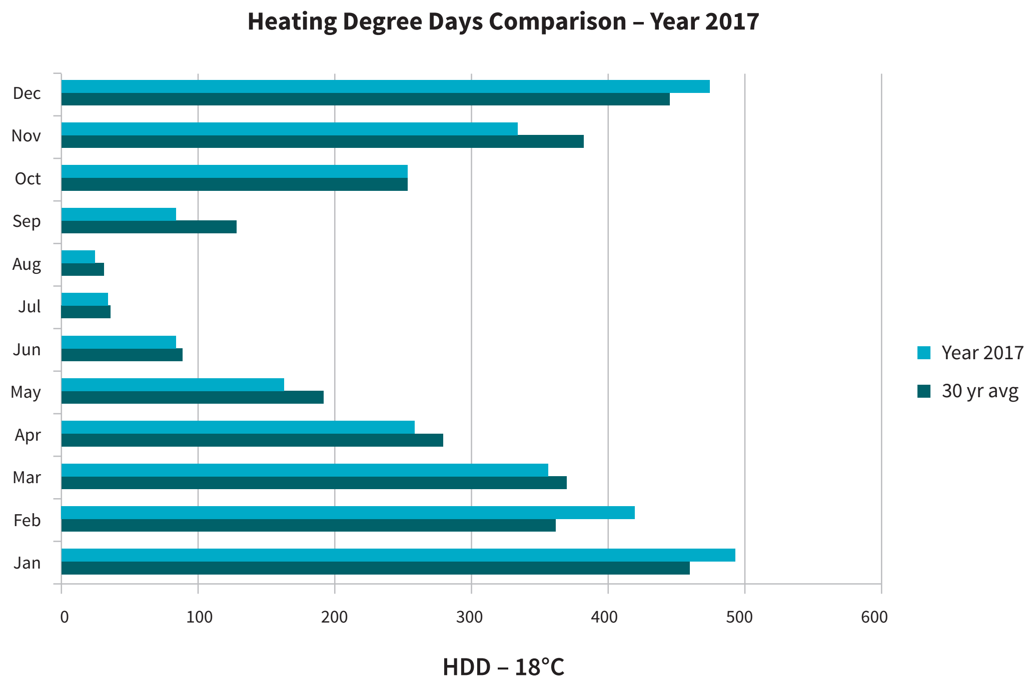


Figure 3.3: 30-year Average HDD vs 2017 HDD

For 2016, there were 14.9% less HDD than the 30-year average. As seen in Figure 3.2, all the heating months had less HDD except December, which had 18% more than average. For 2017, there was 2.2% less HDD than the 30-year average. As Figure 3.3 suggests, the coldest months of January, February and December demonstrated a total of 9.2% more HDD than the ones used in the energy model. Other typical heating months in 2017, including October, November, March and April had 6.9% less HDD.

Regression analysis for a building's total energy consumption was performed to check the correlation between HDD and energy consumption. It should be noted that no sub-metering systems were available in the buildings. The intercept of the linear equation theoretically represents the baseload energy consumption. The correlation coefficient R^2 represents how accurate the prediction is when calculating the energy consumption according to the HDD. The coefficient R^2 floats between 0 (no correlation) and 1 (100% correlation). In general, a value of 0.7 or above reveals a strong relationship between energy consumption and HDD [4]. Correlations varied from one building to the next, with part of the analysis aiming to identify reasons for lower correlations.

3.3.2 Examine Individual Sites

The comparison of modelled and actual building performance levels was followed by examining individual building sites. The primary purpose of the site visits was to identify mechanical system issues, control sequence conflicts, operational challenges, the effectiveness of the Building Management System (BMS) and offsets related to tenant behaviour. Facility managers were asked about:

- Occupancy and vacancy rate
- If there were any individual sub-meter for different end-use such as lighting, heating/cooling equipment, and plug-loads
- Inspection/maintenance frequency of operating equipment
- Maintenance/repair record
- Working conditions of equipment
- Comfort (thermal/ventilation) complaints from occupants and if they could be assigned to certain regions of the building

3.3.3 Questionnaire Survey Design

From the literature review, it is evident that one of the common causes for the performance differences is related to occupant behaviours and their influence on the unanticipated increase in energy use. To better understand the observed social housing performance results, one of the buildings was selected for the "occupant satisfaction survey." The survey was conducted under the direction and supervision of BC Housing.

The survey focused on exploring the thermal/ventilation comfort level of occupants and how their behaviours may have contributed to the energy loss. Besides simply providing yes/no answers to the questions, their satisfaction/comfort levels were described in the survey. Twenty-eight out of 49 tenants participated in the survey. A full copy of the occupant satisfaction survey can be found in Appendix A.

The feedback from maintenance managers was also gathered through questionnaires. The questions were developed based on visits to the building sites and in-person discussions with building staff, including facility managers. The questionnaire addressed specific building issues, factors contributing to performance issues, equipment requiring more frequent repair and maintenance, obstacles in operating or maintaining new technologies, and suggestions or recommendations for future green building design – from the point of view of maintenance managers. A full copy of the building performance survey can be found in Appendix B.

4 Results and Discussions

4.1 Case Study: Building A

4.1.1 General Description

Building A is a three/four–storey LEED Gold, a mid-rise residential building located in Victoria, British Columbia. The building meets all of the National Energy Code of Canada for Buildings (NECB) mandatory requirements. It was occupied in 2011 and approved as a LEED Gold building in 2013 under LEED Canada-NC 1.0. It has a total conditioned floor area of 2,740m^2. The building accommodates 38 bachelor suites, 6 one-bedroom suites with amenity rooms, parking, and bicycle storage. The orientation of the building is 45° North to make use of solar gain. Large windows were installed in common areas on the main floor to provide sufficient sunlight during the day.

4.1.2 Envelope and Construction

The U-shape of the Building A enclosure retains a high perimeter envelope. It can offer a large quantity of fresh air for natural ventilation and sufficient daylight for individual suites. The wood-frame building reduces energy consumption taking the life-cycle analysis into account because less energy was consumed during the material extraction and fabrication phase. The off-site pre-manufacturing of the frame also helped to reduce the overall construction time. The glazing to wall ratio is at a low value of 27%, which offers a better thermal performance without affecting the in-suite livability.

4.1.3 Mechanical System

Air Handling Unit Loop

Table 4.1: Envelope and Internal Loads Specifications of Building A

Wall-Main Floor	Brick cladding with wood framing Spandrel panels used in the curtain wall area
Wall-Other Floors	Wood siding cladding with wood framing
Roof (hr • ft^2 •° F/Btu)	Type 1: Concrete built-up roofing with wood framing Type 2: Concrete built-up roofing with glass fiber insulation and wood framing Type 3: green roof On average, R=29.7
Wall (hr • ft^2 •° F/Btu)	On average, R=18.1
Glazing Type	Interior window: Single glazed with tempered or aluminum glass frame Exterior window: Double glazed aluminum window with thermal break
Glazing to Wall Ratio	27%
Window (hr • ft^2 •° F/Btu)	U assembly=0.39

Whole Building (hr • ft² •° F/Btu)	On average, R=8.6
Lighting Fixture	Suspended in space
Lighting Power Density (W/ft²)	0.99
Plug Loads (W/ft²)	Based on the space function
Outside Air Rate (cfm/ft²)	0.15

The main floor of the building is conditioned by a central air-handling unit that operates on a Direct Digital Control (DDC) schedule. The DDC system monitors the supply, return and mixed air (a combination of return and fresh outdoor air) temperature, supply air duct pressure, variable speed drive feedback motor speed and freeze stat.

The Air Handling Unit (AHU) system consists of a return fan, a supply fan, an outside air control damper, a cooling coil and multiple VAV boxes with reheat coils along with a two-pipe heating/cooling change-over control valve as shown in Figure 4.1. Outdoor air moves through the wall louvre to the mixed air section of the AHU system. The exhaust air volume is damped to equal the outdoor air volume. The combined air then travels through the air filter, cooling coil and arrives at the inlet of the supply fan. The supply fan releases the supply air to multiple VAV boxes that extend to ceiling-mounted air diffusers or sideway supply air grilles. Return air is ducted from each zone to the common corridor and then enters the return air duct, which connects to the mixed air inlet. The return and supply fan operates continuously during occupied periods through sensor-controlled mechanisms or connections with the lighting system. The supply fan modulates the speed and air volume to satisfy the supply air static pressure requirement that further controls the return fan speed in proportion to the supply fan.

Table 4.2: HVAC System Specifications of Building A

Temperature Set-point	Heating set-point: 21°C Cooling set-point: 24°C
Ventilation Air Handling Unit	AHU-1: 100% outdoor air ventilation serving common spaces of the main floor ERV-1: 100% outdoor air ventilation with energy recovery serving west wing of the building ERV-2: 100% outdoor air ventilation with energy recovery serving east wing of the building
Heat Recovery Efficiency	ERV-1: 75% effectiveness for heating 78% effectiveness for cooling ERV-2: 58% effectiveness for heating 60% effectiveness for cooling
Space Heating System	Preheated ventilation air via heat recovery to suites AHU-1 heated supply air to common spaces Radiant floor heating for amenity spaces and suites
Space Cooling System	AHU-1 cooled supply air to common spaces

The cooling coil is placed in the AHU loop as the supply equipment to provide the variable volume of cooled air to amenity rooms and management offices. Readjustment of the cooling set-point temperature is altered to reflect the average zone cooling demand. This is achieved in OS and EnergyPlus by using a Set-point Manager: Multizone: Cooling: Average at the end of the supply side of the air loop. Free cooling may be provided by regulating the outdoor air damper position if the outdoor air temperature (OAT) is lower than the return air temperature. Activation of the unoccupied cooling mode is only enabled when all of the following conditions are met: 1) zone temperature is higher than 28°C, 2) all zone temperatures exceed the occupied setpoint by more than 1°C, 3) zone temperature exceeds the outdoor air temperature by more than 5°C, and 4) unoccupied cooling mode has been out of commission for more than 10 minutes.

Space heating is served by heated air that passes through the reheat coils in the VAV boxes. Each VAV-box consists of an airflow control damper, a heating coil and a heating water control valve. It operates upon the VAV's DDC system which monitors the airflow rate, room temperature and supply air temperature. A 30-minute early morning warm-up is enabled before the operation of the building during hotter days. The full run of the AHU system is set up with the heating coil control valve tempering to maintain the supply air temperature at set-point. The unoccupied heating mode is enabled if any two space temperatures fall below the recommended heating temperature when the building is unoccupied.

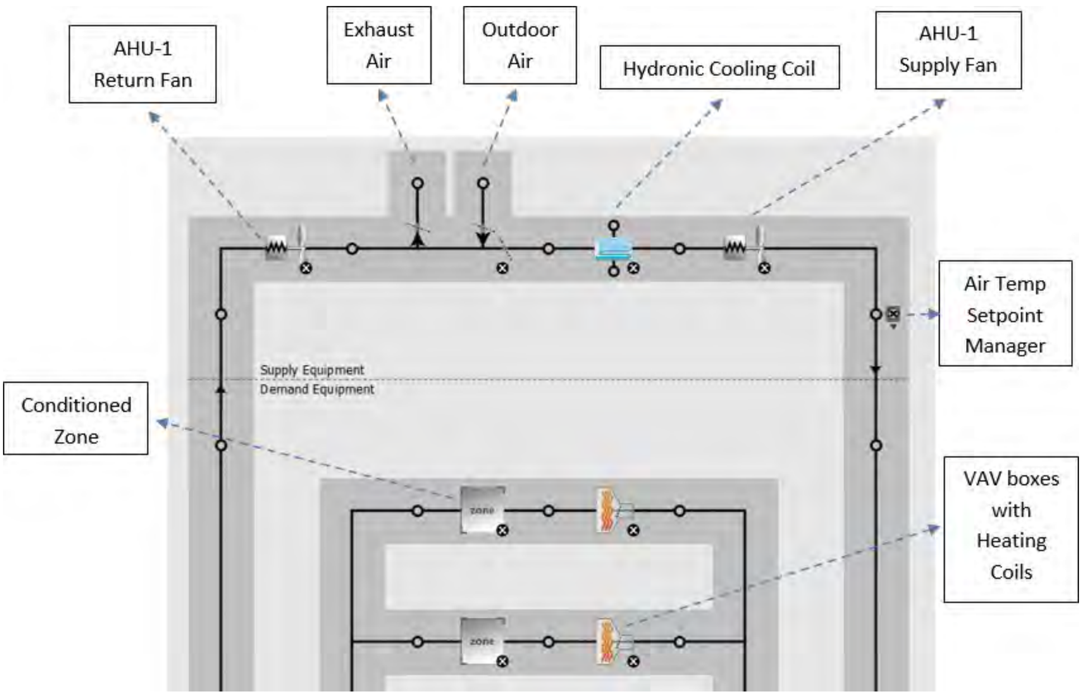


Figure 4.1: Air System for the Main Floor

Subsequently, the airflow from the VAV boxes is set to its maximum value and the heating control valve is 100% opened. In the case that the room temperature exceeds the unoccupied heating set-point by 2°C, the VAV boxes modulate the airflow at its minimum volume and the heating control valve is closed completely.

Energy Recovery Ventilation Loop

The other levels and suites on the main floor are conditioned directly by two Energy Recovery Ventilation (ERV) systems. The ERV system works as an exchanging unit that makes use of energy from exhaust air to precool or preheat the outdoor air and subsequently reduces the heating and cooling energy consumption of a building.

The pollutants and small particles in the outdoor air can be removed after passing through the filtration component of the ERV unit. Purified air is sent to the conditioned zones to provide a high-quality indoor air environment. While a typical Heat

Recovery Ventilator (HRV) can only capture and transfer energy from the air, ERV in this building can also transfer moisture from the exhaust air. Additionally, it can transfer some of that moisture and heat to the incoming airstream by moving water vapour directly from one airstream to another. Conditions for possible frosting are negligible since the average winter temperature in Victoria is higher than the minimum operating temperature of the ERV unit (-23.3°C). Additionally, as indicated in the manufacturing sheet, the infrequent extreme weather should not affect the normal operation or performance of the component.

Figure 4.2: Schematic of a Typical ERV System

Each ERV air loop consists of a return fan and a supply fan to push air to the outside and inside, respectively. Exhaust air is drawn through the individual ceiling mounted exhaust air grilles and travels through ducts to the exhaust air inlet of the ERV unit. After exchanging energy with outdoor air, the exhaust air is sent to the outside by the exhaust fan. At the same time, fresh air passes through the air filter and the heat recovery core for ducting to each conditioned zone. Continuous operation of the unit guarantees consecutive oxygenation and serving of clean air through single duct ceiling diffusers to the living units and corridors.

Cooling is provided by the cooling coil that is placed on the supply equipment side. The average cooling demand for multi-zone is considered as the cooling standard for the suites. Occupants have full control over the opening and closing of windows at any time. The natural ventilation makes it possible to provide an individually preferred level of comfort that is not restricted by ambient temperature. Moreover, it has a chance to reduce the cooling load when the outside temperature is not too high compared to the cooling set-point. The increased flow of air has an overall positive effect on the cooling of a zone.

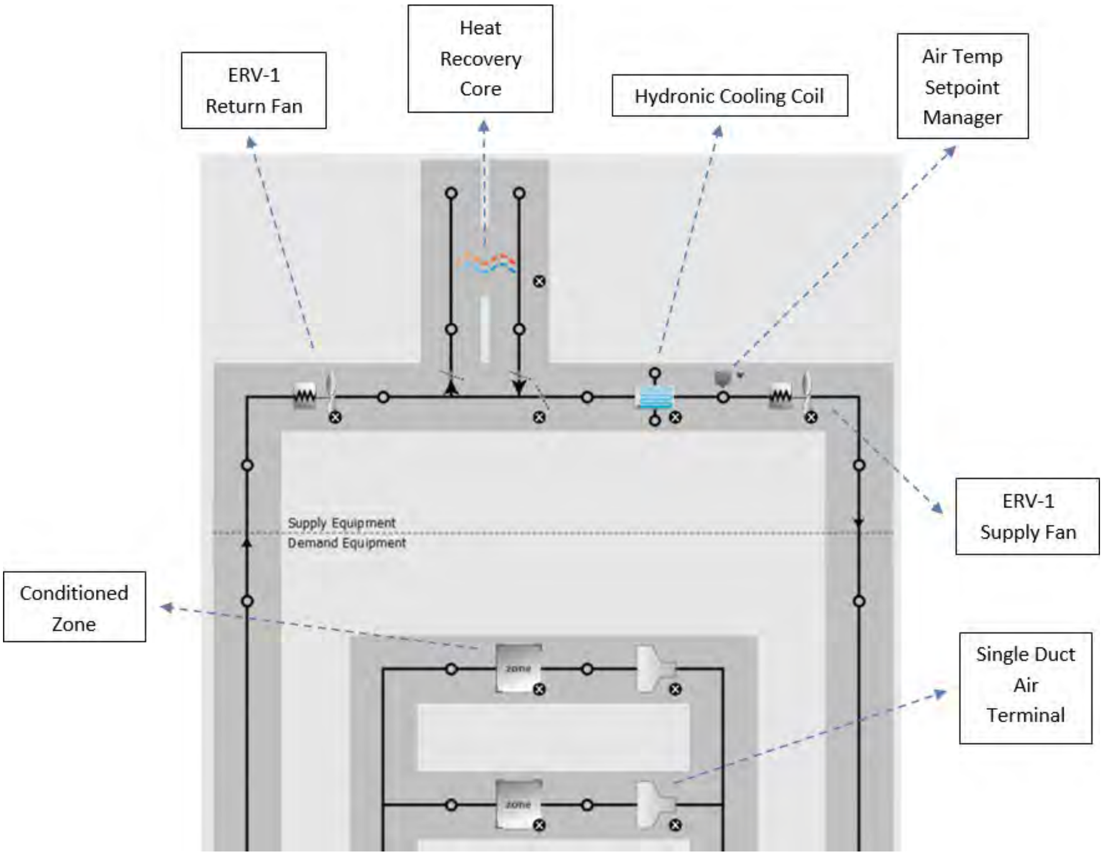


Figure 4.3: ERV Loop for Residential Suites

In-floor Heating System

An in-floor heating system is used to provide heating for the entire building. Each conditioned space receives heating fluid from a manifold in the respective zone. When the temperature sensor installed in the suite detects a lower room temperature than the set-point, a need for heating is transmitted to the DDC system. In line with the control command, the zone control valve can be opened allowing the heating fluid to circulate in the floor heat piping loop. Once room temperature achieves the heating setpoint, the valve is closed until the room temperature drops again.

4.1.4 Central Plant

To design a low energy building, it is essential to maximize the energy efficiency of the HVAC equipment and minimize the use of electricity or other primary energy sources. In the case of Building A, an air-to-water heat pump placed on the rooftop is used for providing cooling/heating water circulation in fan coil systems and radiant heating loops inside the floor. The circulated fluid always enters the heat pump first and then may flow through a boiler that is added to the plant loop as an additional heating resource. When the temperature of the water leaving the heat pump is lower than the set-point, extra energy for the water heating process is provided by the boiler. Once the set-point is attained, first the boiler is disabled and followed by the heat pump.

The load water is made up of 25% propylene glycol, which is introduced in the heating/cooling hydronic system in the mechanical room. A glycol feed tank automatically pumps glycol into the make-up fluid if there is a drop in the loop pressure. The ASHP can operate under low ambient temperatures since the freezing point of the 25% glycol-water is as low as -9.4°C [86].

The DDC system controls the heat pump, boiler, and water control valves. Water circulation pumps open/close based on monitoring parameters that include the temperature of the water leaving the heat pump/boiler, supply/return water temperature to/from radiant floors, and AHU heating/cooling coils. The water heating system starts if more than two zones request heat and close when all zone temperatures are higher than their set-points. During the heating supply period, the control valve is 100% open to keep the radiant floor system at its normal operational level. The DDC system also monitors all the equipment alarm contacts to keep the mechanical system working effectively. To investigate if the ASHP was effective, the simulation of Building A for this project removed the heat pump and only kept a boiler, as shown in Figure 4.4.

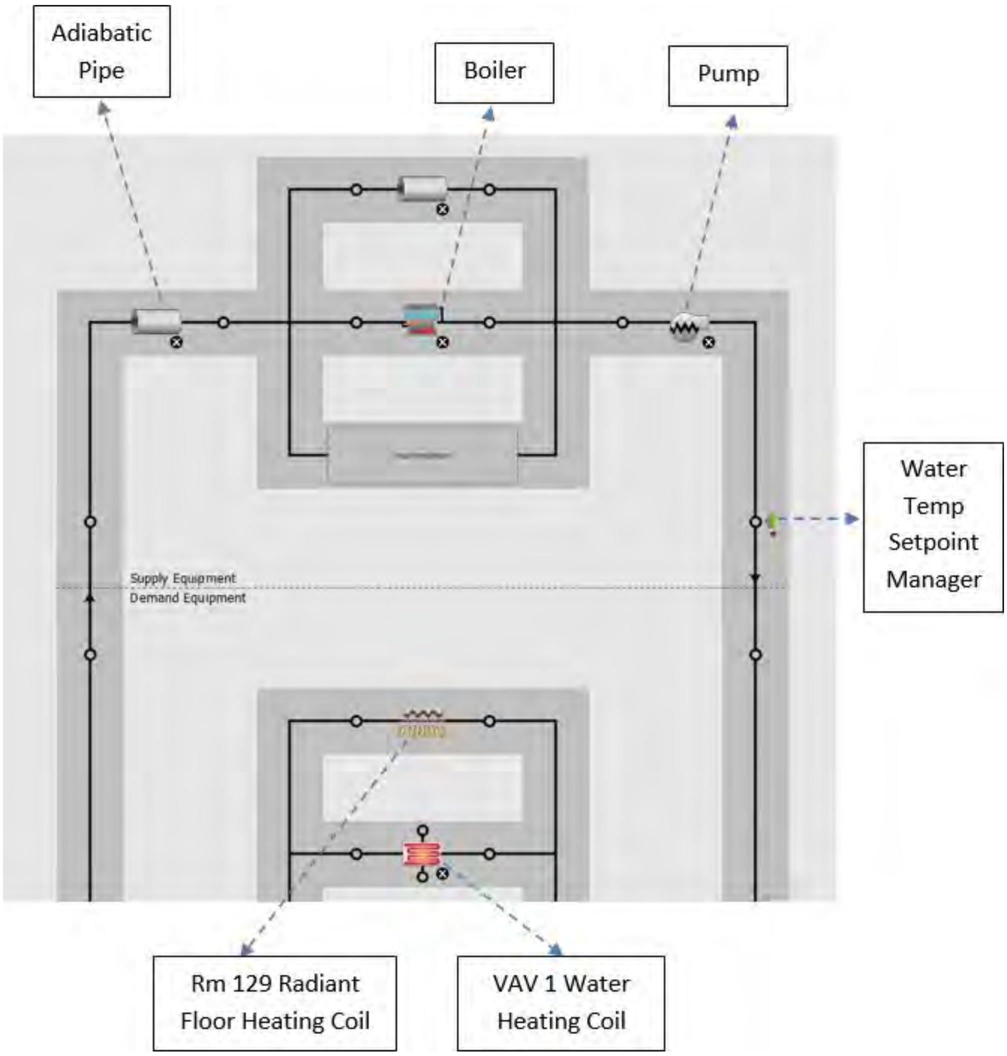


Figure 4.4: Modified Heating Plant of Building A (no ASHP)

4.1.5 Domestic Hot Water System

An array of solar panels is mounted on the rooftop at a specific angle to produce renewable energy for the building. With an on-demand domestic hot water system, the solar water heating system works to satisfy the water set-point initially. A pump is then activated to circulate the water in and out of the heat exchanger and up to the solar panels.

The water, heated by solar energy, flows into two preheated storage tanks that continuously maintain the storage water at 54°C to prevent Legionella. Additionally, an electric water heater is connected to the storage tank and functions as the secondary water heating equipment. It is only used when the solar system is unable to heat the domestic hot water to its set-point at 60°C. In the meantime, two recirculating pumps run continuously to supply hot and tempered water to the whole building.

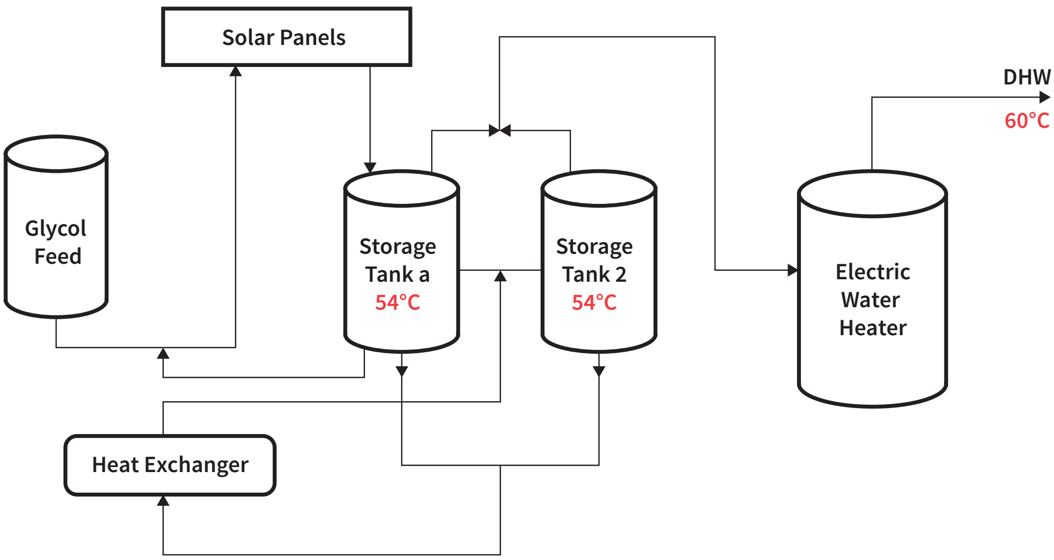


Figure 4.5: Domestic Hot Water System of Building A

The DDC system monitors the solar loop pressure, pump amperage, and various temperature sensors. The temperature of solar-heated water, incoming cold water, water leaving the electric DHW heater, and preheat storage tank are tracked all the time. All of the DHW loop equipment is controlled through a building management system to ensure precise and efficient operation.

The heat exchanger activates only when all of the following conditions are satisfied: 1) the heat pump is in heating mode, 2) the preheat storage tank temperature is lower than 32°C, and 3) central plant supply water is higher than 36°C. The system stops if the preheat tank temperature exceeds 54°C or the temperature difference between the preheat tank and the central heating supply water is less than 2°C.

The DDC system calculates a sunrise time and sunset time based on the historical weather data of Victoria. The solar panel is then activated/deactivated at sunrise or sunset respectively. If the solar loop pump does not work properly (as expressed by amperage) or the pump is unable to follow the DDC system command while running, an alarm is activated.

4.1.6 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

Building A consumed 94.2% and 102.7% more energy in 2016 and 2017 respectively than the modelled consumption and still avoided 23% and 19.6% of annual energy usage compared to the baseline building as depicted in Figure 4.6.

The electricity data showed 62.1% and 41.3% higher consumption than modelled. This is partially a result of the improper estimation of the non-regulated loads such as the elevator and parkade lighting during the design stage. However, this significant discrepancy cannot be completely explained by non-regulated consumption.

The inefficiency of the solar system and air source heat pump may also have contributed a lot to the performance gap. As expected, more electricity was required to heat domestic water if sufficient renewable solar energy was not available. The ASHP on the rooftop cycled multiple times during cold days when it was not operating well, while associated pumps and fans were operating at the same time. This supposition can be proven by examining the unusually high natural gas firing data as shown in Figure 4.6. Also, the building consumed 42.1% more natural gas in 2017 than the modified modelling with only a boiler supplying space heating energy. Although the building facility manager stated that all the equipment functioned properly in 2016 and 2017, the sustainable design features did not perform as predicted.

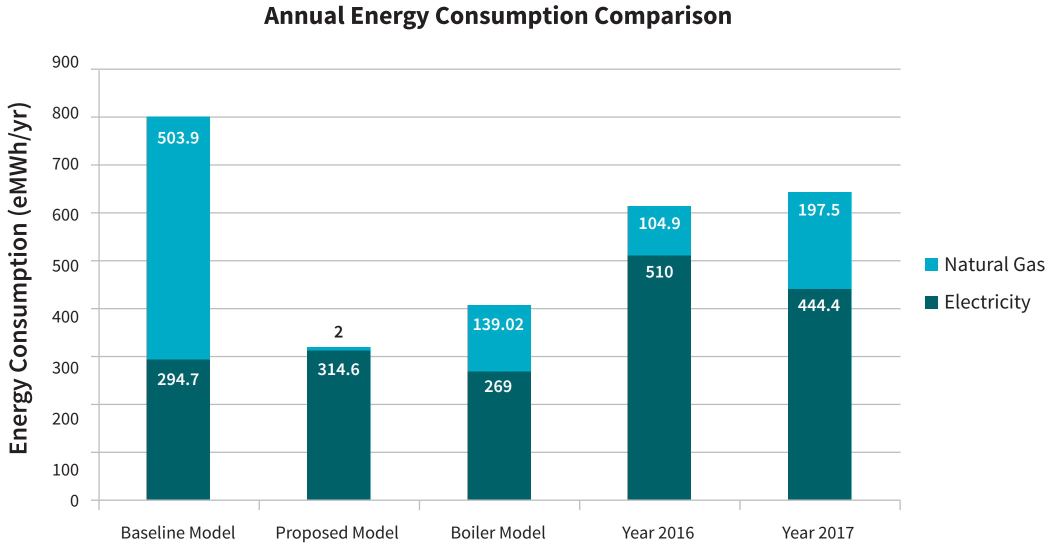


Figure 4.6: Annual Energy Consumption Comparison of Building A

To investigate how the ASHP performed in the real world, the monthly natural gas use between the boiler models for 2016 and 2017 was compared. Figure 4.7 suggests that during January and February 2016, the ASHP was working as expected. However, fewer HDDs in February led to overall lower natural gas consumption than January. This abnormal trend can be a reason to suggest that the ASHP was starting to have some issues.

HDDs from March to November 2016 were fewer than those used in the modelling process while the natural gas consumption was almost the same. From December 2016 to December 2017, the actual gas consumption was kept higher than the boiler model results, regardless of whether the actual weather was warmer or colder than the weather file used in the modelling.

Natural gas use should be zero according to the model prediction in summer 2017 (second trough on the graph with red line) but the actual gas usage was more than zero in the summer of 2017.

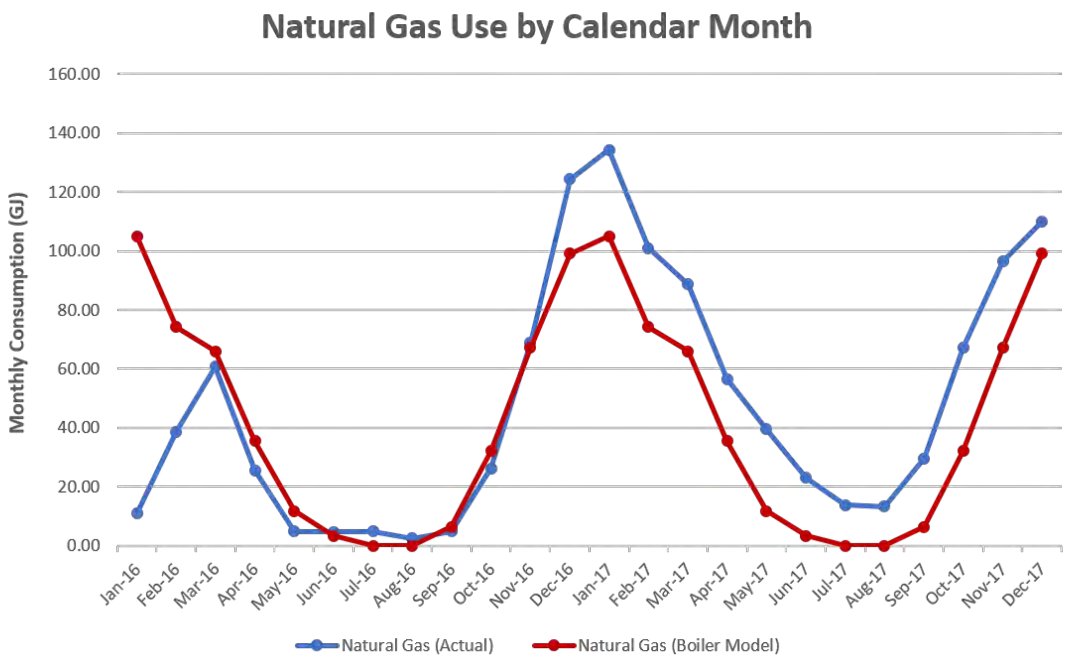


Figure 4.7: Monthly Natural Gas Use Comparison between the Boiler Model and Actual Consumption

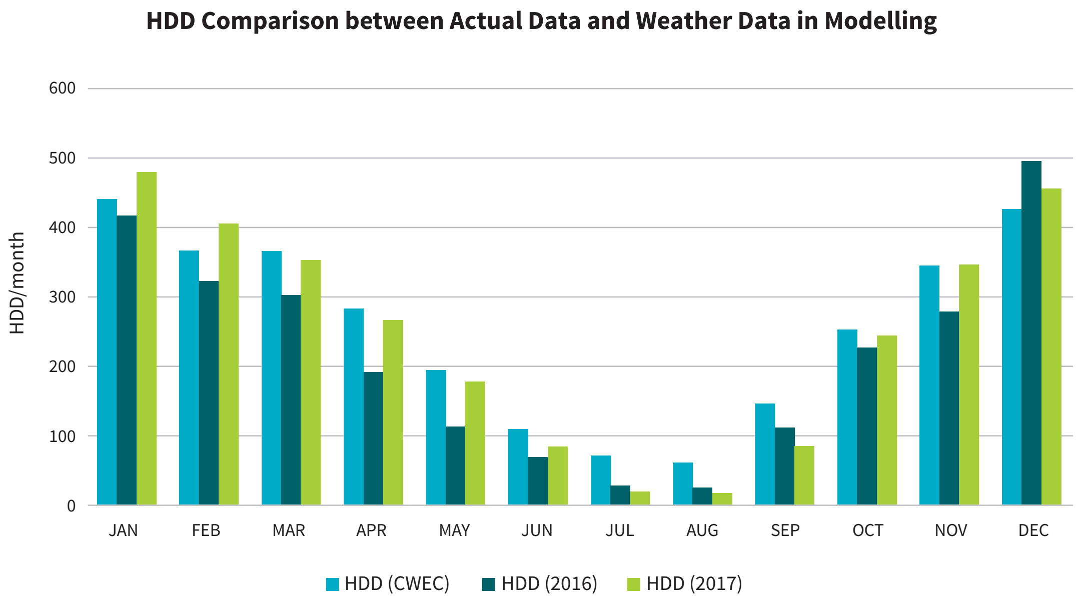


Figure 4.8: Monthly HDD Comparison between Actual Data and 30-yr Average Data

Another possible reason for the variation between predicted and actual models could be related to unanticipated occupant behaviour (as seen from the occupant satisfaction survey) and boiler model results. Tenants kept opening windows during winter months for direct fresh air, which increased the heating burden for the ASHP loop. From the occupancy satisfaction survey, it was noted that 42.9% of tenants used additional heaters in winter, and 85.7% of tenants relied on extra fans in summer for ventilation and cooling.

The rules of LEED v1 could have partially contributed to the difference in electricity results as well. This is due to the rules not accounting for some non-regulated loads, such as contribution to space heating gains from elevators, parking fans and other components. Furthermore, the total energy use of non-regulated plug loads is based on rough estimates and code defaults and actual use could vary substantially based on operations and type of equipment use.

Building Energy Performance Index Comparison

Taking the annual energy usage into consideration as described in the previous section, Building A performed much worse than anticipated. In parallel, it is essential to compare the EUI of Building A with benchmark buildings. Two building types were selected from NRCan's database of Multi-unit Residential Buildings (MURBs) and Health Care and Social Assistance (HCSA) buildings. Building A is not a typical apartment; it has staff on-site 24/7 and various support services are offered. Accordingly, it should be classified as a particular type of social housing that provides accommodation and social assistance.

The comparison was performed using the building's annual EUI per floor area as the measurement criteria. The actual EUI for 2016 and 2017 was greater by 87.8% and 96.1% respectively, in comparison to the benchmark MURBs. However, the EUI was 36.9% and 34.1% lower for 2016 and 2017 respectively when compared to HCSAs. The electricity consumption in 2016 was 8.1% more than HCSAs with a savings of 78.9% for natural gas. As a result, it tends to follow the proposed model for reducing fossil fuel usage despite its higher energy consumption.

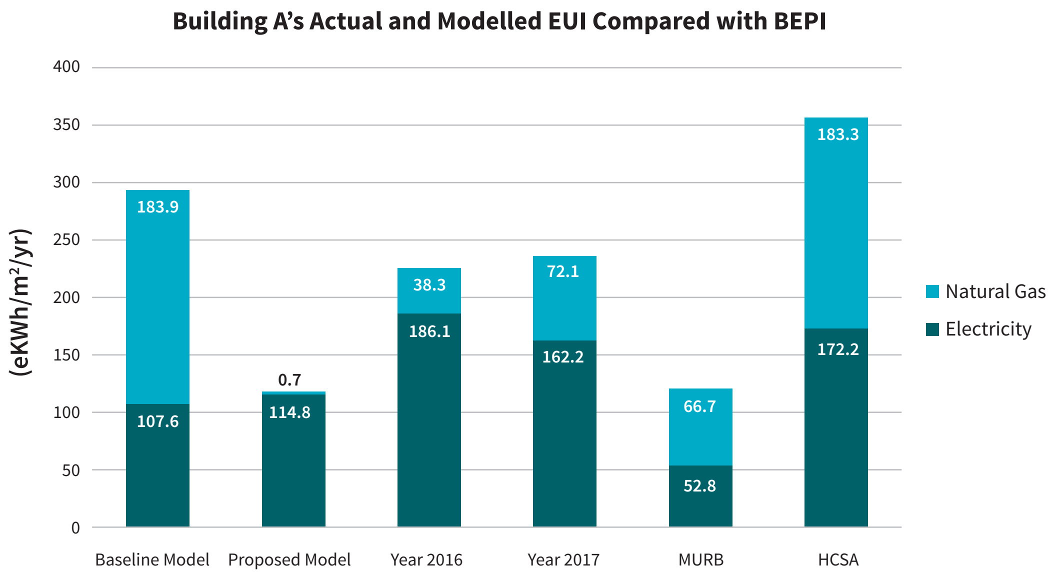


Figure 4.9: BEPI comparison of Building A

Effects of Weather on Results

With 14% less HDD for the year 2016, lower energy consumption for space heating was expected. However, the utility data demonstrated higher electricity and natural gas usage than predictions. A regression analysis was performed to check the correlation level between HDD and energy consumption since the higher gas consumption was not consistent with the presumptions. For 2016, the correlation coefficient was 0.88 for Building A, which indicates a close relationship between the high energy consumption and specific weather conditions. Figure 4.11 demonstrates frequent natural gas firing during cold months and especially in December. This observation confirms the inefficiency of the ASHP under extreme weather. Furthermore, the continuous gas consumption shows that excessive heating supply was used during summer nights when outdoor air temperature fell below a certain value. Subsequently, it is recommended that the control sequences should be reviewed to avoid any unnecessary heating.

From the comparison shown in Chapter 3 Methodology, it cannot be concluded that lesser heat energy was used in 2017. When compared to the utility data, Building A is shown to consume more energy than the modelling. Regression analysis indicates that the high energy consumption is strongly correlated to HDD and more gas firing.

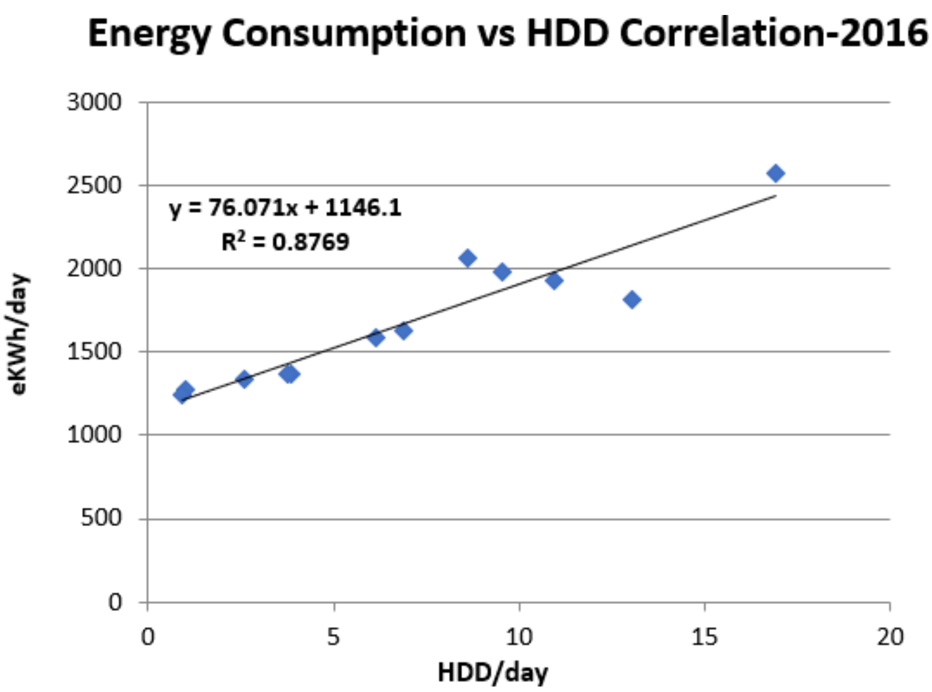


Figure 4.10: Effects of Weather on Building A for 2016

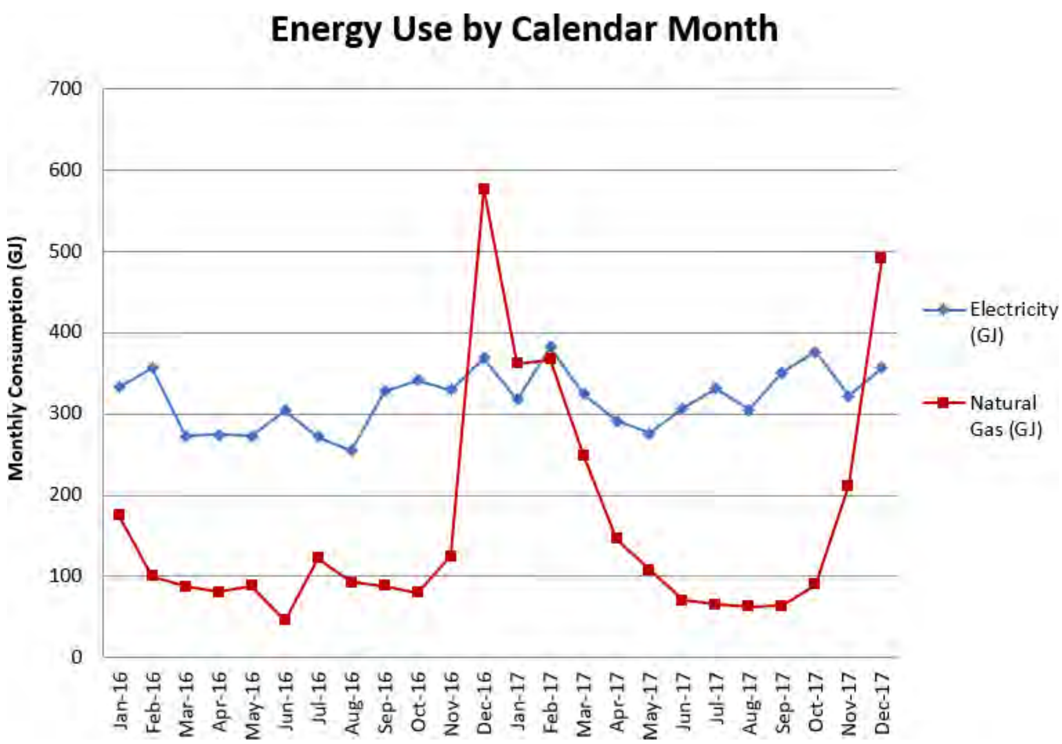


Figure 4.11: Monthly Utility Data by Types of Building A

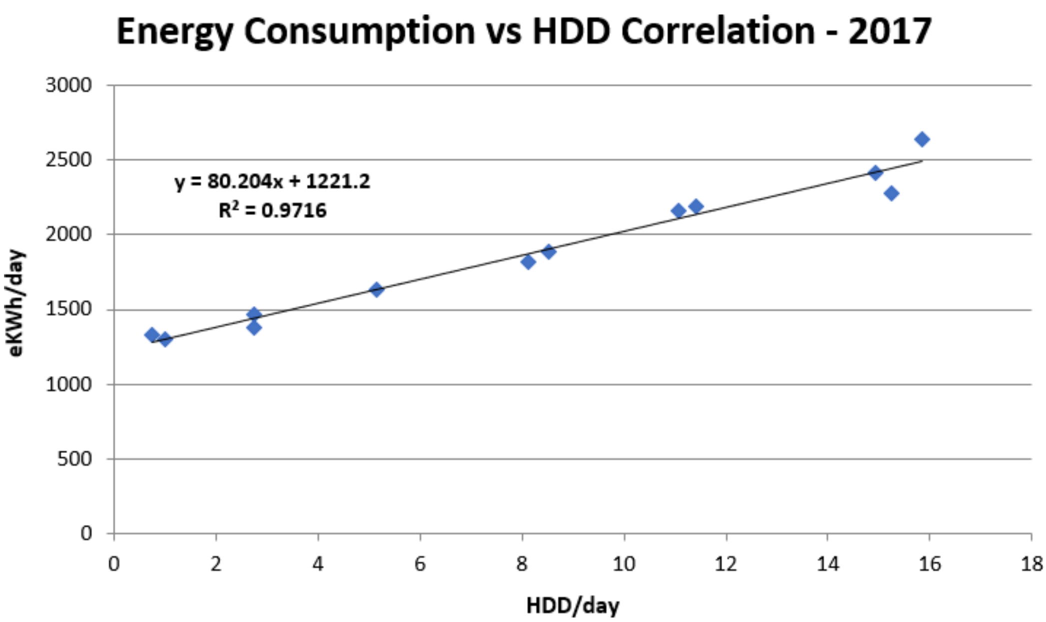


Figure 4.12: Effects of Weather on Building A for 2017

Monthly Electricity Consumption Comparison

Figures 4.13 and 4.14 show the comparison between the predicted and actual electricity usage for 2016 and 2017 respectively. The biggest discrepancies for 2016 happened in January, February, May and October with an average 72.2% electricity usage above the predictions. In 2017, April and May had an average of 67% more electricity usage than predictions. Typically, heating and shoulder months are more likely to produce unexpected electricity usage results because of occupant behaviour.

Other factors causing the discrepancy were discovered from discussions with the facility manager and inspection reports. These factors included in-suite temperature sensor issues, failures in control valves, overheating or failure of the DHW tank, heat pump low-pressure alarm, and leakage of the glycol feeder. All these factors can affect the efficiency of the heating/cooling system.

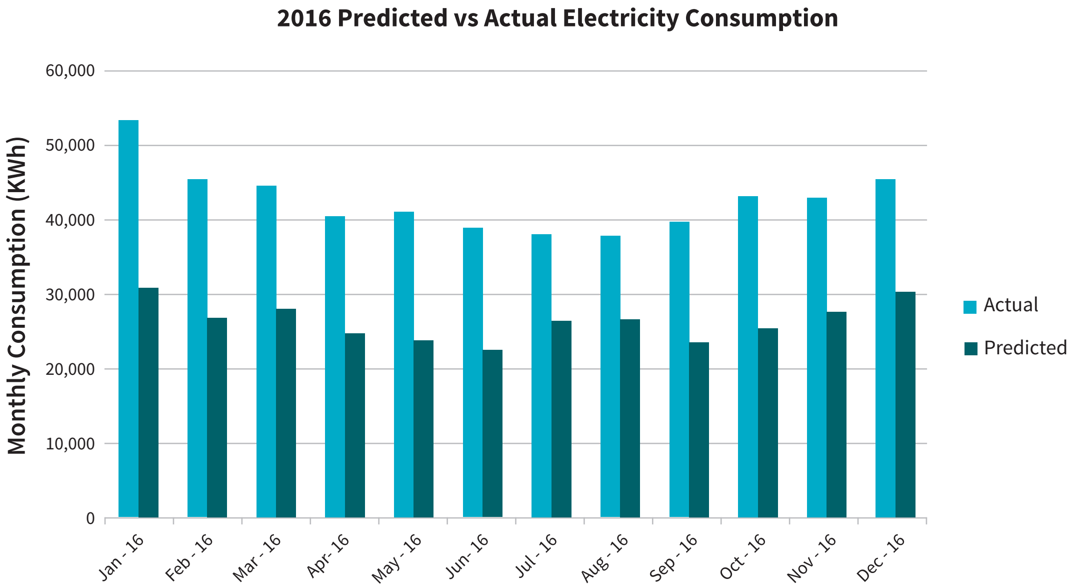


Figure 4.13: 2016 Electricity Consumption Comparison for Building A

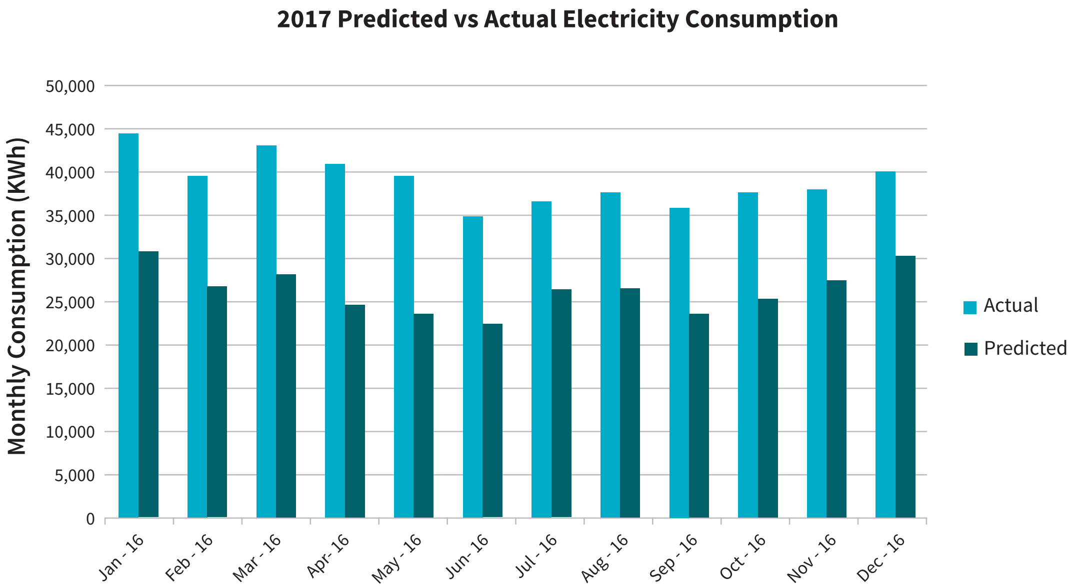


Figure 4.14: 2017 Electricity Consumption Comparison for Building A

Recommendations

- Examine the ASHP system to determine the reason for its inefficiency and reduce the related energy penalty.
- Verify how the solar energy system is operating to ensure its optimal performance.
- Review and adjust the control sequences of the DDC system to avoid unnecessary heating (and subsequent energy use) during summer nights.
- Install sub-meters to monitor various end-uses such as heating/cooling equipment and lighting so that mechanical and other controls can be easily and quickly addressed.
- Perform seasonal commissioning which is essential to optimize building performance by regulating the associated heating/cooling accessories.
- Calibrate future energy models based on the previous post-occupancy evaluation of similar buildings/systems.

4.2 Case Study: Building B

4.2.1 General Description

Building B is a ten–storey, sustainably built, high-rise residential social housing building located in Vancouver, British Columbia. The site was formerly a small hotel consisting of 24 rooms. After its redevelopment, the building has a floor area of 10,989m^2 (excluding parking area) and accommodates 106 studios, 41 one-, two-, or three-bedroom suites with amenity rooms, parking, and bicycle storage. It has three retail stores on the first floor that are leased and a non-profit society office on the second floor.

A children's playroom is connected to the outdoor playground along with a garden. It has large windows (heights are almost floor to ceiling size) and amenity rooms receive abundant natural light in the day. In contrast, these windows are also a source of heat loss. It has been occupied since 2015 and currently under application for LEED Gold certification under LEED Canada-NC 1.0.

4.2.2 Envelope and Construction

In consideration of both safety and effectiveness, high-rise Building B was designed and built for durability using long-lasting concrete walls along with high thermal resistance insulation. It has high R-values in exterior walls and roofs to enable lower heat loss and thus save energy.

The fenestration accounts for more than 30% of the main exterior wall. This brings a lot of sunlight inside and reduces the need for lighting in the daytime as well as reduces heating demand in the winter. This is especially true for the lobbies and lounges, where large floor-to-ceiling windows are installed.

Windows in suites are self-operable to provide natural ventilation and cooling for occupants. The materials sourced for the building followed the basic LEED material principles wherever possible. The prescribed materials are expected to be durable, recyclable, and regionally manufactured.

Table 4.3: Envelope and Internal Loads Specifications of Building B

Exterior Wall (hr • ft^2 •° F/Btu)	Brick cladding wall R=22 Metal cladding wall R=19 Spray insulation concrete wall R=24 On average R=21 (238% higher than the baseline)
Roof (hr • ft^2 •° F/Btu)	R=30 (254% higher than the baseline)
Overall Glazing **U-Value** (Btu/hr • ft^2 •° F)	U assembly=0.34 (41% lower than the baseline) SHGC=0.32
Glazing to Wall Ratio	32%
Lighting Controls	Daylight sensors Occupancy sensors in shared space, resulting in 18.9% savings compared to the baseline
Lighting Power Density (W/ft^2)	As per lighting drawings and Specifications
Plug Loads (W/ft^2)	Based on the space function
Infiltration (cfm/ft^2)	0.05

4.2.3 Mechanical System

The air handling units with heat recovery wheels AHU-1 and AHU-2 operate continuously to supply pre-conditioned air to suites, corridors and common areas. Once a signal is received for heating or cooling, the DDC system starts the hydronic coil circulating pump and modulates the coil control valve at a specific position to provide conditioned air at set-point. The DDC system controls the supplied air temperature between 13°C and 22°C according to room temperature sensors. The fans used in the system operate at variable speeds to economize energy costs.

The DDC system enables heat recovery wheels when 1) the AHU is in heating mode; 2) the AHU is in cooling mode, and outdoor air temperature is higher than the indoor air temperature. The DDC system disables heat recovery wheels when free cooling is available, which means that the AHU is in cooling mode and the outdoor air temperature is lower than the indoor air temperature. The common space supply and exhaust air dampers are closed when free cooling is activated.

In addition to the heated air from the AHU system, the suites also receive heat from an in-floor radiant heating system. The zone control valve for radiant floor heating is operated from DDC system commands.

To minimize the overall energy consumption including natural gas, the central plant of Building B consists of a high-efficiency air-to-water heat pump AHP-1 along with a gas-fired boiler as backup. When AHP-1 is in heating mode, it functions as the primary heating source. If it operates at its full load and still cannot satisfy the heating demand, the DDC system starts to cycle the boiler to provide additional heat to the building. The heat pump provides low-temperature hot water for radiant floors, hydronic coils, and distributed water-to-air heat pumps. In warmer months, it produces chilled water for 2-pipe fan coils and water source heat pumps to keep the building cool.

AHP-1 operates in heating mode when the outside air temperature is below 15°C and in cooling mode when the outside air temperature is higher than 18°C. The DDC system controls AHP-1 cycles in heating/cooling mode based on the building heating/cooling load when the outside air temperature is between 15°C and 18°C.

Table 4.4: Mechanical System Specifications of Building B

HVAC System Specifications	
Temperature Set-point	Heating set-point: 22°C Cooling set-point: 24°C
Ventilation Air Handling Unit	AHU-1: 100% outdoor air ventilation serving west wing of the building AHU-2: 100% outdoor air ventilation serving east wing of the building Dummy system (a control such as a thermostat that doesn't affect settings) Underground parking area
Heat Recovery Efficiency	AHU-1: 68.5% effectiveness with heat wheels AHU-2: 71.5% effectiveness with heat wheels
Space Heating System	Preheated ventilation air via heat recovery units Radiant floor heating in suites Electric baseboard heating for remaining spaces
Space Cooling System	2-pipe fan coils
Central Plant Specifications	
Heating Plant	Air source heat pump (AHP-1) with natural gas boiler backup serving radiant floor, 2-pipe fan coils and distributed water to air heat pumps Fixed speed primary circulating pump VFD secondary circulating pump
Cooling Plant	Air source heat pump (AHP-1) serving 2-pipe fan coils and distributed water to air heat pumps

4.2.4 Domestic Hot Water System

Building B has installed low flow toilets, faucets and showerheads, which helps to save approximately 40% more water in comparison to its baseline model. An additional air source heat pump AHP-2 is used to preheat the domestic hot water. When a hot water request is received, the gas-fired condensing boilers are engaged to heat DHW to its set-point.

Table 4.5: DHW System Specifications of Building B

DHW System	Preheated by an air-to-water heat pump (AHP-2) Reheated by four gas-firewall mounted condensing boilers Low flow fixtures

4.2.5 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

Monthly electricity and natural gas consumption data for Building B was collected and reviewed. The total annual energy consumption observed from the utility bills for the 2016 calendar year was 54.8% higher than the energy model of the proposed design and energy consumption for the calendar year 2017 was 79.6% higher than the predictions. The results are above the +/-15% range for accuracy level. However, the actual energy used during the 2016 and 2017 calendar year was 43.8% and 34.8% less than the baseline model.

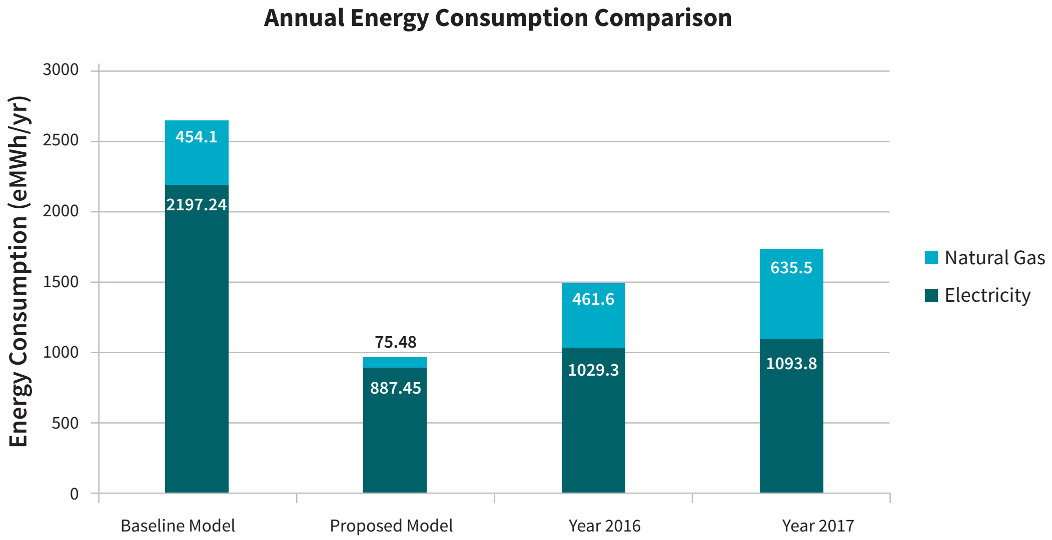


Figure 4.15: Annual Energy Consumption Comparison of Building B

The discrepancy between the modelled and measured results of natural gas consumption had a more significant impact on the total energy performance gap than electricity, as shown in Table 4.6. The considerable discrepancy in natural gas usage indicates that the backup boiler for space heating and condensing boilers for DHW were firing much more than expected. From discussions with the building facility manager, all the equipment functioned properly and regular maintenance was performed, although daily inspections by operators were not always performed. One possible reason for the inconsistency can be an issue with the low-efficiency of the heat pump in winter, which is a common problem for air source heat pumps in Vancouver.

Another probable cause can be that the building was not used by the residents in a manner which the modelling anticipated: some windows may have been kept open all winter, doors left propped open to the hallways, ovens kept on when not in use, ducts and vents covered, and taps left running. There was a whole range of occupant behaviours that the building systems did not take into account. Some occupants living in supportive housing were not aware or concerned about the utility bills because they were not responsible for these costs.

Table 4.6: Electricity and Natural Gas Consumption Comparison of Building B

Electricity	Natural Gas
The Proposed Model + 16.0% = Year 2016	The Proposed Model + 511.6% = Year 2016
The Proposed Model + 23.3% = Year 2017	The Proposed Model + 741.9% = Year 2017

Building Energy Performance Index Comparison

The comparison between Building B and benchmark buildings was performed to investigate the outcome of sustainable design. Building B is more than a conventional apartment since it has commercial retail stores on the main floor, administrative offices on the second floor, a large kitchen that provides meals, and different types of amenity spaces such as a children's playroom.

Accommodation and Food Service (AFS) building type was selected from NRCan's database for making the comparison and ensure a rigorous analysis. The baseline model used 101.9% more energy than the benchmark of typical MURBs but 32.1% and 31.6% less energy than HCSA and AFS respectively. Even though the building performed worse than the proposed model, it only consumed 13.6% and 31.6% more energy than the benchmark Building Energy Performance Index (BEPI) for MURBs building type in the year 2016 and 2017 respectively. However, the building saved 60% less energy in comparison to HCSAs and AFSs. In general, the building used much less natural gas compared to all the three types of benchmark buildings.

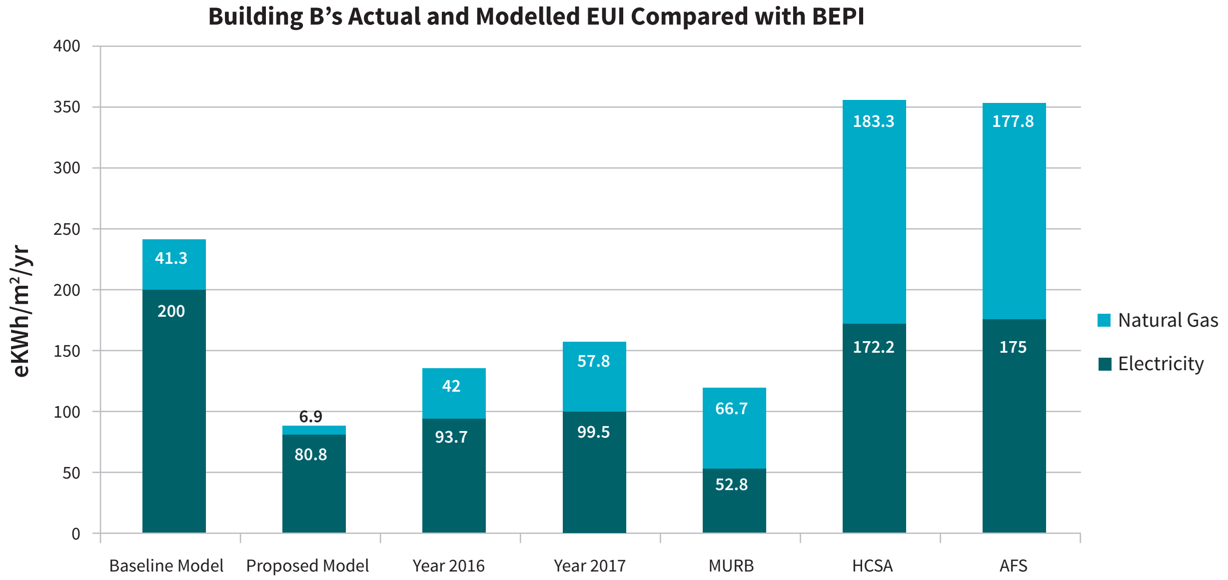


Figure 4.16: BEPI Comparison of Building B

Effects of Weather on Results

A regression analysis was performed to check the correlation level between HDD and energy consumption. The extremely high gas consumption was not consistent with the presumption. The R^2 of 0.5831 indicates a poor correlation between energy consumption and HDD for the year 2016 and suggests that the high natural gas consumption was not related to space heating. The DHW preheating issues may be a probable cause for this observation. Even after excluding the abnormal point, the coefficient still has a low value of 0.5181. It may also be a result of operational issues and equipment wear and tear. Another explanation could be occupancy behaviours, as mentioned in the previous section. Furthermore, the energy model may need to be calibrated according to the inputs from space heating and peak load for DHW.

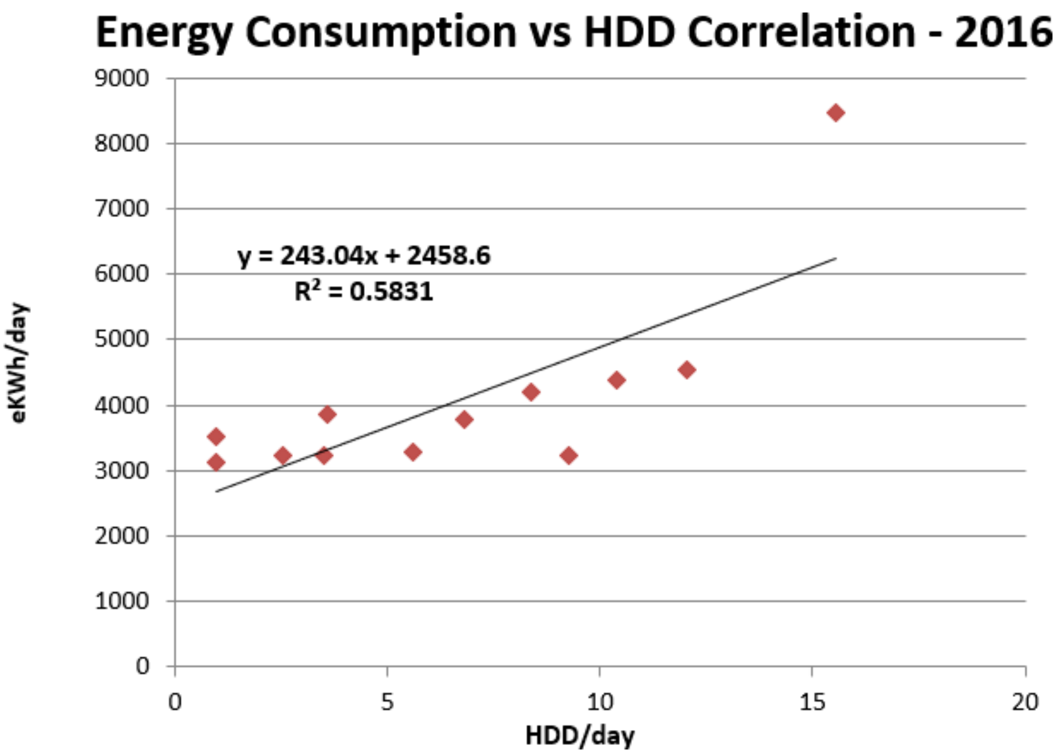


Figure 4.17: Effects of Weather on Building B for 2016

By comparing the utility data, it was observed that Building B consumed 23.3% more electricity and 741.9% more natural gas than the predictions. Subsequently, regression analysis was necessary to evaluate the interdependence between HDD and energy consumption. As shown in Figure 4.18, the baseload energy consumption for the year 2017 was 2,790.1 eKWh/day which was 13.5% higher when compared to the year 2016. The higher baseload energy consumption could be a result of the colder climate in 2017 that led to higher electricity consumption by pumps and fans.

The R^2 of 0.7857 indicates a good correlation between energy consumption and HDD for the year 2017. However, it cannot explain the excessively high natural gas consumption of 741.9% in 2017. The building uses an air source heat pump for heating supply and a gas-fired boiler as a back-up. The inefficient operation of AHP-1 during very cold days may have contributed partly to the unexpected natural gas use. Moreover, the demand for DHW can increase in cold winters that could result in higher gas consumption in 2017 compared to 2016. Factors related to occupant behaviour and equipment operation must be further investigated as well.

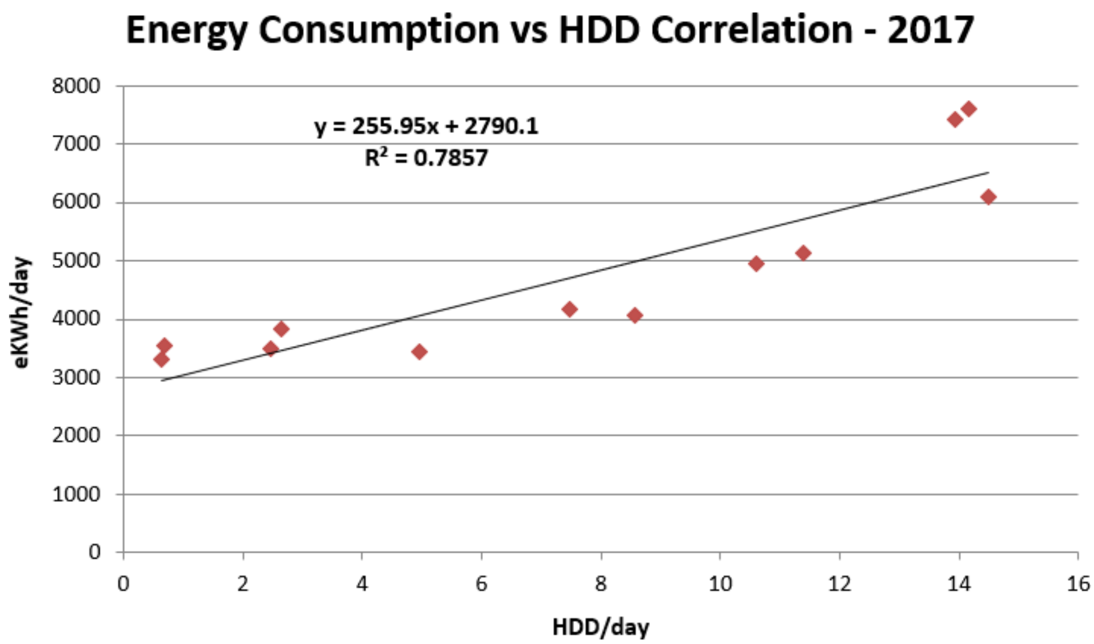


Figure 4.18: Effects of Weather on Building B for 2017

Monthly Energy Consumption Comparison

Figure 4.19 and Figure 4.20 show the comparison between monthly modelled (i.e. predicted) results and hydro bills for 2016 and 2017 respectively. For both years, the actual electricity consumption for Building B was consistently higher than the predictions. The greatest discrepancy from the predictions was observed during the same period in 2016 and 2017 namely February, September, and October. The three-month average energy gaps for the two years were 46.6% and 58.4%. Cold weather and the inefficiency of the air source heat pump cannot explain this disparity because other cold months did not display this major variation. The energy model needs further assessment to evaluate the inputs for these three months.

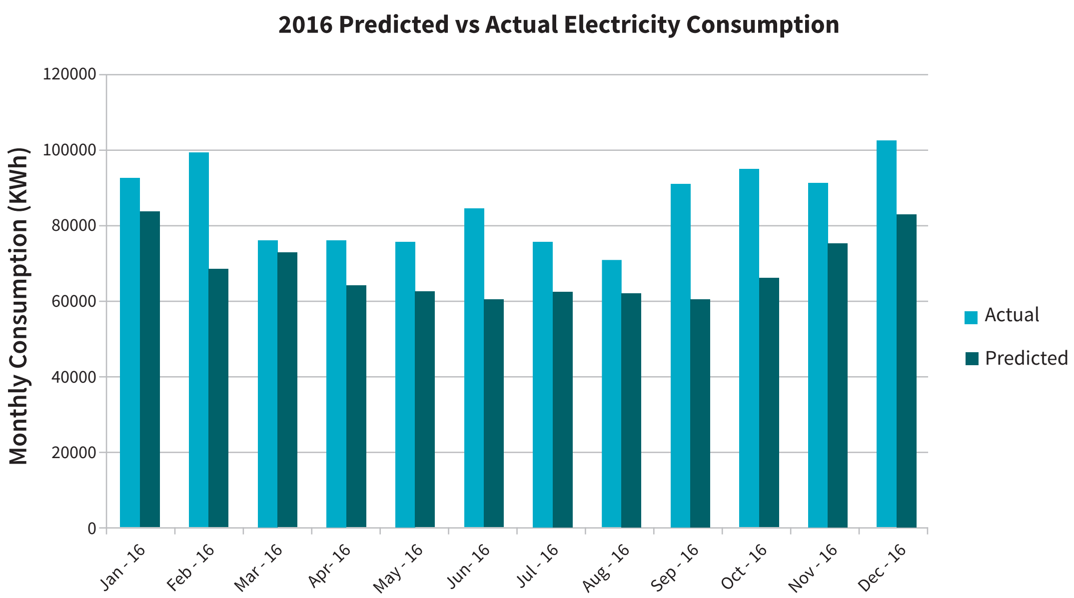


Figure 4.19: Electricity Consumption Comparison for 2016 of Building B

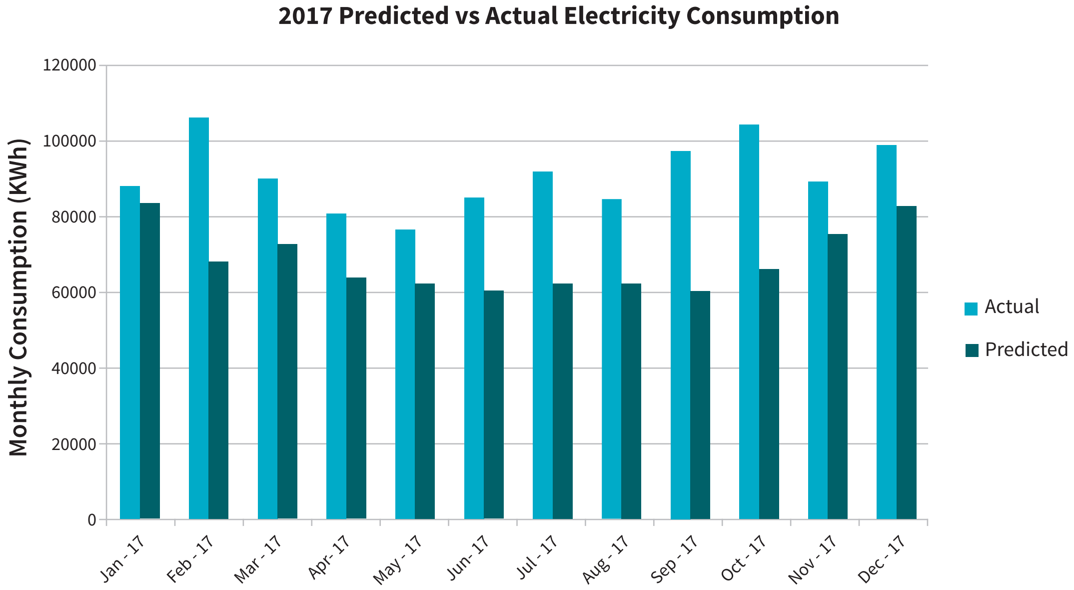


Figure 4.20: Electricity Consumption Comparison for 2017 of Building B

Figure 4.21 shows the electricity and natural gas consumption by calendar month between 2016 and 2017. Natural gas consumption increased rapidly during the winter months between November and March both years. This can be explained by the inefficiency of the air source heat pump under cold weather circumstances. It is necessary to modify the performance curves when modelling buildings using air source heat pumps to get more accurate results.

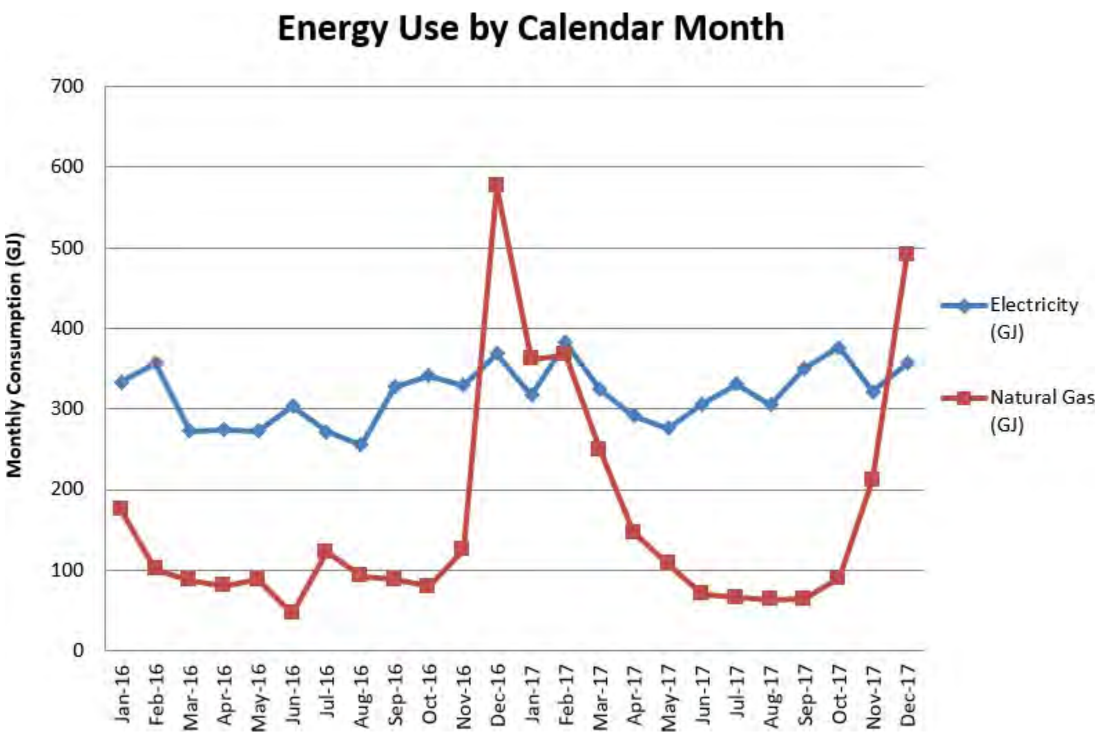


Figure 4.21: Monthly Utility Data by Types of Building B

Recommendations

- Examine the operation of HP-1 for space heating and HP-2 for DHW preheating and find solutions to reduce the high natural gas consumption.
- Install sub-meters on heating related equipment to better understand the breakdown of extra energy use.
- Continuous commissioning is recommended to improve energy efficiency and occupant comfort.
- Review the control settings of the DDC system to avoid unnecessary heating during the summer months.
- New energy modelling process that uses experienced performance curves for ASHPs in real operation is recommended.

4.3 Case Study: Building C

4.3.1 General Description

Building C is a four-storey, sustainable, mid-rise residential social housing building located in Vancouver, British Columbia. It is located within 400 meters of four bus routes. The building was designed to provide accommodation for low-income people struggling with physical disabilities and/or mental health. The site has a total floor area of 3,852m^2 that includes 412m^2 of commercial retail units on the first floor. It offers 51 suites in total out of which 47 are single-room occupancy (SRO) and four are wheelchair accessible. A large lounge, located on the first level, is equipped with a television and several computers and provides direct access to an outside garden. Extra-large windows allow plenty of daylight into the common spaces. This saves energy for lighting and enables warming from the sun's heat in cold winter months.

The building was redeveloped on a previously contaminated site (gas station) and effective remediation was performed. It has been occupied since 2011 and received certification as a LEED Gold building under LEED Canada-NC 1.0 in 2013.

4.3.2 Envelope and Construction

Building C is equipped with high thermal resistance materials in exterior walls and roofs to minimize the energy cost. The roof of the building makes use of durable white SBS membranes that help to reflect the sunlight in summer and are long-lasting. The application of a high R-value envelope can scale down the heat island effect to a certain extent. The insulation, including metal panels and brick masonry, work to break the heat bridge. In this building, 15% of construction materials consist of recycled ingredients and 25% of materials were extracted and manufactured regionally [87].

Table 4.7: Envelope and Internal Loads Specifications of Building C

Exterior Wall (hr · ft^2 ·° F/Btu)	Overall R=15
Roof (hr · ft^2 ·° F/Btu)	R=28
Lighting Controls	7% better than the reference model
Lighting Power Density (W/ft^2)	As per lighting drawings and specifications
Plug Loads (W/ft^2)	Based on the space function

Mechanical System

Table 4.8: Mechanical System Specifications of Building C

HVAC System Specifications	
Temperature Set-point	Heating set-point: 21°C Cooling set-point: 23°C
Ventilation Air Handling Unit	HRV-1: 100% outdoor air ventilation with heat recovery serving corridor pressurization MUA-1: Make-up air unit located in parkade mechanical room serving kitchens Dedicated exhaust fans: Parkade and elevator rooms
Heat Recovery Efficiency	66%
Space Heating System	Electric baseboard heating in suites
Space Cooling System	Split heat pumps supply cooled air to common spaces, offices and commercial retail units
Central Plant Specifications	
Heating Plant	N/A
Cooling Plant	N/A

The mechanical system of Building C is relatively simpler compared to other LEED Gold buildings. There is no central air source heat pump for space heating or cooling. Suites are heated by electric baseboard heaters individually. Common spaces, offices and retail stores receive cooled and heated air through split heat pumps mounted on the ceiling of the parkade.

The heating and cooling setpoints listed in Table 4.8 are the basic settings that can be adapted according to the space function and thermal comfort of the individual occupant. Corridors are ventilated and pressurized through preconditioned air from air handling unit HRU-1 with heat recovery wheels. The commercial kitchen is equipped with a direct-fired make-up air unit (DFMUA), which uses the combustion of natural gas to heat the outdoor air sent straight to the zone. The utilization of DFMUA grants high combustion efficiency and helps to keep the positive pressure in each zone.

4.3.3 Domestic Hot Water System

Building C has a solar heating system on the roof to preheat the DHW water that can be stored in four preheated tanks. A gas-fired boiler reheats the preheated service water, which is then stored in four DHW storage tanks to maintain the DHW at 60°C. This helps to prevent bacterial growth as well. With the installation of low flow fixtures, the building can recover 42% of the water consumed when compared to the baseline model.

Table 4.9: DHW System Specifications of Building C

DHW System	Solar vacuum tubes Preheat storage tanks PHT-1,2,3,4 Gas-fired DHW boiler DHWB-1 Gas-fired DHW storage tanks DHWT-1,2,3,4 Dry cooler DC-1 Low flow fixtures

4.3.4 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

Monthly electricity and natural gas consumption data for Building C was collected and reviewed. The total annual energy consumption, as calculated from utility bills for 2016, was 204% higher than the predicted energy use in the proposed design. Similarly, for 2017, it was 282% higher than the predictions. These results are far beyond the +/- 15% accuracy level target range. Additionally, the actual energy used in the 2016 and 2017 calendar year was 82.6% and 129% more than the baseline model.

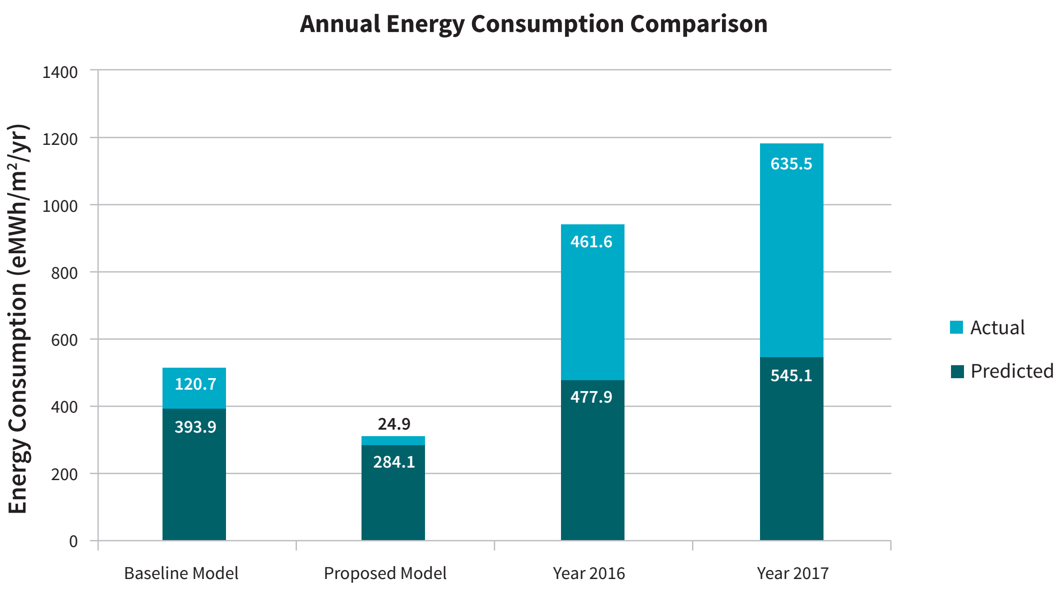


Figure 4.22: Annual Energy Consumption Comparison of Building C

Overall, the actual amount of natural gas used was 17 and 24 times higher than the predictions for 2016 and 2017 respectively. This is shown in Table 4.10. This significant inconsistency between the energy model and reality was expected given that the rooftop solar system did not ever function when the building was occupied. As a result, the condensing boiler was the only source of hot water service available for the facility.

Table 4.10: Electricity and Natural Gas Consumption Comparison of Building C

Electricity	Natural Gas
The Proposed Model + 68.2% = Year 2016	The Proposed Model + 1753.8% = Year 2016
The Proposed Model + 91.9% = Year 2017	The Proposed Model + 2452.2% = Year 2017

The building management system graph is shown in Figure 4.23 that highlights the abnormal operation of the solar panels from 2012 to 2018. The y-axis indicates the solar valve % opening level and water temperature in the solar vacuum tubes. The dry cooler DC-1 was only turned on during 2013 and 2014. This is erroneous since there was no glycol fluid inside the dry cooling system. During 2016 and 2017, there was no heating operation with both solar tubes 01 and 02, and the valve was kept closed.

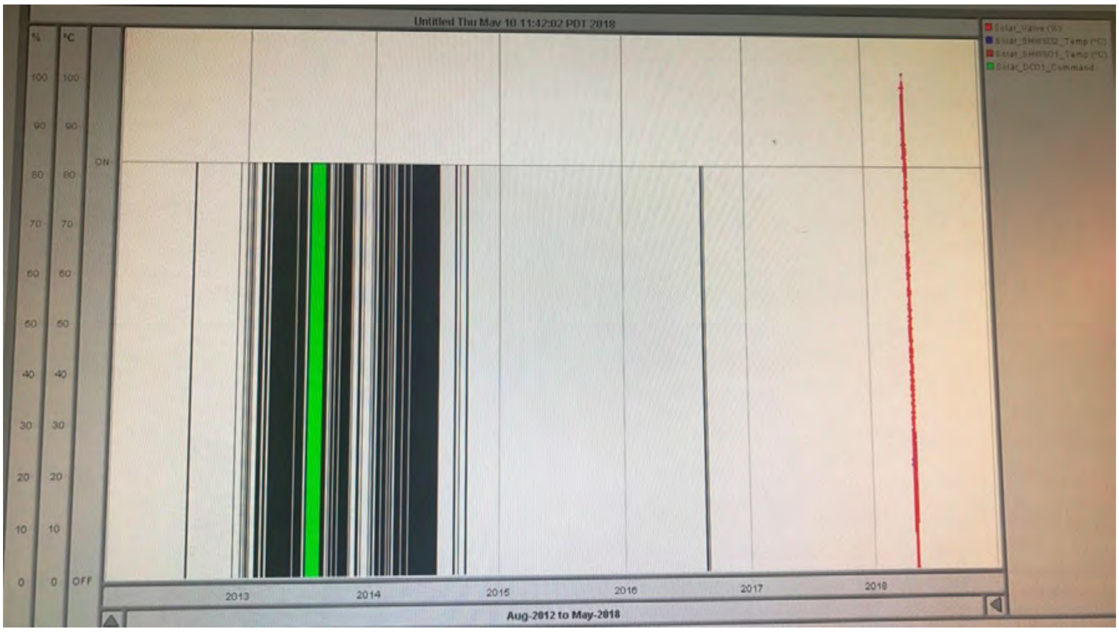


Figure 4.23: Trend log Graph of Solar Panels of Building C

The discrepancy in electricity use was related to the unexpected occupancy behaviours mentioned in the analysis of Building B, as well as the mechanical and operational issues of Building C. The commercial kitchen in Building C provides a hot meal once a day and breakfast three times a week. Energy consumption for preparing these meals was not accounted for in the original energy model. This type of non-regulated plug load is likely to contribute significantly to the actual electricity usage.

Another concern would be the electric baseboard heaters used in suites. Given that most tenants of this building struggle with physical and/or mental illness, their behaviours may result in heating and energy use that doesn't fit the traditional expectation used in the calculations of the energy model. The deviations in mechanical and operational components are discussed in the next section.

Mechanical and Operation Deviations

The following mechanical and operational deviations were noted from the previous mechanical inspection reports and discussions with the building maintenance manager.

Solar System Failure

The solar system was not set in motion from the first day of building operation. As a result, the design did not account for extreme cold weather and resulted in damage to some of the solar vacuum tubes because of freezing. This happened shortly after the system was turned on.

The commissioning phase was also one of the reasons for the system breakdown as it didn't recognize the limitations before occupants moved in. For the panels that remained in good condition, there was no glycol feed tank installed to inject anti-freeze liquid into the tubes for the solar energy transfer process. Moreover, the system was switched on without fluid in the tubes which led to a pump failure.

Air Handling Unit HRV-1

In 2016, the system was diagnosed for having short cycling of the compressor. Furthermore, the heat wheel was exposed to the unfiltered air. Short cycling was expected to cause significant energy loss because set-point was difficult to achieve and subsequently the compressor had to operate continuously. With unfiltered air entering the heat exchanger core, there was a risk that unhealthy air was being supplied to indoor areas. This was a major concern because of the human health risk.

Another critical issue reported in 2016 was that the HRV-1 unit was not able to provide free cooling for the building. This problem was not resolved because of the high maintenance fees. The corresponding record could not be found because the DDC system used for Building C did not save historical data for more than one week. However, the recent trend data shown in Figure 4.24 on the control strategy for free cooling/heating provides some insight.

Since May is not typically considered as summer or winter weather, running the heat wheel to warm the rooms during this period is not necessary. In contrast, the heat exchange core cycled on and off during the night from 10 pm to 6 am in May. The supply air temperature set-point was 18.3°C, which was lower than the actual supply air temperatures during most of the night. This suggests that the heat wheel was operational. At the same time, the zone temperature could reach 24°C (shown in the red rectangle in Figure 4.24), from which a waste of energy could be predicted during the actual summer months.

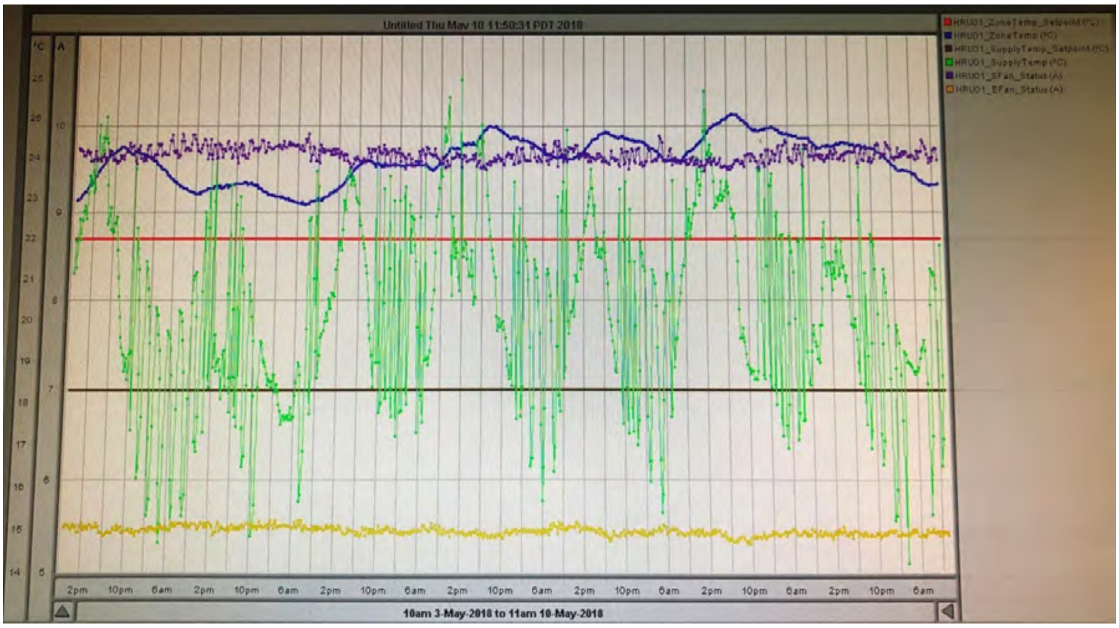


Figure 4.24: Trend log Graph of Heat Recovery Unit of Building C

Gatekeeper DHW System

Gatekeeper is a high-temperature tank that is equipped to deliver hot water to the fixtures. The gatekeeper tank is used to eliminate Legionella bacteria in tempered water. It was shown to be out of service for a period, which was a concern and potential risk to the health of the occupants.

Split Air Conditioners (heat pumps)

In the parkade, poorly installed plumbing and design issues prevented heat from leaving the parkade. This made the area feel like a sauna. The heat accumulated inside the parkade required more ventilation to leave the area. Furthermore, the DDC system did not anticipate common areas requiring free cooling in the summer and hence was not programmed for such a scenario.

Building Energy Performance Index Comparison

From the annual EUI comparison above, Building C performed far below the anticipated results. It is essential to compare the EUI of Building C with benchmark buildings. Considering that the solar system of Building C was abandoned, the natural gas consumption was within +/-15% range of the baseline model. Nevertheless, for both years it consumed three to five times more gas than the baseline building. In comparison with BEPI for the building type MURBs, it utilized two to three times more gas and electricity but consumed around 30% less energy compared to HCSA and AFS.

Building C offered hot meals once a day, three breakfasts a week, and individual health care support. As such, this building is more complex than a typical residential building. It is recommended that the inputs to the energy model are modified according to the characteristics of different building types.

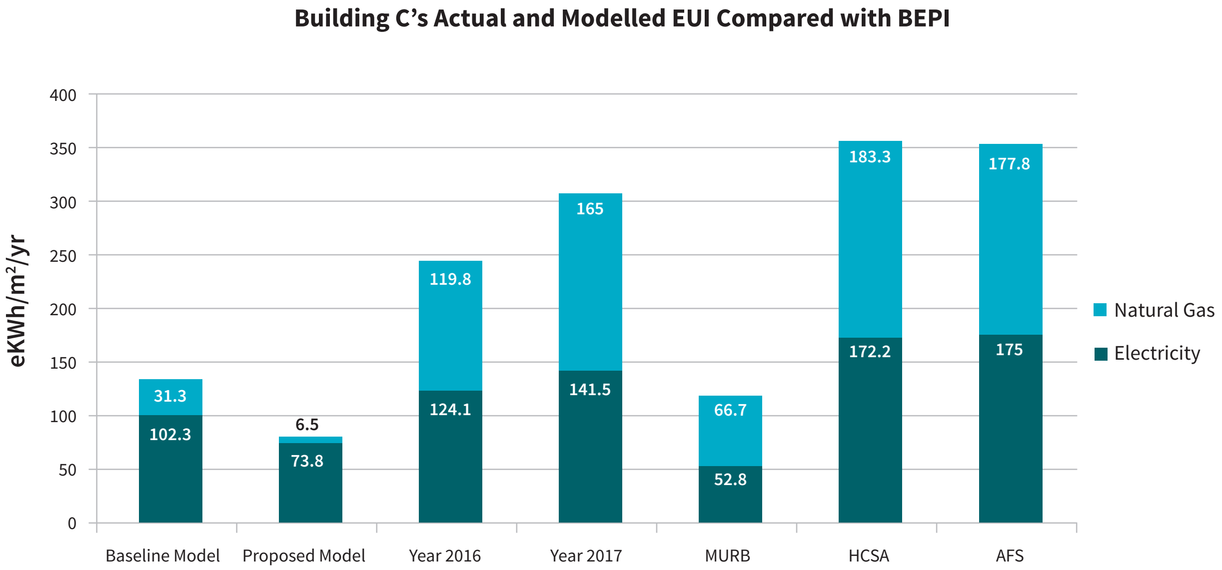


Figure 4.25: BEPI comparison of Building C

Effects of Weather on Results

For the energy model, daily temperatures from 2016 and 2017 were compared with the 30-year average weather data. For 2016, HDD was 14.9% less than the 30-year average. However, Building C utilized 68.2% more electricity and 1753.8% more natural gas based on the energy model results. A regression analysis was performed to explore the interrelationship between heating degree days and actual energy usage.

The energy model had an R^2 of 0.9016, signifying a strong relationship between HDD and energy consumption. The R^2 for 2016 was 0.6737, which is lower than the reasonable coefficient of 0.7.

The building uses electric baseboard heaters in the suites, and tenants have full control to adjust the temperature. The reason for the weak correlation is that occupants often kept electric baseboards on and left windows open in winter. In this case, extra electricity would dissipate with the poor heating control procedure. The poor condition of the solar systems for preheating DHW had a huge impact on the total natural gas consumed and could be another explanation for the weak correlation. The baseload energy for 2016 was approximately 170eKWh/day more than the energy model, which may be partly the result of excluding some non-regulated plug loads.

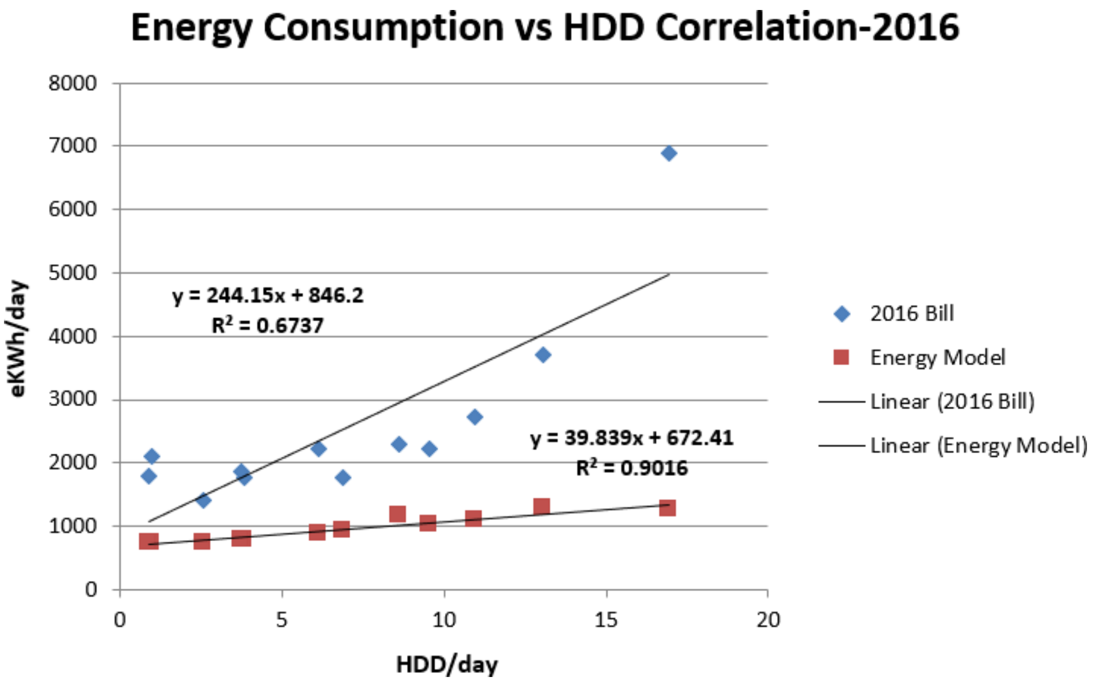


Figure 4.26: Effects of Weather on Building C for 2016

In 2017, the energy consumption had a much better fit for HDD, with R^2 of 0.8771. People kept their windows closed in the colder weather conditions resulting in the building performing close to the model. The underlying assumption in the models is that people will keep their windows closed during winter. However, people often leave them open unless it is very cold.

The electricity consumption was much higher than the model because of the heat wheel cycling during summer nights. According to the monthly natural gas consumption trend for a calendar year shown in Figure 4.28, it is evident that colder days consumed more gas and had higher DHW demand. It parallels the strong relationship between energy consumption and high-temperature days.

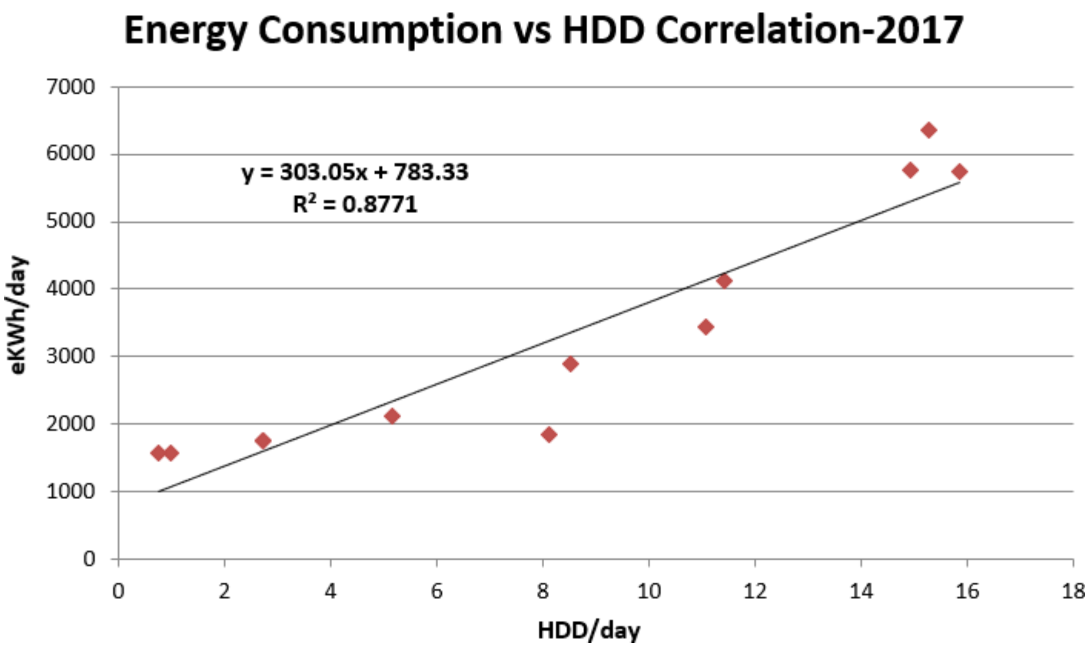


Figure 4.27: Effects of Weather on Building C for 2017

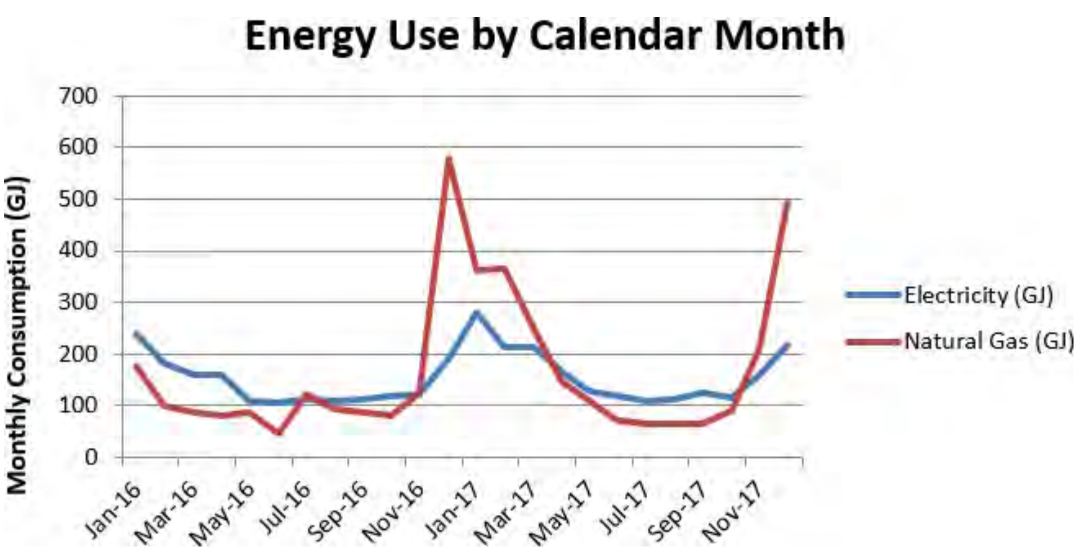


Figure 4.28: Monthly Utility Data by Types of Building C

Monthly Electricity Consumption Comparison

Figure 4.29 and Figure 4.30 show the comparison between monthly modelled results and electric utility bills for 2016 and 2017 respectively. For 2016, the three biggest differences occurred in January (67.7%), February (60.2%), and April (67.5%). In 2017, the three biggest differences were greater than 2016 amounts: January (95.1%), February (88.5%) and March (83.5%). This was generally due to the colder weather in 2017 and unexpected occupant behaviour. It is recommended that future energy modelling should take supportive housing characteristics into account to enable an accurate prediction of consumption data.

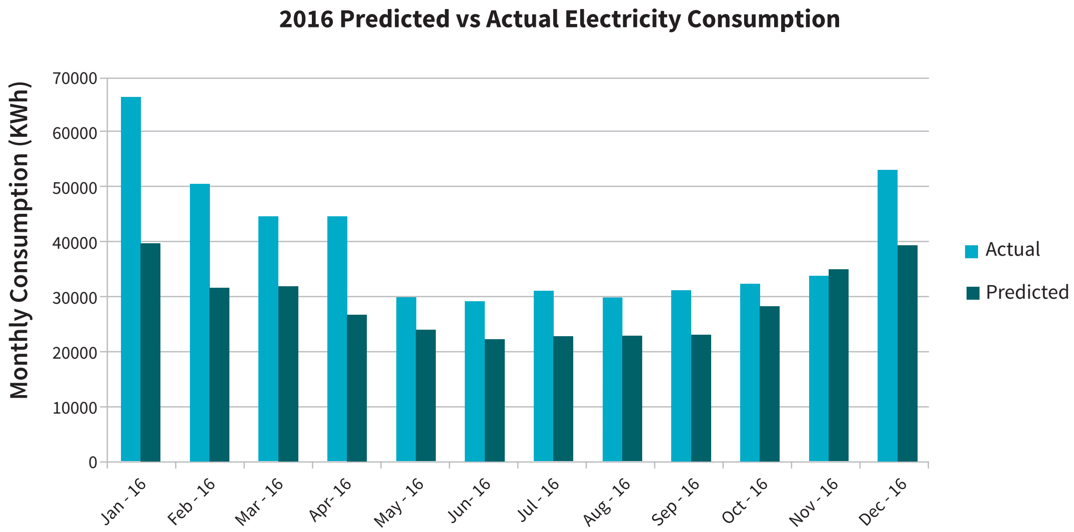


Figure 4.29: Electricity Consumption Comparison for 2016 of Building C

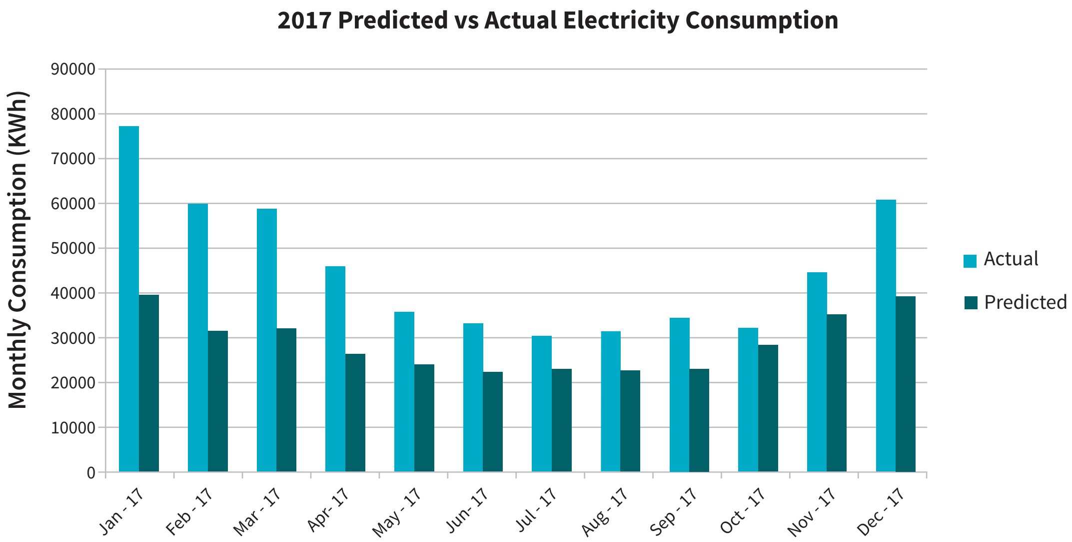


Figure 4.30: Electricity Consumption Comparison for 2017 of Building C

Recommendations

- Careful and proper installation of equipment is one of the most critical factors to ensure the smooth operation of mechanical systems. Based on learnings from the solar system failure of Building C, working with experienced contractors is key to ensure an accurate installation process.
- Add sensors to equipment that is likely to break down or operate abnormally and program its alarms in the DDC system.
- Review and tune the control sequences of HRV-1 to prevent excessive heating energy consumption during summer nights.
- Professional and experienced contractor teams are recommended to design and build LEED Gold buildings with complex mechanical systems.

- Recommissioning is recommended for Building C. The solar system being abandoned, the dry cooler not functioning, and various issues that emerged were a result of the ineffective commissioning process.

4.4 Case Study: Building D

4.4.1 General Description

Building D is an eleven–storey sustainably built high-rise in Vancouver, British Columbia. The 147-unit residential building offers supportive housing. The building was designed as two parts with eleven and six floors in an "L" shape structure. Along with the suites, it has an administrative office on the first level with a total floor area of 9,476m^2.

A sub-basement was designed to promote less dependence on cars and has only 18 parking spots and 123 covered bicycle storage slots. A broad courtyard wrapped around the backside of Building D provides a beautiful activity area for tenants. Various amenity spaces such as gardens, lounges, libraries, and dining areas are spread across different floors.

Common spaces on the main floor are covered with large floor-to-ceiling windows that allow abundant sunlight inside. This helps to lower lighting consumption and heat demand during cold sunny days. High window placement in units maximizes sunlight penetration and contributes to the overall livability. All non-emergency interior lighting is controlled automatically according to a scheduled business hour. With well-designed irrigations system and specific plant selection, the need for potable water for irrigation has reduced by over 50%. Building D has been occupied since 2013 and received LEED Gold certification under LEED Canada-NC 1.0 in 2014.

4.4.2 Envelope and Construction

The framing and materials were selected for their long lifespan with an expected service life of at least 50-years. All reinforcement bars in the building are made from 100% recycled materials and manufactured regionally. 54% of the roof area is covered with vegetation, which reduces the urban heat island effect to some extent. The vegetated roof creates a natural ecosystem and minimizes energy loss by absorbing solar heat in summer and limiting heat loss in winter. It also protects the waterproofing membranes from damage resulting from extreme weather conditions and extends the overall life of the roof.

4.4.3 Mechanical System

Building D participated in a Neighborhood Energy Utility (NEU) program to reduce reliance on electricity and fossil fuels. It is in a district heating system with renewable heating energy restored from raw urban wastewater and solar energy collected from the roofs of neighbourhood buildings.

The NEU contributes significantly to the GHG reduction and offers a 50% emission reduction compared to conventional peer buildings. A total of 70% of energy can be recovered annually from the NEU [88].

Table 4.11: Mechanical System Specifications of Building D

HVAC System Specifications	
Temperature Set-point	Heating set-point: 21°C Cooling set-point: 24°C
Ventilation Air Handling Unit	HRV-1: 100% outdoor air ventilation with heat recovery supplying preconditioned air to residential suites and corridors MUA-1: The kitchen ventilation system with heating and cooling determined by FCU-5 MUA-2: 100% outdoor air ventilation serving the first level
Space Heating System	HRU-1 supplies conditioned air to suites and corridors Radiant in-floor heating in residential suites Radiant heating panels in stairways and laundry rooms Distributed fan coil heating systems (FCU-1 to FCU-11) in administrative offices and amenities
Space Cooling System	Split DX cooling units (FCU-1 to FCU-11) deliver cooled air to shared spaces and offices on the ground floor
Central Plant Specifications	
Heating Plant	Solar thermal panels system NEU heat exchanger
Cooling Plant	N/A

The NEU works similarly to a geothermal heating loop that moves heat from wastewater to surrounding buildings. The heat transfer is achieved using a heat pump system complemented by gas-fired boilers as auxiliary heating during cold days. The refrigerant circulating in the heat pump absorbs heat from sewage and evaporates into a gas. The evaporated gas then passes through the compressor and is converted to high pressure and temperature gas. The heat is distributed to underground pipes connected to neighbourhood buildings via the condenser. After transferring heat to pipes, the refrigerant gas condenses back into the working fluid to start the cycle again [89]. The heat exchanger of Building D takes thermal energy from NEU to heat the circulating water in hydronic coils for fan coil units and a radiant heating system. The DDC system modulates NEU control valves to maintain heating plant supply temperature at set-point.

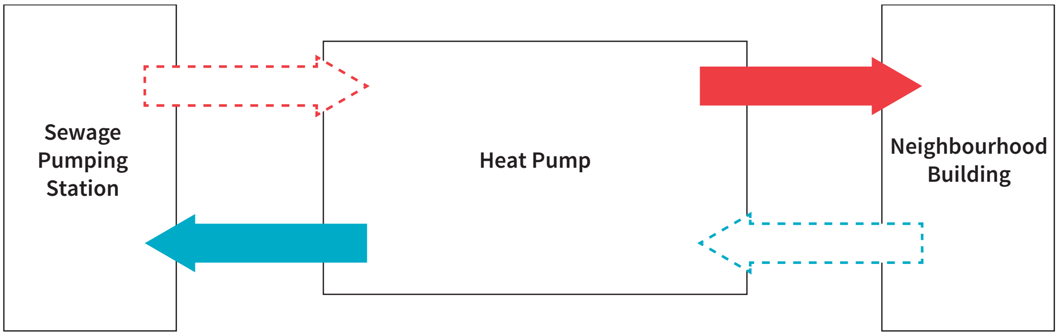


Figure 4.31: Schematic of NEU Working Principle

The heat recovery unit runs all round the year to provide fresh air and warm air, preheated by a heat pipe, to the building. In heating mode, the DDC system modulates the control valve to maintain the supply air temperature at 23.5°C. Free cooling is not available since the unit cannot control the tilt angle of the heat pipe to disable heat recovery action.

In the MUA-1, the ecology unit and exhaust fan are activated simultaneously when the grease hood is switched on. In heating mode, the MUA-1 heating control valve adjusts to discharge supply air temperature at 23.5°C. FCU-5 operates when MUA-1 is running for additional space heating. During cooling mode, the control valve modulates to keep supply air temperatures at reset set-point according to the FCU-5 schedule.

MUA-2 provides 100% outdoor heated air to the first-floor common areas when they are in use. The supply air temperature set-point is primarily achieved by a hydronic heating water control valve and supplemented with a heating coil pump if the heating demand cannot be satisfied. Solar panels supplemented with the NEU system prepare heating to air-handling units (HRU-1, MUA-1 and MUA-2). When the solar panel loop temperature is not capable of complying with the demand, the DDC system triggers the NEU loop water to mix with the solar loop water for providing higher water temperature to air handling units.

When the DCC signals the need for heating or cooling, the fan coil units are independently switched on. The FCUs have a gateway interface to the DDC system for control of various functions, including occupied/unoccupied mode, temperature of the room, room temperature set-point, fan status monitoring, and air conditioning operation. The outdoor air damper for FCUs remains closed when in the unoccupied mode.

4.4.4 Domestic Hot Water System

Both solar panels and the NEU system are DHW heating sources for Building D. The rooftop solar thermal system can reject heat to the NEU system when solar panels loop temperature exceeds 90°C. The solar panels work as the primary preheating source for DHW. When the water temperature difference between the solar loop and preheat storage tanks is greater than 3°C, preheated water flows into PHT-1 to PHT-8. The NEU heat exchanger has a control valve on its district side to modulate water flow into DHW storage tanks when the water temperature in DHWT-4 is lower than 55°C. If the NEU supply cannot satisfy the DHW heating demand, the DDC system forwards the command to the heat storage tanks via natural gas.

Table 4.12: DHW System Specifications of Building D

DHW System	Solar heating system Preheat storage tanks PHT-1 to 8 NEU heating exchanger Gas-fired DHW storage tanks DHWT-1,2,3,4 Low flow fixtures

4.4.5 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

The utility data shows a total of 59.9% and 69.5% higher electricity and natural gas consumption than the proposed model for 2016 and 2017, respectively. This gap was partially a result of energy modelling inaccuracy resulting from not taking the electricity consumption of residential units into account. Furthermore, separate meters for each unit are not installed, which restricts the recording of electricity consumption of each suite. In this research, the discrepancy between the first year's operational data and the proposed model of – 255MWh was assumed to be the proposed residential electricity usage. Subsequently, after calibrating the model, the performance gap reduced to 22.1% and 29.4% for 2016 and 2017, respectively, which is slightly above the accuracy level of +/- 15%.

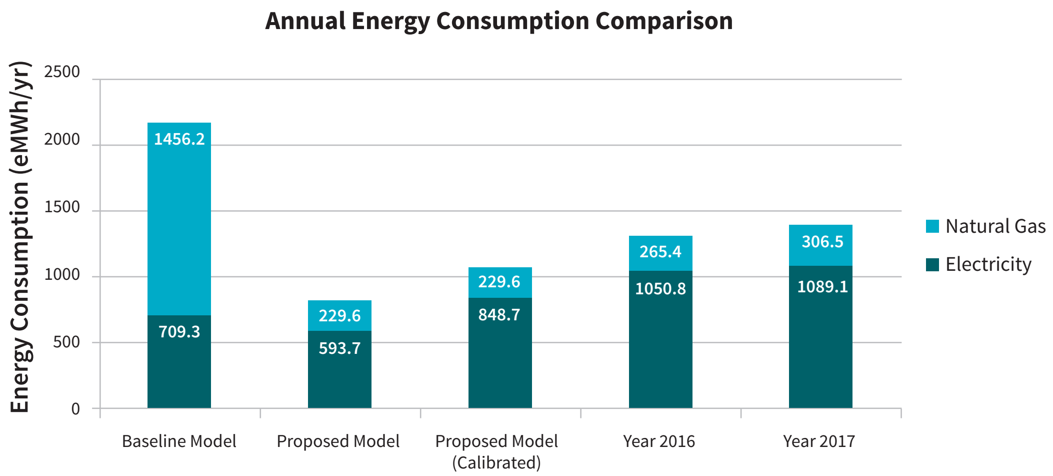


Figure 4.32: Annual Energy Consumption Comparison of Building D

By comparing the actual 2016 and 2017 Building D consumption data with the anticipated amounts, 23.8% and 28.3% more electricity was consumed, and 15.6% and 33.5% more natural gas was consumed for the two years, respectively. There were no substantial equipment failures or operational issues reported by the maintenance manager. The main concern was the unpredictable behaviours of occupants, which were identified through discussions with building staff.

Some occupants broke temperature sensors, opened windows in the winter, blocked smoke detectors, and smashed lights in corridors. Another consideration was that the energy modelling excluded non-regulated loads (the need from the commercial kitchen, elevators, and the parkade) in the simulation process. Moreover, the modelling standards for social housing were not adequate that led to imprecise inputs for some parameters such as the intensity of DHW use.

Table 4.13: Electricity and Natural Gas Consumption Comparison of Building D

Electricity	Natural Gas
The Proposed Model + 23.8% = Year 2016	The Proposed Model + 15.6% = Year 2016
The Proposed Model + 28.3% = Year 2017	The Proposed Model + 33.5% = Year 2017

Building Energy Performance Index Comparison

The comparison of Building D's actual usage data with the benchmark building showed significant fossil fuel savings. Although both years had a higher natural gas usage than proposed, Building D utilized only around 20% of the gas because of the support from the NEU system compared to the baseline building. Furthermore, it saved more than half of the gas energy compared to BEPI for the MURB type. The actual electricity consumption was higher than the benchmark conventional MURBs and marginally higher than the baseline model. However, it was within a reasonable range with around 35% less electricity consumption than HCSAs and AFSs.

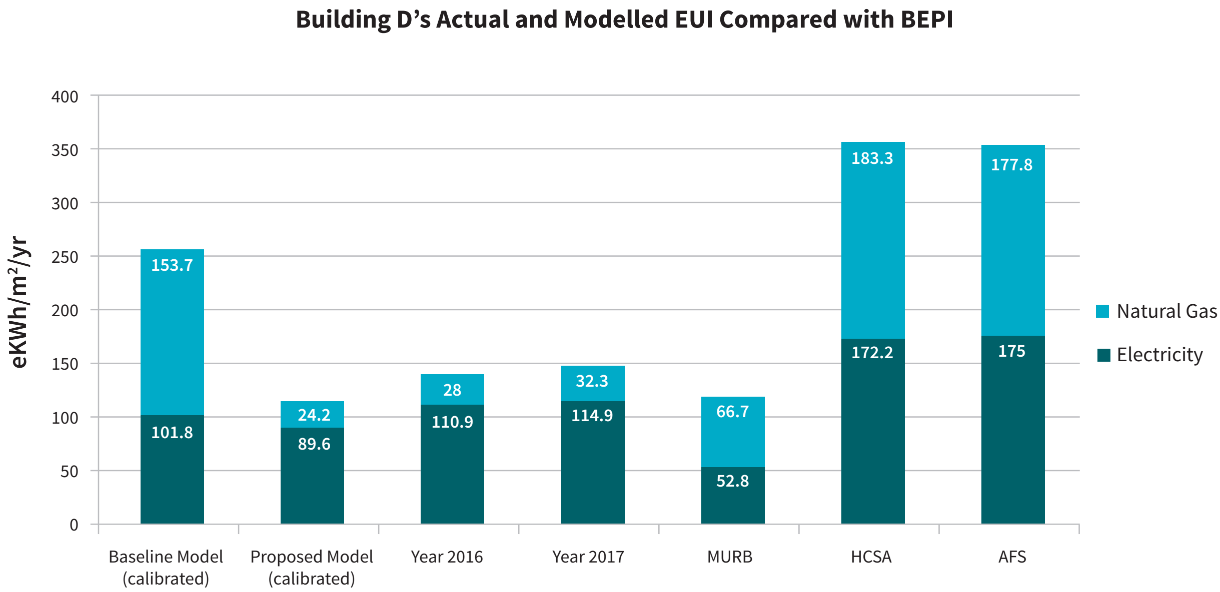


Figure 4.33: BEPI Comparison of Building D

Effects of Weather on Results

The daily temperatures for 2016 and 2017 were compared against the 30-year average weather data for the energy model. In 2016, HDD was 14.9% less than the 30-year average yet 23.8% and 15.6% more electricity and natural gas were consumed, respectively. In 2017, there was 2.2% less HDD overall compared to the weather data applied in the energy model. However, a total of a 29.4% performance gap was noted in 2017. A regression analysis was carried out to investigate if the energy consumption in 2016 and 2017 was plausible.

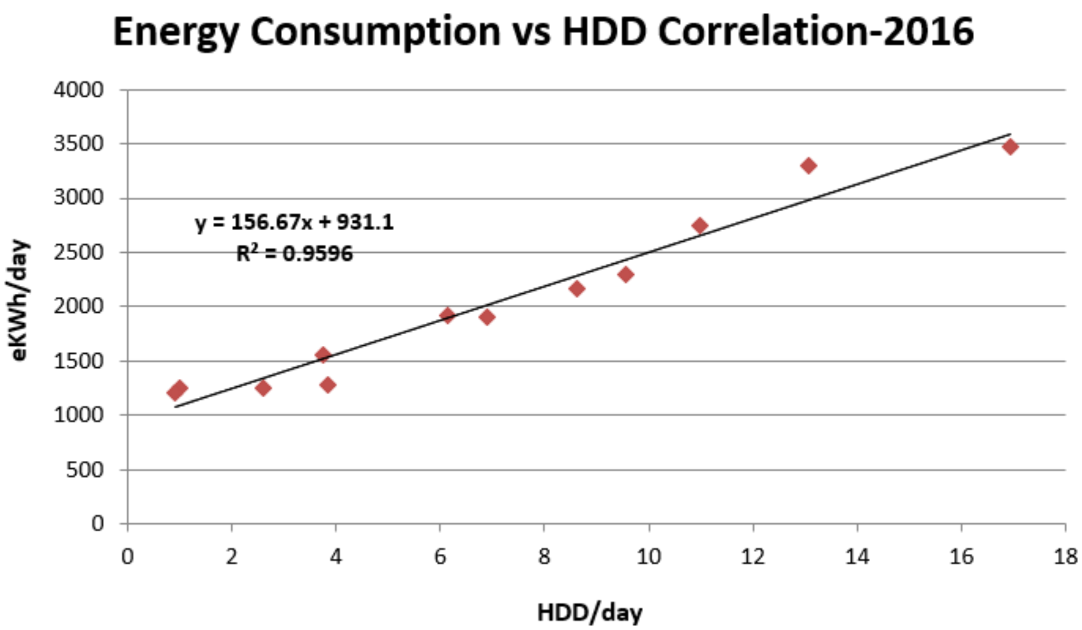


Figure 4.34: Effects of Weather on Building D for 2016

Both 2016 and 2017 featured a high value of R^2 of 0.9596 and 0.9565, respectively. It indicates a strong interconnection between HDD and energy consumption. The trend line for both years shows the daily energy consumption closely following the growth of HDD/day. The energy used by calendar month further shows that the electricity utilization does not fluctuate with the weather, whereas natural gas consumption parallels the seasonal changes. This is mainly dependent on the heating system of Building D, which uses renewable energy, the NEU system for space heating, and a DHW heating source. For the NEU system, only natural gas consumption was included in the research. This precise match proves that the design intention was met because of the stable operation and control of equipment as well as regular and quality maintenance by building staff.

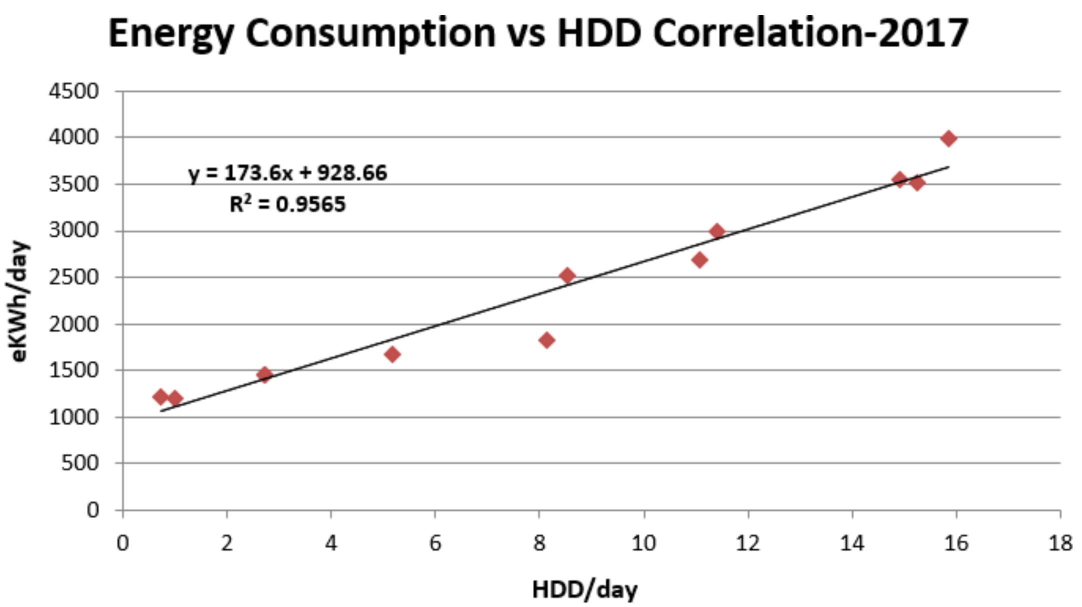


Figure 4.35: Effects of Weather on Building D for 2017

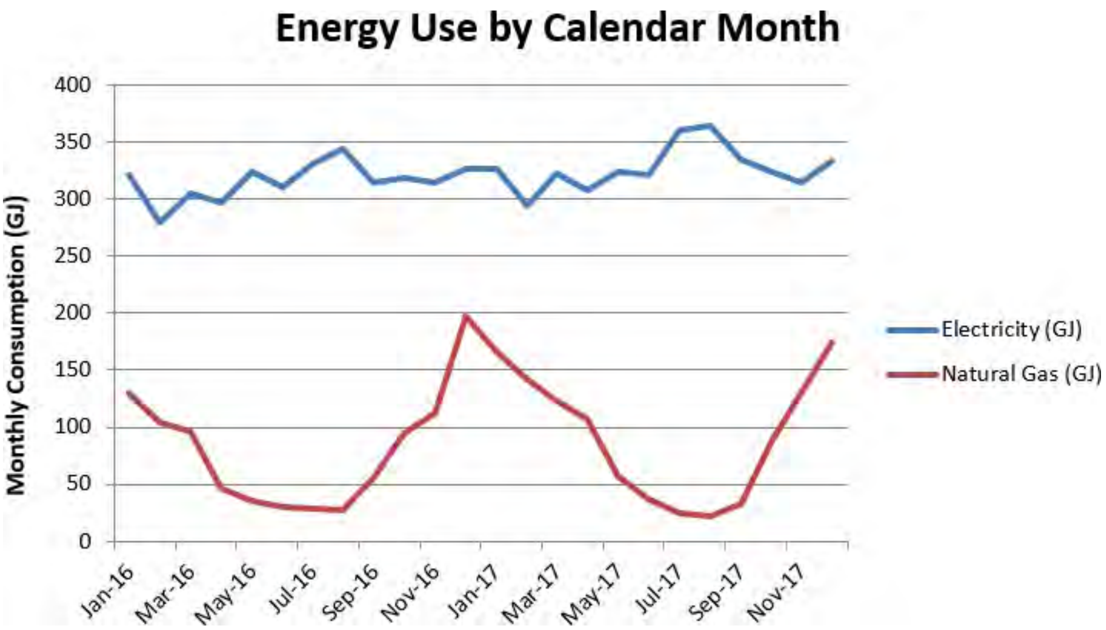


Figure 4.36: Monthly Utility Data by Types of Building D

Monthly Electricity Consumption Comparison

The electricity comparison between 2016 and 2017 was performed to verify the normal operation of building facilities. From Figure 4.37 shown below, the greatest discrepancy occurred in July, August, and September. This can be primarily attributed to the changes in weather conditions during the two years, which specifically had a total of 57% more CDDs in 2017 [90].

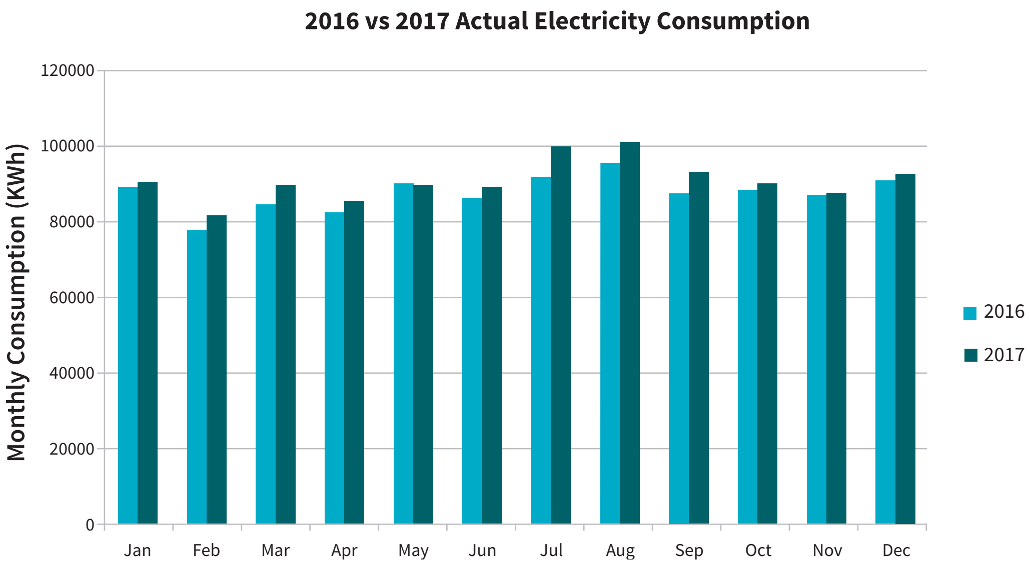


Figure 4.37: Electricity Consumption Comparison Between 2016 and 2017 of Building D

Recommendations

- The energy model did not consider the electricity use of residential suites into its calculation. It is recommended that all the energy modelling processes include as much information as possible to avoid inaccurate evaluation for any research.
- Use specific modelling packages (for example, unique tenant schedules, tendencies to open windows and typical shower durations) to model the energy use in social housing buildings.

4.5 Case Study: Building E

4.5.1 General Description

Building E is a six-storey sustainable, mid-rise residential supportive housing building located in Vancouver, British Columbia. The building has a total floor area of 4,208m^2 with a patio, four retail stores, amenity spaces with computers, and a piano on the ground floor. Eighty studio apartments are available and ten of them are wheelchair accessible. A commercial kitchen provides a hot meal once a day. Large windows in common spaces economize lighting consumption during the daytime. Building E has been occupied since 2010 and received LEED Gold certification under LEED Canada-NC 1.0 in 2013.

4.5.2 Envelope and Construction

Building E utilizes mainly masonry products for the exterior walls with a small portion of metal siding for walls on the first level of the building. The clay masonry and metal siding products are energy-efficient design materials due to their durability, lifespan of at least 50 years, and limited maintenance requirements. The materials used for construction consist of 13% recycled content. The construction process was executed in an environmentally conscious way by diverting 75% of waste materials from landfills.

Table 4.14: Envelope and Construction Specifications of Building E

Exterior Wall (hr · ft^2 ·° F/Btu)	Clay, with steel stud inside, R=23 Clay, with concrete inside, R=23 Metal panels, with steel stud inside, R=12 Metal siding, with steel stud inside, R=12 On average, R=19.31
Roof (hr · ft^2 ·° F/Btu)	Flat roof with concrete inside, R=30 Sloped metal roof with concrete inside R=30
Overall Glazing U-value (Btu/hr · ft^2 ·° F)	U assembly=0.518 SHGC=0.36
Lighting Controls	Automatic control
Lighting Power Density (W/ft^2)	Average = 0.88 11% less than the baseline model
Plug Loads (W/ft^2)	Based on the space function

4.5.3 Mechanical System

Table 4.15: Mechanical System Specifications of Building E

HVAC System Specifications	
Temperature Set-point	Heating set-point: 18°C Cooling set-point: 25°C
Ventilation Air Handling Unit	MAU-1: 100% outdoor air ventilation with heat recovery supplying preconditioned air to individual suites and main floor spaces
Heat Recovery Effectiveness	Heating recovery efficiency=83.7% Cooling recovery efficiency=79.5% Average=82%
Ventilation Rate (ACH)	1.0
Space Heating System	Electric baseboard heating for units Auxiliary electric baseboard heating for stairwells MAU-1 supplies preconditioned air to suites and corridors Ceiling mounted heat pumps serving amenity and retail areas on the first level
Space Cooling System	Ceiling mounted heat pumps serving amenity and retail areas on the first level
Central Plant Specifications	
Heating Plant	Vertical geothermal heat pump Distributed heat pump loop On average, heating COP=3.23
Cooling Plant	Vertical geothermal heat pump Distributed heat pump loop On average, cooling COP=4.73

The air-handling unit MAU-1 on the roof runs highly efficiently with VSDs controlling the airflow of supply and exhaust fans. The ventilation for the main floor spaces is disabled by closing the corresponding dampers according to a control schedule. The airflow sent to residential units is reduced by 40% between 11 pm to 7 am. When the average building temperature achieves 25°C in summer, the DDC system resets the supply air temperature to the minimum set-point of 13°C. During heating seasons, when the average building temperature falls below 18°C, the DDC system commands the supply air temperature to discharge at 25°C.

The high-performance mechanical system benefits from the installation of a vertical geothermal closed loop, including a ground source heat pump and multiple water-to-water/air heat pumps. The working principle of a ground source heat pump is similar to an air source heat pump with the exception that it extracts heat from the soil instead of the ambient air. The vertical loop is protected from soil temperature change when compared with a horizontal loop because the equipment is buried deep underground.

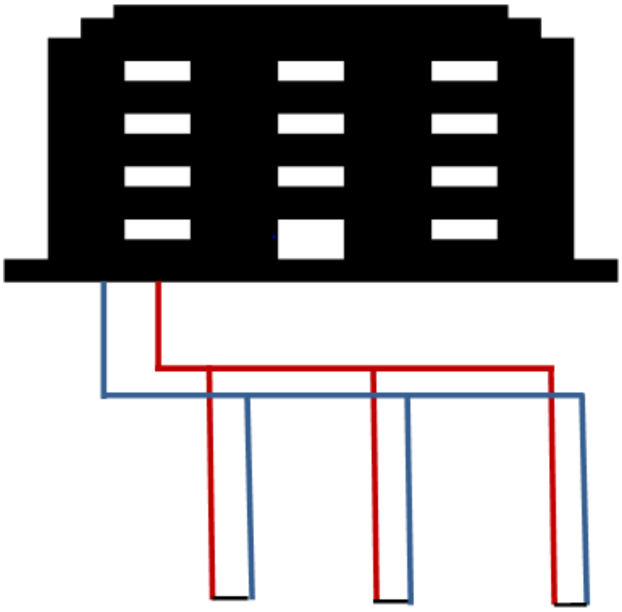


Figure 4.38: Schematic of Vertical Geothermal Loop

The geothermal source side of the loop connects to several distributed heat pump equipment:

1) water-to-water heat pump HP-1 serving the central air unit MAU-1
2) water-to-water heat pump HP-2 serving DHW preheat storage tanks
3) multiple water-to-air heat pumps serving amenity areas, retail stores, and offices on the first floor

Each water-to-air heat pump is equipped with a DDC controller to enable/disable the heating/cooling is supplied to specific zones.

4.5.4 Mechanical and Operation Deviations

The following mechanical and operational deviation record was obtained from the building management system record, and discussions with the building maintenance manager.

Thermal Wheel Operation in Cooling Mode

The control strategy for the thermal wheel of MAU-1 is to activate when the Outdoor Air Temperature (OAT) is lower than 18°C. During summer nights, the HRV wheel cycles between on and off based on the OAT as shown in Figure 4.39 and Figure 4.40. The operation of heat recovery during the cooling season can negatively impact energy consumption and possibly increase the maintenance costs due to equipment wear and tear. Free cooling by disabling the heat wheel is recommended during cooling months.

Figure 4.39: Trend Log Graph of Thermal Wheel Amps during August 2016

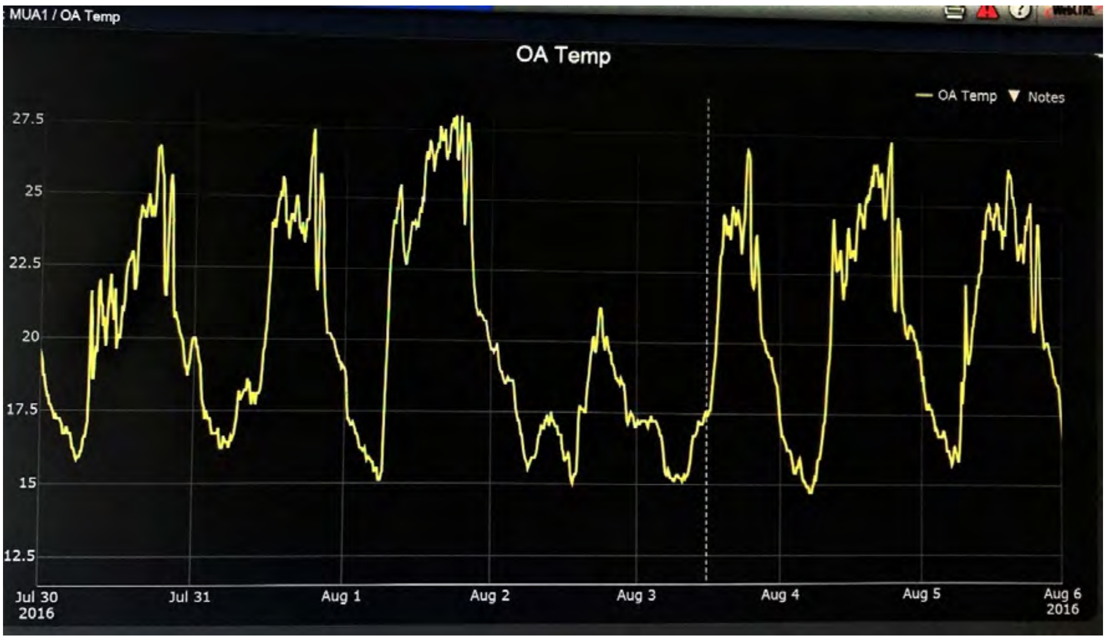


Figure 4.40: Trend Log Graph of Outdoor Air Temperature during August 2016

4.5.5 Domestic Hot Water System

Building E reached the goal of reducing water consumption by nearly half compared to the reference model by installing various high-efficiency, low flow fixtures. Although the three large-capacity DHW preheat storage tanks require HP-2 to operate approximately 12 hours a day, 59% of the energy is saved because of the DHW heating system.

Table 4.16: DHW System Specifications of Building E

DHW System	Vertical geothermal loop
	Water-to-water heat pump HP-2
	Preheat storage tanks DHWT-1 to 3
	Gas-fired water heating tanks DHT-1 and 2
	Single flush low flow water closets
	Low flow lavatory faucets
	Low flow kitchen sink faucets
	Low flow showerheads

4.5.6 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

Building E performed better than the energy model by 29.3% and 19.2% for 2016 and 2017, respectively. Total energy consumption was 58.5% for 2016 and 52.6% for 2017 when compared to baseline building from NECB standards. During 2016, both the electricity and natural gas consumption were less than the proposed building. The 29.3% discrepancy above the accuracy range +/-15% can be a result of the specific weather conditions in 2016, which is discussed in subsequent sections.

In 2017, 24.2% less electricity was used but had almost the same gas used as the proposed model. The energy consumption resulting from laundry machines, the commercial kitchen, and the elevator were added to the proposed and baseline model for calibration according to the Measurement and Verification (M&V) analysis. The unexpected occupant behaviours did not considerably affect the additional energy consumption that was recorded.

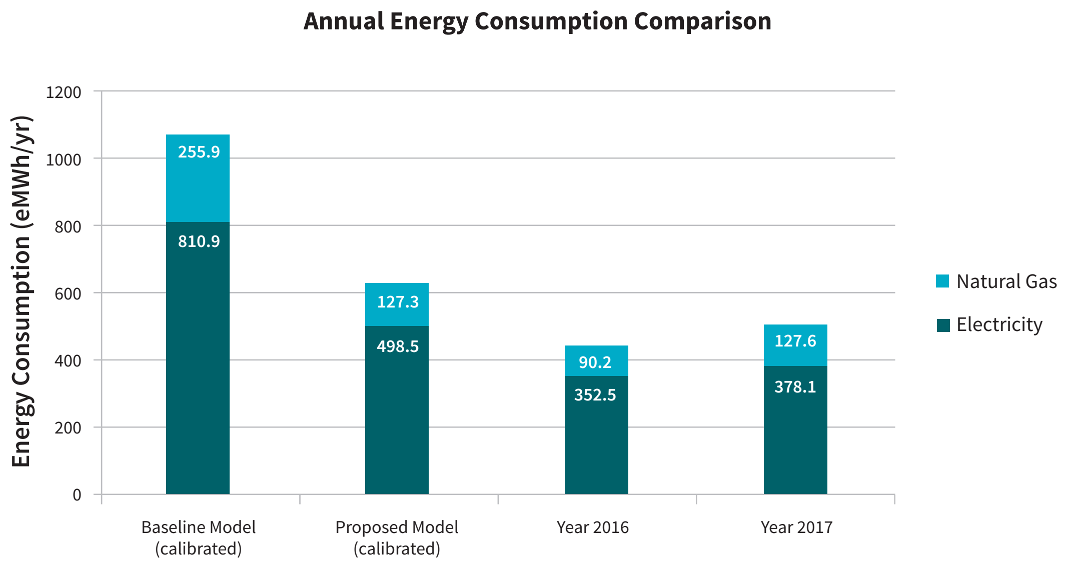


Figure 4.41: Annual Energy Consumption Comparison of Building E

Building Energy Performance Index Comparison

On comparing the energy performance of Building E with BEPI, natural gas consumption is observed to be much lower than conventional peer buildings. For 2016 and 2017, gas utilization was less than half of the BEPI buildings for MURB type. Considering that Building E is more than a residential building with administrative offices, common spaces, and a commercial kitchen, the electricity use being more than 50% higher compared to BEPI is acceptable for a MURB. Moreover, the total EUI for 2016 was 12% lower than the BEPI residential buildings. In contrast, for 2017, the EUI was 0.6% higher than the same benchmark. The utilization of a vertical geothermal loop for mid-rise apartments proved to be an effective method for achieving better energy performance.

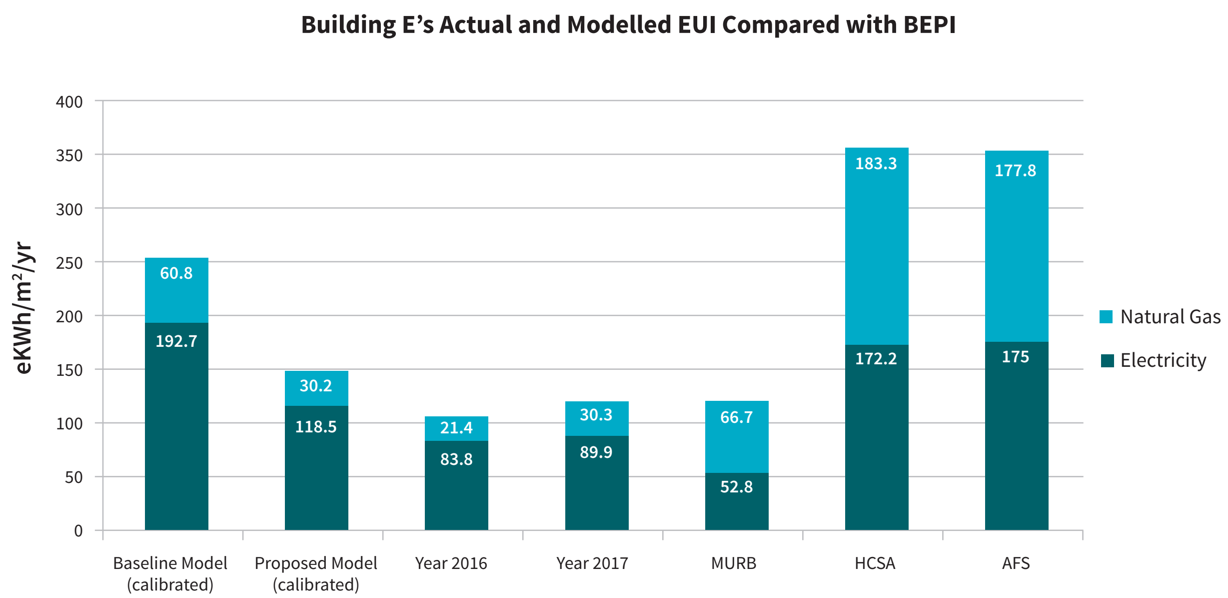


Figure 4.42: BEPI Comparison of Building E

Effects of Weather on Results

The heating degree days (HDD) for 2016 and 2017 were 14.4% and 2.2% lower compared to the 30-year average weather data used in the energy model. Since the performance gap for 2016 and 2017 was not within the accuracy range of 15%, it was necessary to calibrate the proposed model according to the real weather data of 2016 and 2017.

This building is located in a climate zone that is subjugated by the need for heating. The difference in cooling degree days (CDD) and 30-year average weather data was negligible. The primary space heating system for Building E is motorized electricity. The normalization of natural gas consumption was not included during analysis due to its independence from HDD. Accordingly, the space heating energy use of the initial energy model was calibrated based on the annual HDD data for the same location. The discrepancy between the normalized energy model and utility bill was reduced to 25.5% for 2016 and 23.6% for 2017, which are better results than the predictions.

Recommendations

- Review and fine-tune the control sequences of HRV to reduce excessive heating in summer.

4.6 Case Study: Building F

4.6.1 General Description

Building F is an eleven–storey, environmentally-friendly, high-rise, residential supportive housing facility located in Vancouver, British Columbia. The building consists of different types of units: 105 studio units (20 are 30m^2 per unit), five wheelchair accessible units, and 30 units for addiction recovery.

It has a floor area of 4,667m^2 with a variety of common areas on the ground floor. South and west-facing walls of Building F are designed to be shaded with slatted metal overhangs. The horizontal louvres can decrease solar heat gain in summer months, which contributes to the cooling energy-saving and in-suite thermal comfort.

The slatted metal structure allows daylight to enter interior rooms to reduce lighting energy consumption. It also allows sunlight to enter the units in winter to take advantage of heat from solar energy.

The partial curtain wall system is inserted on the main floor facades to maximize daylight. Natural ventilation is enabled through operable windows installed at the end of the corridor on each level. Building F was occupied in 2011 and received LEED Gold certification under LEED Canada-NC 1.0 in 2013.

4.6.2 Envelope and Construction

Thick and well-insulated walls and roofs are one of the most straightforward methods to attain the high performance of a building. Building F utilizes cost-effective brick walls with concrete and steel stud back-up to deliver a stable structure. The mixed-use of composite and masonry cladding enables exceptional weather resistance and takes advantage of recycled material utilization ratio of up to 16%.

Table 4.17: Envelope and Construction Specifications of Building F

Exterior Wall (hr · ft^2 ·° F/Btu)	Brick veneer with steel stud back up, R=23 Brick veneer with concrete wall back up, R=22 Composite wall panels with steel stud back up, R=14 Composite wall panels with concrete wall back up, R=13
Roof (hr · ft^2 ·° F/Btu)	Roof assembly, R=30 Roof deck, R=30 Patio deck, R=30
Overall Glazing U-value (Btu/hr · ft^2 ·° F)	U assembly=0.45 SHGC=0.36
Glazing to Wall Ratio	37%
Lighting Controls	Occupancy sensors
Plug Loads (W/ft^2)	Based on the space function

4.6.3 Mechanical System

The energy recovery unit MAU-1 of Building F runs continuously all round the year to provide fresh and conditioned air to all suites and hallways. Exhaust air drawn from the washrooms into MAU-1 is used to preheat the building. The ventilation unit runs at full speed during the day (7 am to 11 pm) and at a reduced speed during the night (11 pm to 7 am). The specific control dampers for ventilation of the ground floor remains closed at night. The supply air temperature set-point can vary between a minimum of 13°C for cooling and a maximum of 22°C for heating. The energy recovery wheel is activated under the following conditions: 1) In heating mode when the room temperature is higher than OAT but lower than the room temperature set-point; and 2) In cooling mode when the room temperature is lower than OAT but higher than the room temperature set-point.

The distributed water-to-air heat pumps HP-2 to HP-9 are monitored by electronic and programmable thermostats instead of the DDC system. When an area is occupied during the day, the fans in the heat pumps cycle on/off to maintain its temperature. During the night, cooling is disabled and ceiling-mounted heat pumps operate to maintain a minimum set- back room temperature.

The vertical geothermal loop provides heating/cooling fluid to hydronic coils built into the MAU-1 and HP-2 to HP-9. The loop also serves the radiant floor heating system and DHW preheating. Two secondary circulating pumps P1 and P2 work according to the lead/lag order on the geothermal source side. P1 and P2 are variable speed driven pumps that can provide different fluid flow based on the pressure difference between the supply and return pipes.

Table 4.18: Mechanical System Specifications of Building F

HVAC System Specifications	
Ventilation Air Handling Unit	MAU-1: 100% outdoor air ventilation with heat recovery supplies preconditioned air to residential suites and corridors
Heat Recovery Effectiveness	Heating recovery efficiency=79.69% Cooling recovery efficiency=78.62% Average=79%
Space Heating System	MAU-1 supplies preconditioned air to suites and corridors Radiant floor heating for residential suites Electric baseboard heating and force flow heating for stairwells Distributed water-to-air ceiling mounted heat pumps HP-2 to HP-9 heat offices and amenities
Space Cooling System	Distributed water-to-air ceiling mounted heat pumps HP-2 to HP-9 cool offices and amenity rooms
Central Plant Specifications	
Heating Plant	Vertical ground source heat pump with two boilers as back up Distributed heat pump loop On average, heating COP=3.20
Cooling Plant	Vertical ground source heat pump Distributed heat pump loop On average, cooling COP=4.73

The water-to-water heat pump HP-1 connected to a buffer tank serves MAU-1 and the radiant floor system. During the heating mode, the water temperature in the buffer tank is set between 40°C and 49°C by the OAT. During cooling mode, the water temperature in the buffer tank is set between 7°C and 12°C by the OAT. The compressor in the heat pump is disabled when the difference between the heat pump water supply temperature and the buffer tank water temperature is less than 1°C.

4.6.4 Domestic Hot Water System

DHW is preheated by the geothermal loop heat pump HP-10 and stored in the preheat storage tanks ST-1 and 2. HP-10 works to maintain the water temperature of both preheat storage tanks at set-point 52°C. It is activated when the return water temperature is below 46°C and the preheat storage tank's average temperature is below 52°C. DHWT tanks work as the second stage of the DHW heating source. The building uses low flow fixtures such as low flow, single flush water closet, lavatory faucets, kitchen faucets and showerheads.

Table 4.19: DHW System Specifications of Building F

DHW System	Water-to-water heat pump HP-10 for DHW preheating Preheat storage tanks ST-1 and 2 DHW storage tanks DHWT-1 to 3 with electricity input DHW heater DHWT-4 for kitchen plumbing fixtures DHW heater DHWT-5 for the lower zone Low flow fixtures

4.6.5 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

The performance gap observed between the proposed model and utility data for 2016 and 2017 was 45.4% and 50%, respectively. This offset was partially a result of the exclusion of unregulated loads such as lighting and plug-loads from residential suites, commercial kitchen, laundry rooms, elevators and parkades.

Subsequently, the proposed model was calibrated according to sub-metering data from the first year of operation. The electricity consumption for 2016 and 2017 was 5.9% and 3.1% lower than the prediction. The excess natural gas usage during actual operation is attributed to the unexpected inefficiency of the central heat pump system. The HP-1 performance curve used in the energy modelling process needs to be examined and regulated based on real weather circumstances.

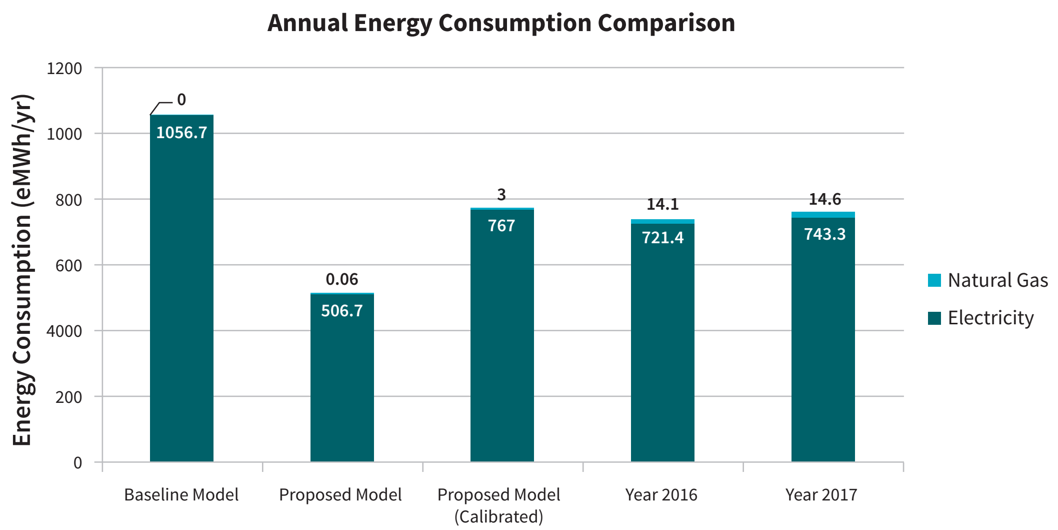


Figure 4.43: Annual Energy Consumption Comparison of Building F

Building Energy Performance Index (BEPI) Comparison

For both years, Building F consumed around five times more natural gas than the proposed model. However, in comparison to the BEPI for MURBs, 95.5% of the fossil fuel consumption was saved by introducing the geothermal heat pump for heating and cooling. The hydro use increased with the reduction in gas usage and was two times higher than typical residential apartments. Considering that the commercial kitchen provides five meals a week and the resource center serves all the tenants, Building F attributes are different than a conventional apartment. The electricity consumption was within an acceptable range of 10% compared to HCSAs and AFSs.

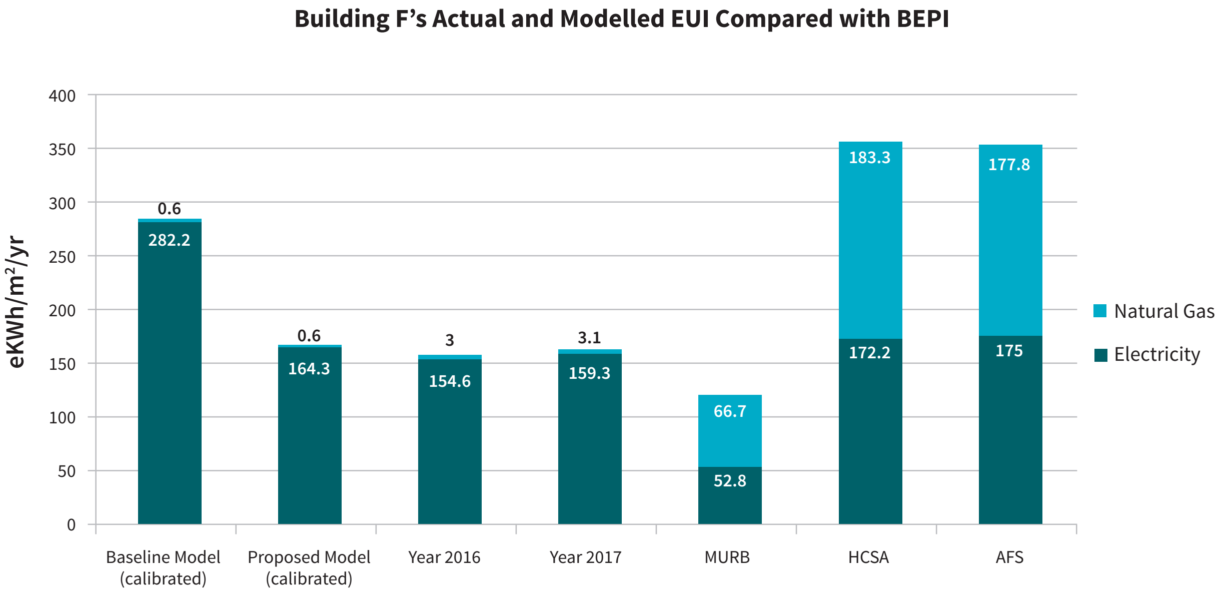


Figure 4.44: BEPI Comparison of Building F

Effects of Weather on Results

The annual energy consumption for 2016 and 2017 for Building F was lower than the predicted model. However, HDD for 2016 was 14.9% lower and for 2017 it was 2.2% lower than the 30-year average weather data used in the modelling process. Calibration of the space heating energy to the weather aberration for the energy model was done to analyze how the equipment was functioning. The building energy used for 2016 was 2.6% lower and for 2017 it was 1.3% lower than the proposed model (regulated), which was within the expected accuracy level of +/-15%.

The regression analysis for both years with R^2 of 0.76 and 0.87 is shown in Figure 4.45 and Figure 4.46. The highest energy use for 2016 happened in February with the third most HDD. During this period, the building used 9.6% more electricity and 47.3% less gas compared to January of the same year. Considering that the performance of the geothermal loop worked as anticipated, the frequent occupant behaviour of opening windows could be the likely cause for these observations. This reasoning is supported by the observation that February was warmer than December and January of 2016.

The year 2017 exhibited a close relationship between energy consumption and HDD with an R^2 of 0.87. The electricity usage firmly followed the heating demand change resulting from seasonal changes, as shown in Figure 4.47.

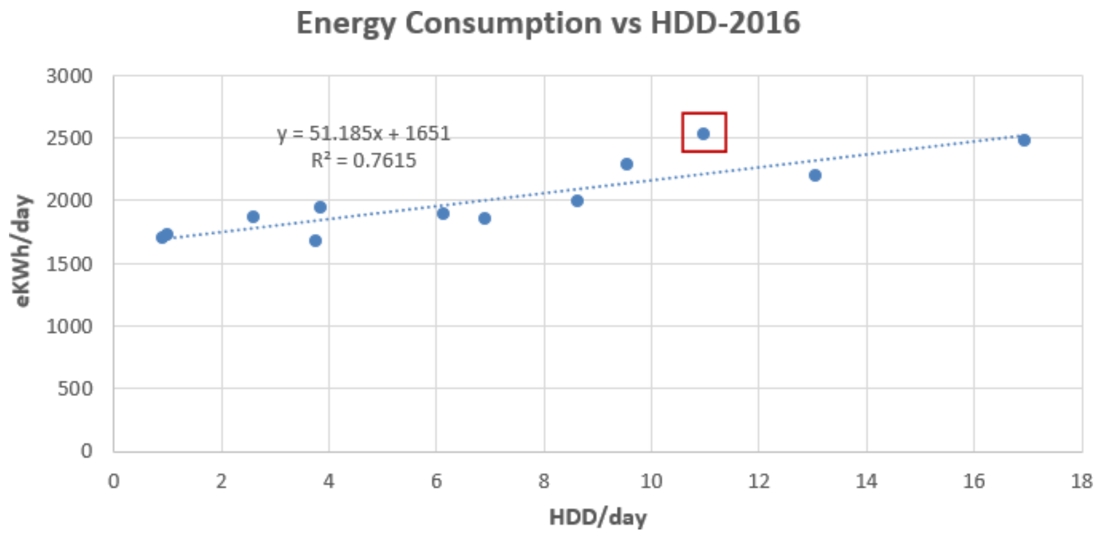


Figure 4.45: Effects of Weather on Building F for 2016

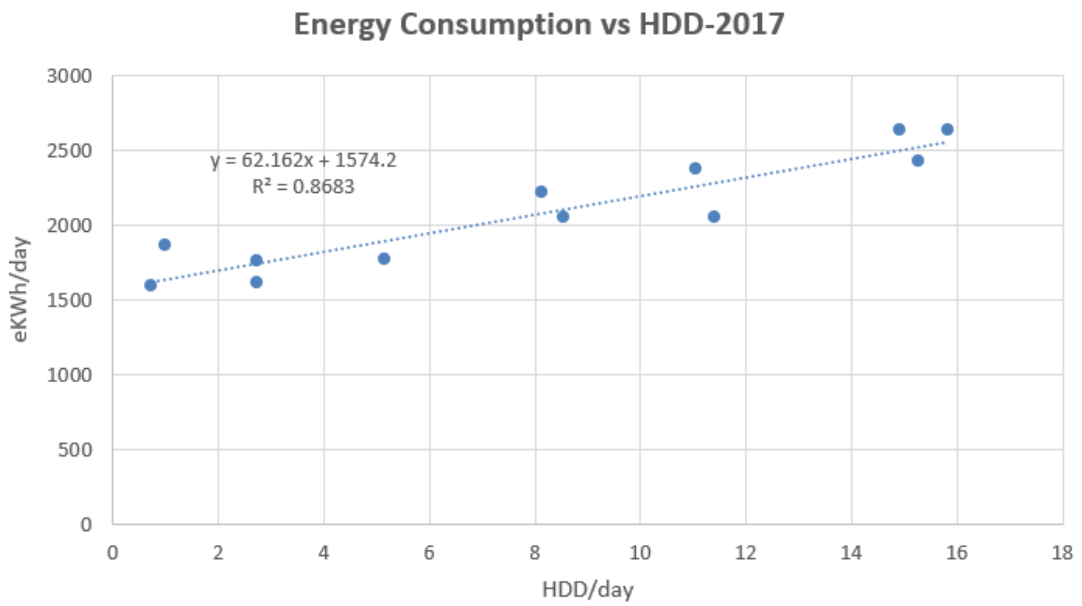


Figure 4.46: Effects of Weather on Building F for 2017

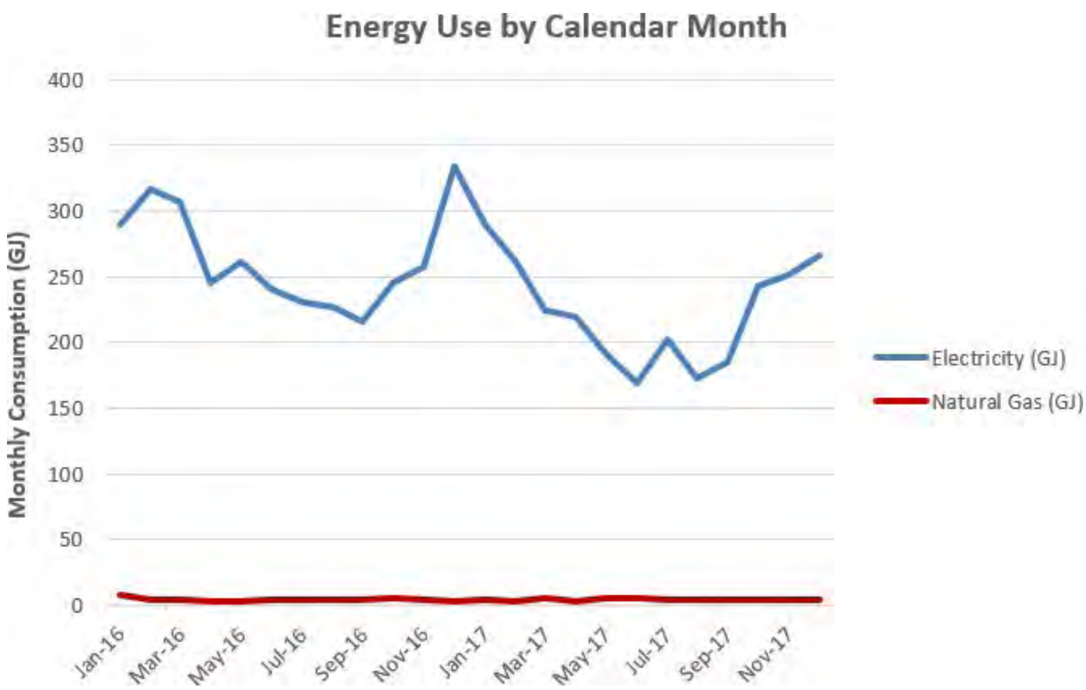


Figure 4.47: Monthly Utility Data by Types of Building F

Monthly Electricity Consumption Comparison

The computer storing data on electrical consumption was hacked a few months before the case study and led to the loss of all historical data. Consequently, the monthly hydro bills between 2016 and 2017 were used to verify whether the building was operating normally. The resulting comparison is shown in Figure 4.48 and Figure 4.49.

The data suggests that significant discrepancies between electrical consumption between 2016 and 2017 happened in three months. In 2017 months of January, October, and November 22%, 20.9%, and 19.1% more electricity was consumed than 2016 respectively. This was primarily due to the increase of HDD in 2017 with 21.2% more in January, 17.8% more in October, and 28.2% more in November as shown in Figure 4.49.

Although February and March 2017 also had more HDD, the electricity consumption trend did not follow the HDD pattern. Unpredictable variables such as occupant behaviours, equipment maintenance, and repair schedules could be a possible explanation.

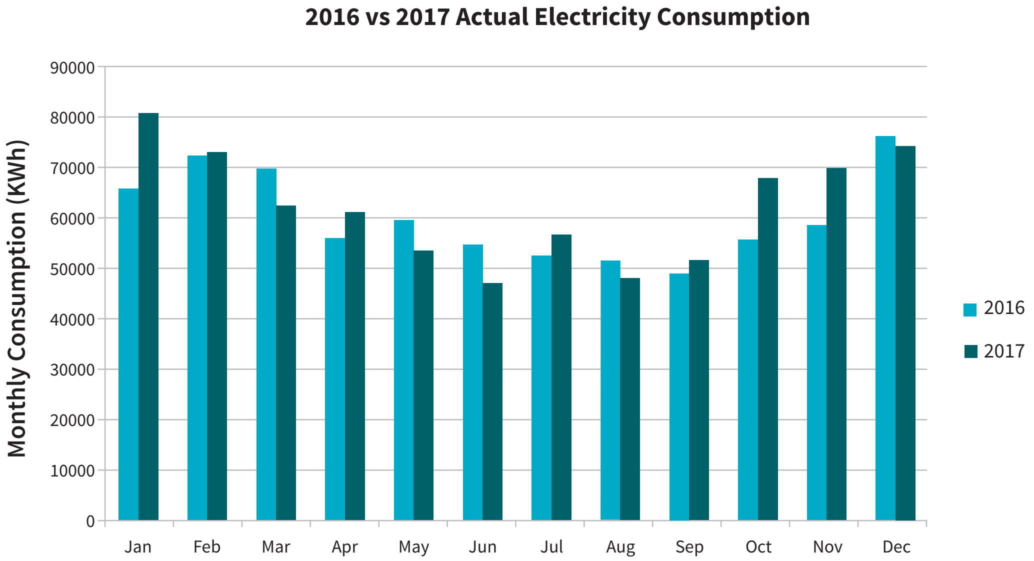


Figure 4.48: Electricity Consumption Comparison between 2016 and 2017 of Building F

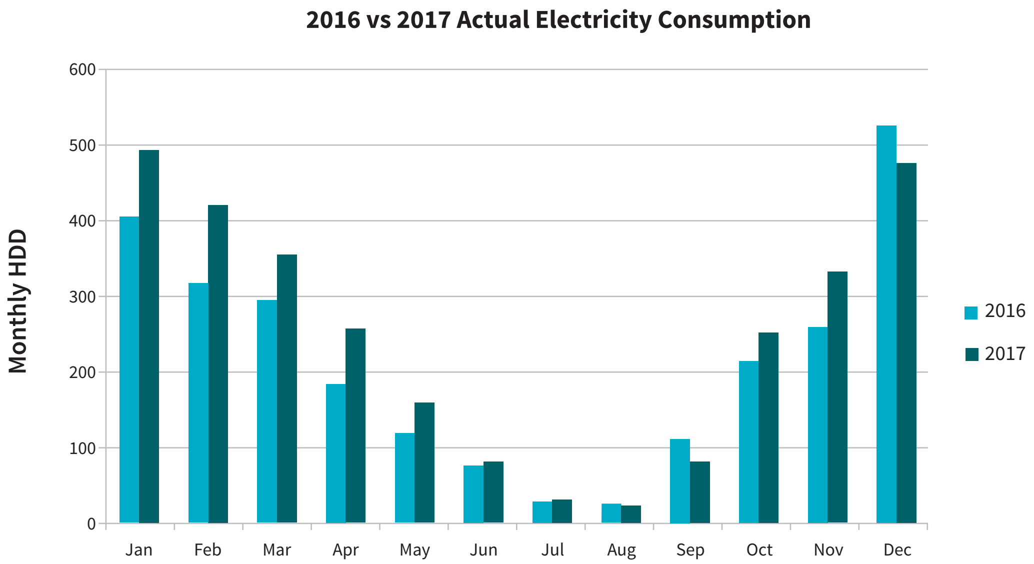


Figure 4.49: Monthly HDD Comparison between 2016 and 2017 of Building F

4.7 Case Study: Building G

4.7.1 General Description

Building G is a nine-storey, sustainable, high-rise, residential supportive housing building located in Vancouver, British Columbia. The building has a floor area of 4,366m^2 and includes 62 studio units, amenity spaces, administrative offices and a social resource center to serve tenants and people in need.

Building G has two levels of underground parking with limited vehicle parking spaces and electric vehicle charging points. The building is located within walking distance of bus lines, SkyTrain stations, and shopping areas. Building G was occupied in 2012 and received LEED Gold certification under LEED Canada-NC 1.0 in 2013.

4.7.2 Envelope and Construction

Materials containing 20% recycled content were used for construction in Building G. They are easy to maintain, long-lasting and achieve a target building life of at least 50 years. The use of fibre cement and metal siding panels for exterior walls increases their resistance to damage from fire, water, insects, thermal damage and rotting. The insulation and low glazing-to-wall ratio contribute to energy reduction and is considered a highly effective and straightforward approach. More than 96% of construction waste was diverted from landfills.

Table 4.20: Envelope and Construction Specifications of Building G

Exterior Wall (hr · ft^2 ·° F/Btu)	Concrete with steel stud walls On average, R=16.6
Roof (hr · ft^2 ·° F/Btu)	R=29
Overall Glazing U-value (Btu/hr · ft^2 ·° F)	U assembly=0.33 SHGC=0.34
Glazing to Wall Ratio	32%
Lighting Controls	Occupancy sensors for shared spaces
Plug Loads (W/ft^2)	Based on the space function

4.7.3 Mechanical System

Table 4.21: Mechanical System Specifications of Building G

HVAC System Specifications	
Ventilation Air Handling Unit	MAU-1 (modelled as two separate air systems HRV-1 and 2) HRV-1: 100% outdoor air ventilation with heat recovery supplies preheated/cooled air to residential suites HRV-2: 100% outdoor air ventilation with heat recovery supplies preheated/cooled air to amenity spaces
Heat Recovery Effectiveness	Heating recovery efficiency=80.1% Cooling recovery efficiency=78.1% Average=79.1%
Ventilation Rate (ACH)	1.0
Space Heating System	Radiant floor heating for residential suites Electric baseboard heating for stairwells MAU-1 supplies preconditioned air to the whole building Ceiling mounted heat pumps serving amenity rooms and office spaces on the first, second and third level
Space Cooling System	Ceiling mounted heat pumps serving amenities and office spaces on the first, second and third level
Central Plant Specifications	
Heating Plant	Vertical geothermal heat pump with two boilers as back up and a buffer tank to avoid energy waste Distributed heat pump loop On average, heating COP=3.25
Cooling Plant	Vertical geothermal heat pump with a buffer tank to avoid energy waste Distributed heat pump loop On average, cooling COP=4.81

The central heat recovery unit MAU-1 was modelled as two separate air units due to its complex control sequences for different types of spaces. HRV-1 was used for suites (third to the ninth floor) and HRV-2 was used for common spaces (main, second, and third floor). Control dampers of HRV-2 close when the corresponding spaces are unoccupied according to the DDC system schedule. The energy recovery wheel is activated when MAU- 1 is in heating mode or the OAT is higher than the average room temperature (RT) in cooling mode. Free cooling is only provided when the OAT is lower than the average RT in cooling mode. The heating coils reheat the air supply when the heat wheel is not sufficient for heating the airflow to the set-point.

Water-to-water heat pump HP-1 supplies heated/cooled fluid to the central heat recovery ventilation unit MAU-1 as well as heated fluid to the radiant floor system. Two variable speed drive (VSD) pumps working in the lead/lag order extract water from the geothermal loop and discharge it to HP-1. Heat is forwarded to the heat exchanger via the operation of the compressor in heating mode or ejected back to the geothermal loop in cooling mode. Additionally, a buffer tank was installed to reduce the time required for heating/cooling water to set points and minimize the overall energy consumption. Two natural gas boilers act as a backup heating source to provide auxiliary heat to the HP-1 loop during the peak heating demand times.

HP-3 to HP-19 are ceiling-mounted water-to-air heat pumps delivering heated/cooled air to designated amenity areas on the first, second, and third floors. A return plenum for each space mixes the returned air with the preconditioned air from MAU-1 to flow through the filter. The clean air is then heated or cooled by the operation of compressors and discharged to various areas through the air diffusers. Each heat pump is equipped with a DDC controller and operates to serve specific zones upon a call for heating or cooling.

4.7.4 Domestic Hot Water System

The water-to-water heat pump HP-2 draws tempered water from the vertical geothermal loop and operates as the first stage heating source for DHW of Building G. The preheated DHW is collected in the preheat storage tanks, DPHT-1 to DHPT-3, to maintain the water at its preheated set-point. Before it is delivered to the tenants, the preheated DHW is heated by gas-fired water tanks, DHWT-1 to DHWT-3, which work as the second stage heating source.

Table 4.22: DHW System Specifications of Building G

DHW System	Vertical geothermal loop Water-to-water heat pump HP-2 Preheated storage tanks DPHT-1 to 3 Gas-fired water heating tanks DHWT-1 to 3 Single flush low-flow water closets Low-flow lavatory faucets Low-flow kitchen sink faucets Low-flow showerheads

4.7.5 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

The annual energy consumption for the reference and proposed models was calibrated based on the previous M&V study. The original energy model did not take the electricity usage of residential suites, commercial kitchen, and elevators into account. The actual energy use in 2016 and 2017 was 50.9% and 64.4%, respectively higher than the proposed model, yet 21.9% and 14.9% respectively lower than the reference building. The additional natural gas consumption from either the space heaters or DHW heating or both contributed to the performance gap.

For the DHW loop, preheat tanks provided service water at a set-point of 40°C to gas-fired water heating tanks. These water heating tanks served the building with domestic hot water at the set-point of 50°C. For the ground loop, boilers provide supplemental heat when the heating demand was high or when HP-1 was not operating efficiently.

The prior verification report suggested that HP-1 was not functioning from March to May in 2013 and January to April in 2014. The additional boiler firing during 2016 and 2017 was predictable based on the ongoing issues of HP-1 in the previous years. The discussions with building staff suggest that the unexpected hydro consumption resulted from the unique operating schedule of the resource center, the unpredictable tenant behaviours, the wear and tear on equipment, and control conflicts with the energy model.

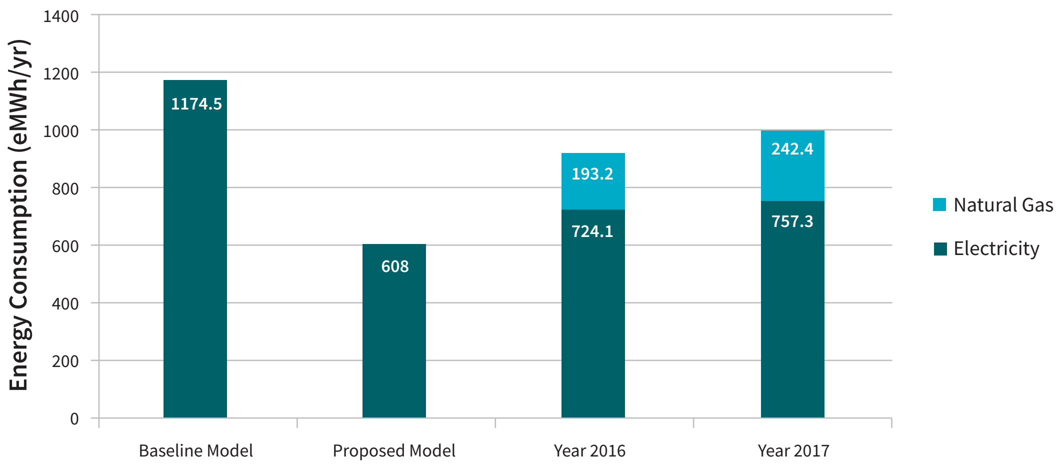


Figure 4.50: Annual Energy Consumption Comparison of Building G

Building Energy Performance Index Comparison

The comparison of the actual performance of Building G with BEPI for this type of MURB suggests that natural gas consumption was avoided at the expense of hydro use. This building is more complicated than a residential apartment because it has a resource center that serves 80 to 100 visitors per day, a commercial kitchen supplying meals once a day, and various amenity rooms. The observed discrepancy can be justified by comparing the proposed model to peer MURBs. The actual electricity consumption for both years is on track with the BEPI for this type of HCSAs and AFSs. The total energy consumption for the building is about 80% greater than MURBs and 40% less than HCSAs and AFSs, which realistically describes its actual operations.

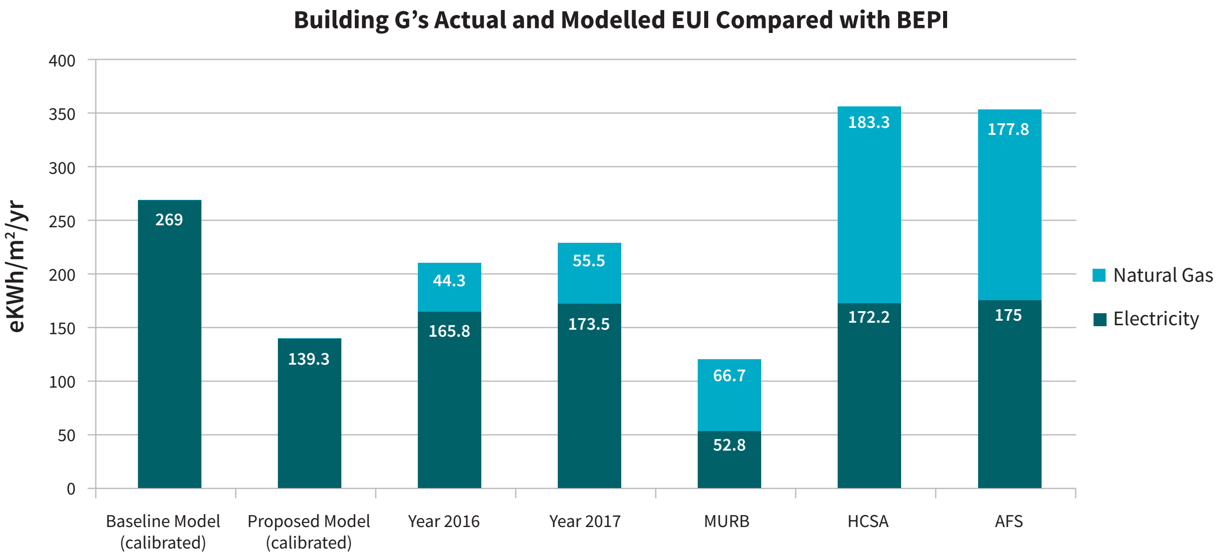


Figure 4.51: BEPI Comparison of Building G

Effects of Weather on Results

The performance gap described in the previous section and the effects of weather were explored further in this study. The regression analysis between energy consumption and HDD was performed and the correlation for 2016 and 2017 was 0.73 and 0.83, respectively. This proves a reasonable relationship between the energy consumption of the building and HDD variation.

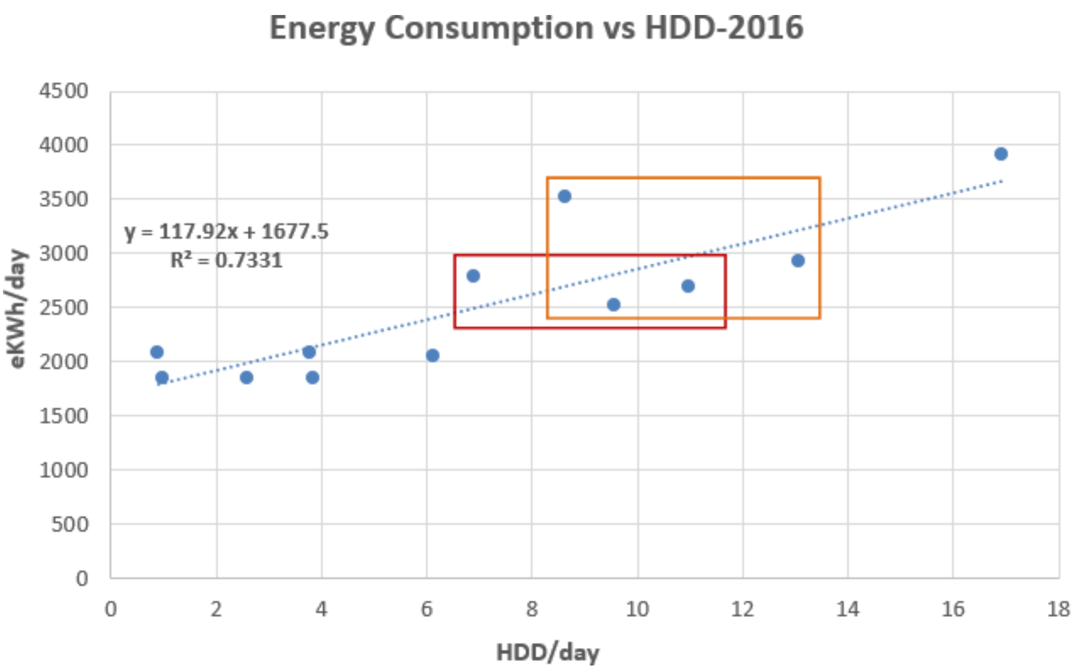


Figure 4.52: Effects of Weather on Building G for 2016

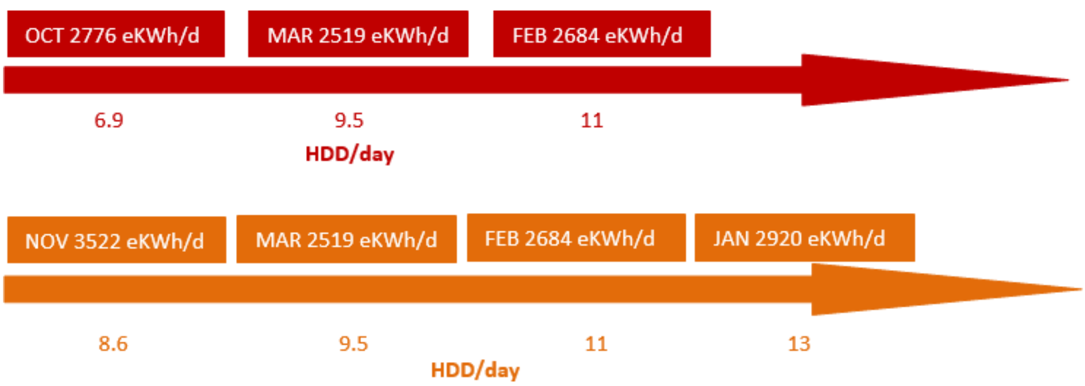


Figure 4.53: Abnormal Energy Consumption Against Weather of 2016

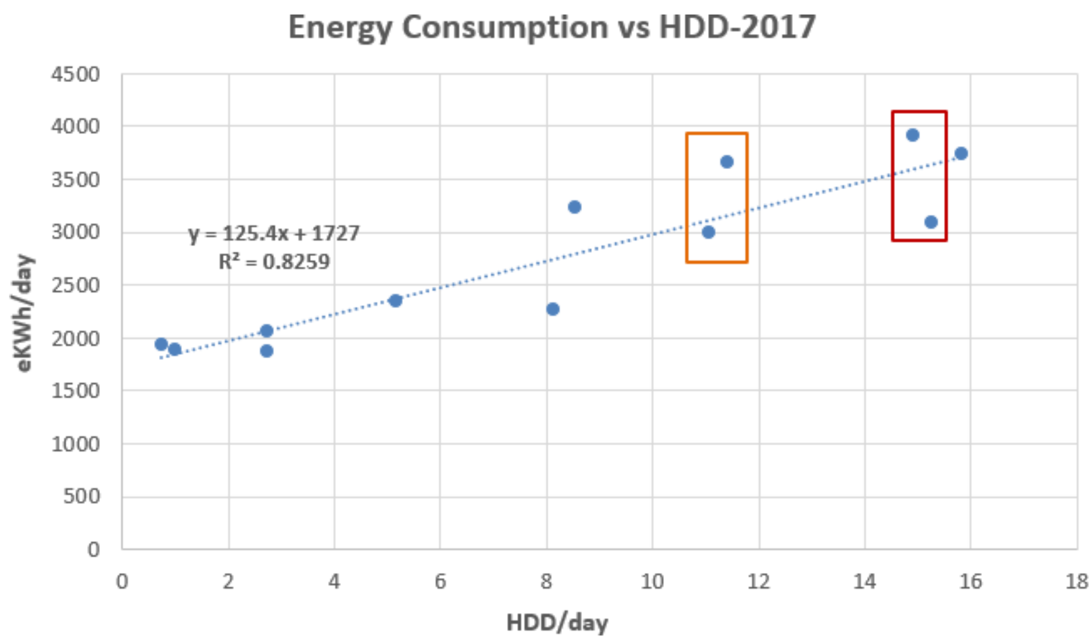


Figure 4.54: Effects of Weather on Building G for 2017

For 2016 and 2017, two groups of plots in red and orange rectangles shown in Figure 4.52 and Figure 4.53 represent the unexpected energy usage. The months with fewer HDD/day in 2016 consumed more energy/day, as shown in Figure 4.52 and Figure 4.53. The months with approximately the same HDD/day in 2017 showed a noticeable difference in energy consumption, specifically, March against November, and February against December, as shown in Figure 4.54.

The analysis of electricity and gas usage by calendar month suggests that there was a considerable increase in the gas firing from October 2016 to March 2017, as shown in Figure 4.55. One of the reasons for this increase could be the extremely cold days in December 2016 and January 2017. This observation also signifies the unforeseen inefficiency of the geothermal loop under extreme weather. The poor performance of the ground source heat pump during cold days between October 2016 and March 2017 could be due to some mechanical issues.

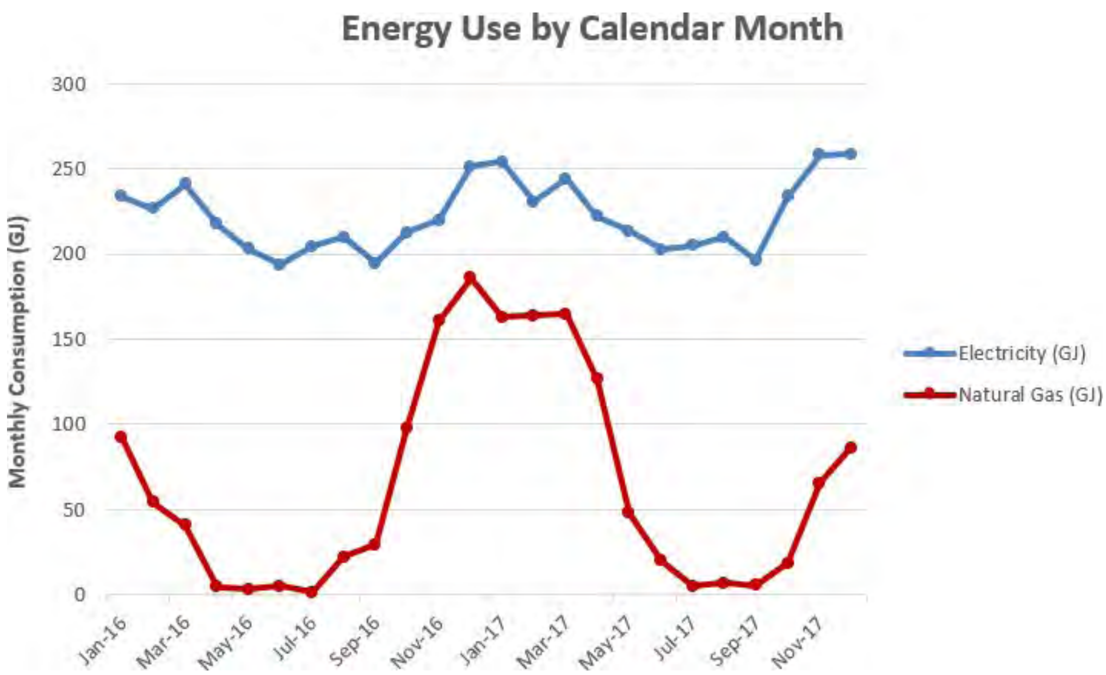


Figure 4.55: Monthly Utility Data by Types of Building G

Monthly Electricity Consumption Comparison

The comparison of hydro data from 2016 and 2017 suggests that most months had approximately the same electricity consumption for each year. The biggest variation occurred in the heating season, specifically the months of November, October and January. The explanation for this variation is not completely attributable to increased cold weather in 2017 because the most significant difference in HDDs happened in February. Unique occupant behaviour patterns, minor control issues, and ineffective equipment maintenance/repair could be contributing factors.

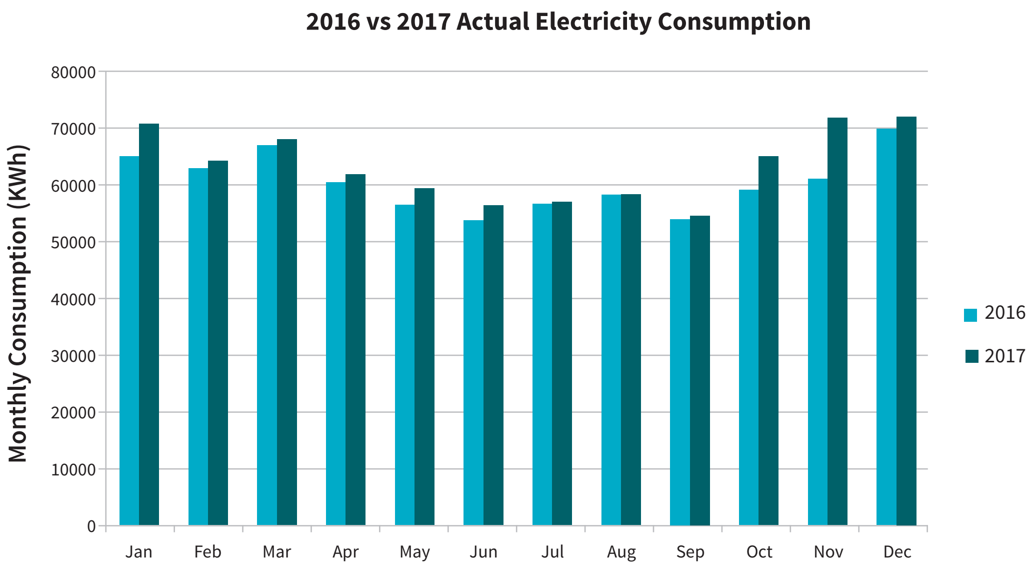


Figure 4.56: Electricity Consumption Comparison between 2016 and 2017 of Building G

Recommendations

- Fix sub-meters on boilers for DHW and space heating to ensure a close match to the actual natural gas bill.
- Identify the source of the high natural gas consumption and quantify the gas end-use break down.
- Examine HP-1 and HP-2 for space heating and DHW loop respectively to modify their operation towards peak efficiency and reduce back-up boilers from firing.
- Review the control sequences of HP-1 to minimize back-up boiler operation.
- Monitor VSD pumps and fans to ensure that their motors follow the heating/cooling demand period.
- Review control sequences of the HRV and radiant floor system to confirm free cooling and avoid heating during summer months.
- Perform continuous commissioning which is recommended to monitor the geothermal loop and verify its ability to supply the expected quantity of heating/cooling energy.

4.8 Case Study: Building H

4.8.1 General Description

Building H is a sixteen–storey sustainable high-rise, with residential support, located in downtown Vancouver, British Columbia. The location provides easy access to public transit, grocery stores and clinics. With a floor area of 9,600m^2, Building H has 111 apartment units for adults, 30 apartment units for youth, amenity rooms, parking area and bicycle storage spaces.

The youth support center is located on the first floor. The second floor offers meals once a day. There are comprehensive medical and support services offered 24 hours a day, 365 days a year.

A garden area allows tenants to grow vegetables, fruits, and herbs. Large floor-to-ceiling windows installed in the shared spaces allow amenity rooms to receive abundant natural light by the day. The windows also contribute to lowering the heating energy consumption to some degree. The Building H has been occupied since 2014 and received its LEED Gold certification under LEED Canada-NC 1.0.

4.8.2 Envelope and Construction

Table 4.23: Envelope and Construction Specifications of Building H

Exterior Wall (hr · ft² ·° F/Btu)	Metal cladding and brick walls with framed mineral fibre insulation R=16.1 (8% higher than the baseline)
Roof (hr · ft² ·° F/Btu)	R=25.32 (62% higher than the baseline)
Overall Glazing U-value (Btu/hr · ft² ·° F)	U assembly=0.413 (36% lower than the baseline)
Lighting Controls	Daylight sensors Occupancy sensors in common spaces
Light Power Density (W/ft²)	Overall 0.95, 19% less than the baseline model
Plug Loads (W/ft²)	Based on the space function

Building H was designed with a target lifespan of at least 60 years. Materials used for construction are durable and cost-effective for maintenance. The building was constructed using 19% of the construction materials containing recycled contents and 21% locally manufactured and extracted materials. The proposed R-values for walls and roofs are 8% and 62% higher than the baseline model, respectively, which significantly decreases the thermal bridge of the building envelope. Operable windows in suites provide occupants with extra thermal comfort and sufficient airflow during summer.

4.8.3 Mechanical System

The air handling unit and heat recovery pipes HRU-1 operate continuously to supply conditioned air to suites and corridors. The heating coil valve modulates to maintain supply air temperature at the set-point of 18°C. The heat recovery bypass damper opens when OAT is between 18°C and 25°C. This makes it capable of saving energy by preconditioning outdoor air.

Another heat recovery unit, HRU-2, runs on an occupancy schedule. This allows for high energy savings because the system shuts down when the space is unoccupied. The supply air temperature set-point can be adjusted based on the outdoor air temperature. The heating coil valve modulates to keep the supply air temperature at set-point. The return fan follows the supply fan speed at 5% less intensity to preserve a positive building pressure compared to the outside.

Residential suites also receive heat from a radiant slab system. Residents have control over the heat supply via adjustable thermostats installed in each suite. When a heat request is sent to the building management system, and the valve position is adjusted according to the computed results from the DDC system. Pumps are disabled when OAT exceeds 18°C.

The heating loop controls the various hydronic heating coils built into the heat recovery units, make-up air units, fan coil units, radiant floor, and DHW system. The air source heat pump HP-1 mounted on the rooftop acts as the primary heating source, and a natural gas boiler functions as a back-up for heating. The heating plant loop contains a buffer tank that helps reduce the time for HP-1 to heat the water to its set point and subsequently save on energy consumption from low HP-1 cycles. The boiler is activated when there is a call for heating because HP-1 cannot maintain the buffer tank temperature for 30 minutes, once HP-1 has been in operation for over an hour.

The boiler is disabled when the tank temperature is at the set-point for at least 15 minutes. The heating-plant return pipes interchange heat with DHW heat exchanger HX-1 to preheat service water in the preheat tanks. An energy meter keeps track of the energy use of the heating system by monitoring the main heating system’s supply water temperature, return temperature, and supply flow rate.

Table 4.24: Mechanical System Specifications of Building H

HVAC System Specifications	
Ventilation Air Handling Unit	HRU-1: Rooftop hydronic heating and ventilating heat recovery unit serving the residential suites of the building with 100% outdoor air HRU-2: 100% outdoor air makes-up air unit that serves the fan coils in the sub-basement Kitchen Ventilation System: • MUA-1: 100% outdoor air, hydronic heating makes-up air unit serving kitchen on level 1 • MUA-2: 100% outdoor air, hydronic heating makes-up air unit serving kitchen on level 3 Fan Coil Units: Distributed fan coil units serving offices and amenity spaces
Space Heating System	Preheated ventilation air via heat recovery units Radiant floor heating in suites
Space Cooling System	Fan coil units for offices and amenity spaces
Central Plant Specifications	
Heating Plant	An air-to-water heat pump (HP-1) connected to buffer tank with natural gas boiler backup serving radiant floor, hydronic heating coils and DHW system Fixed speed primary circulating pump VFD secondary circulating pump
Cooling Plant	Condensing units of the air source heat pump (HP-1) serving 2-pipe fan coils

4.8.4 Domestic Hot Water System

The heat exchanger HX-1 is enabled when the temperature of the warmest preheat tank is 5°C lower than the heating plant's return water temperature (as long as there is no request for heat). The two DHW boilers work in a lead/lag sequence. If the lead boiler has been enabled for 15 minutes and the temperature of the warmest DHW storage tank is still 5°C lower than the set-point, then the lag boiler starts to operate. Once the DHW storage tank has achieved its set point, both lead and lag boilers shut down.

Table 4.25: DHW System Specifications of Building H

DHW System	Preheated by an air-to-water heat pump (HP-1) through heat exchanger HX-1 Four DHW preheat tanks PHT-1 to 4 Reheated by two gas-fired boilers DHWB-1 and 2 Six DHW storage tanks DHWT-1 to 6 Single flush low flow water closets Low flow fixtures in washrooms

4.8.5 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

The total energy consumption for both 2016 and 2017 was 1.3 times higher than the proposed model and 39.5% higher than the baseline building. The performance gap was above the expected accuracy level of +/-15%. This major discrepancy is the result of the difference in the actual operation of Building H in contrast to its energy model.

The youth support center operates 24 hours a day, 365 days a year. This may not have been taken into consideration during modelling at the design stage. The building used approximately 15 times more natural gas than the predicted model for both years. The natural gas usage was more than 15 times higher than the reference building for both years. At the same time, approximately 85% more electricity was consumed than the proposed. The electricity consumption was higher by more than 85% when compared to the reference building.

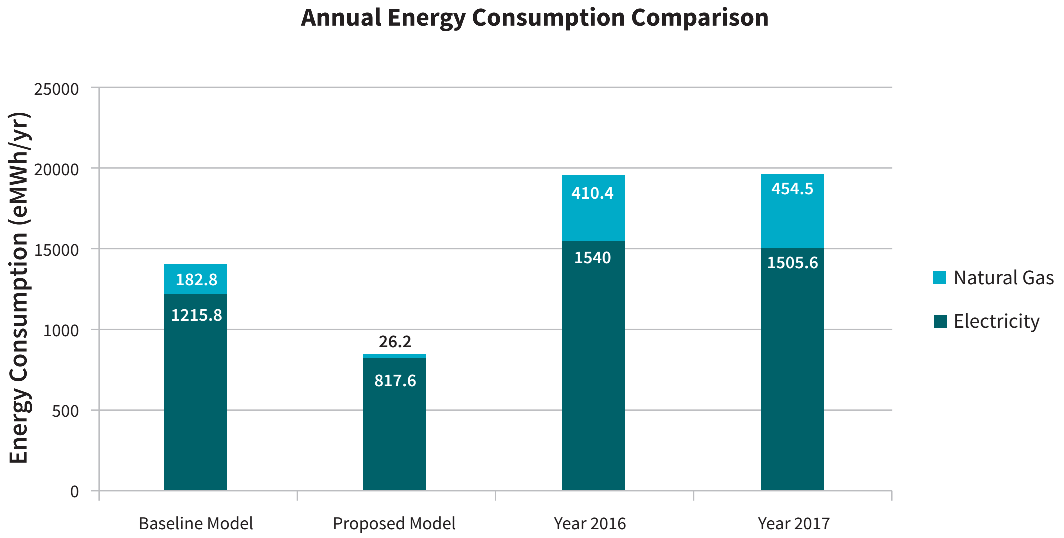


Figure 4.57: Annual Energy Consumption Comparison of Building H

Mechanical and Operation Variations

The following mechanical and operational deviations were determined after discussions with the Building Maintenance Manager.

Failure and Inefficiency of HP-1

The air-to-water heat pump HP-1 broke down for eight months in 2015, three weeks in January 2016, and three weeks in January 2017. The cause for the HP-1 failure was not known due to the absence of detailed overhaul records. Additionally, HP-1 was not working efficiently when the OAT dropped below 5°C when other related equipment, including pumps and fans kept cycling.

Excessive Radiant Floor Heating on Summer Nights

According to the control sequence, pumps for the radiant heating loop shut down when the OAT was higher than 18°C. However, it was common that the OAT on the summer nights dropped below 18°C, which resulted in unnecessary heating energy use. Based on the historical weather data in 2017 shown in Figure 4.58, from June to August, the minimum temperature for each night was below 18°C even when the daytime maximum temperature went up to 30°C. The heat pump cycled on and off, resulting in wear and tear on the equipment.

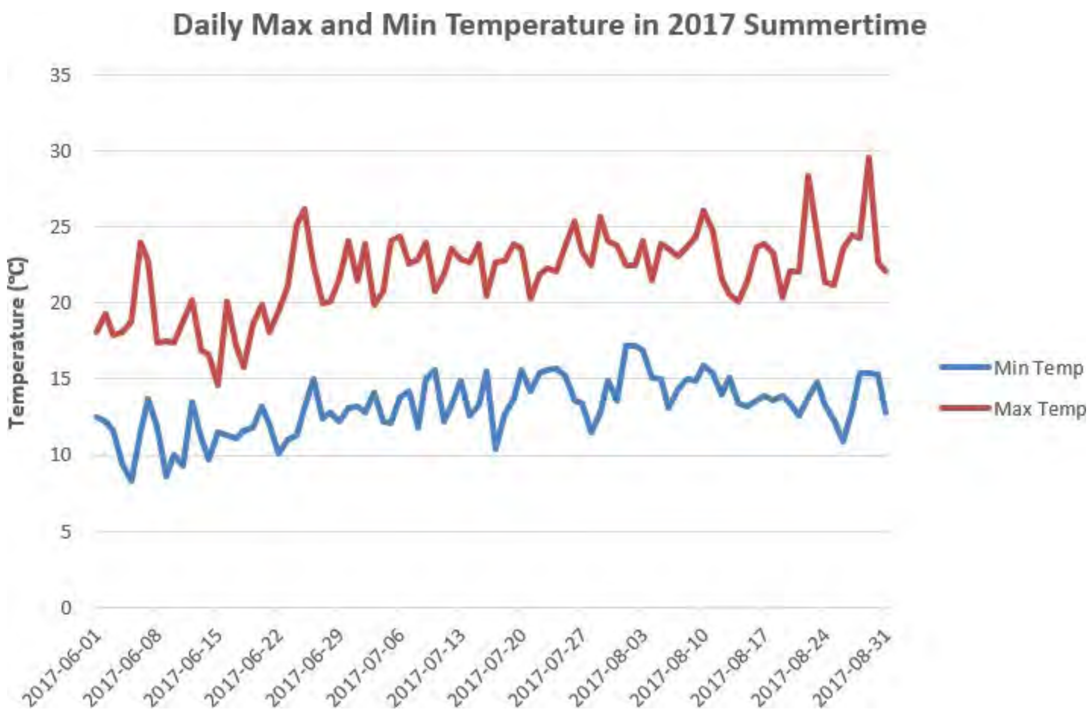


Figure 4.58 Daily Max and Min Temperature in Summer 2017

Radiant Floor Heating Time Delay

There were some complaints from tenants about how long it took to heat their apartments. The radiant floor system in Building H required a long response time to meet occupant demands, especially during extreme weather. Tenants often adjusted the thermostats to a much higher value than needed in the hopes of speeding up the warming process, which often led to unanticipated energy waste.

HP-1 Control Setting

The control settings for HP-1 operation did not involve a deadband. Considering the significant performance gap for Building H, it is recommended to add a deadband of 5°C to minimize the heat pump cycling. The general practice is to direct the heat pump for heating when OAT is lower than 16°C and cooling when OAT is higher than 21°C.

Building Energy Performance Index Comparison

The result of the EUI comparison between Building H and BEPI is shown in Figure 4.59. Both the proposed and baseline models show higher electricity consumption than MURBs. This suggests that the design focused on electricity as the primary source for space heating and service water heating. Although compared to MURBs, the total actual energy consumption for both 2016 and 2017 is approximately 70% higher, more than 30% more gas is saved because of the sustainable design. The actual EUI of Building H is between MURBs and HCSAs (or AFSs), which is reasonable given it offers resource centers on two floors that operate 24 hours a day.

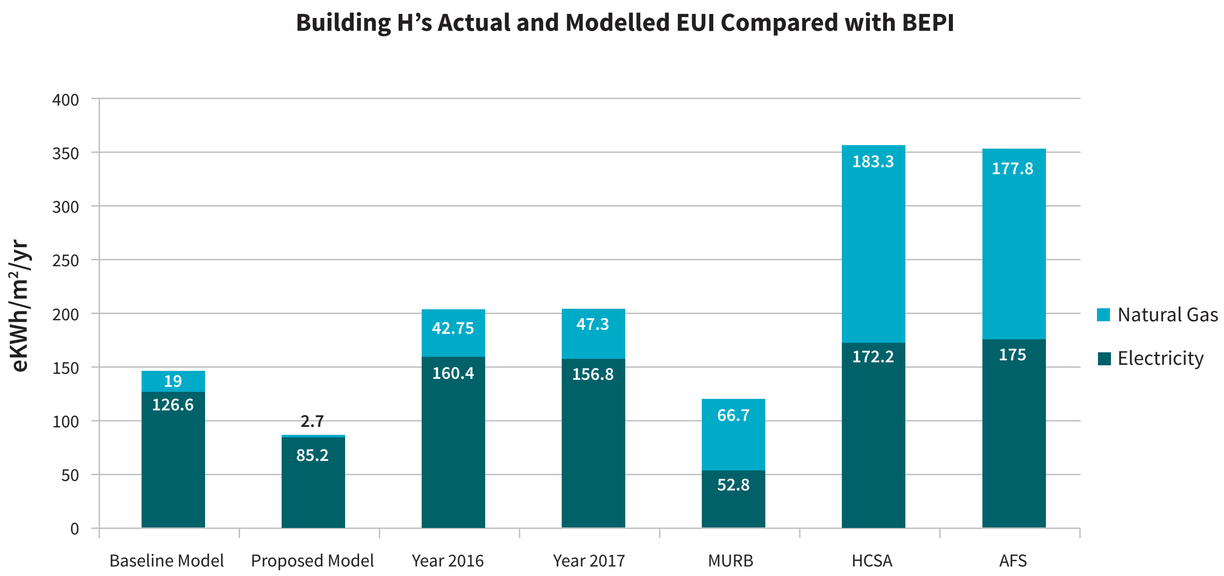


Figure 4.59: BEPI comparison of Building H

Effects of Weather on Results

The analysis of the effects of weather on the performance gap for Building H was performed. The correlation coefficients between energy consumption and HDD are 0.68 and 0.88 for 2016 and 2017 respectively, as shown in Figure 4.60 and 4.61. Although for both years the building consumed significantly more electricity and natural gas than predictions, the higher energy use for 2017 is observed to be closely tied to the weather conditions. The correlation factor for 2016 is marginally lower than the minimum advised value of 0.7 and broadly attributable to the two points represented in red rectangles in Figure 4.60. The analysis shows occasional increases in energy use during June and July; higher than the shoulder seasons of April and October. A possible reason for this observation can be the frequent cooling module operation for common areas.

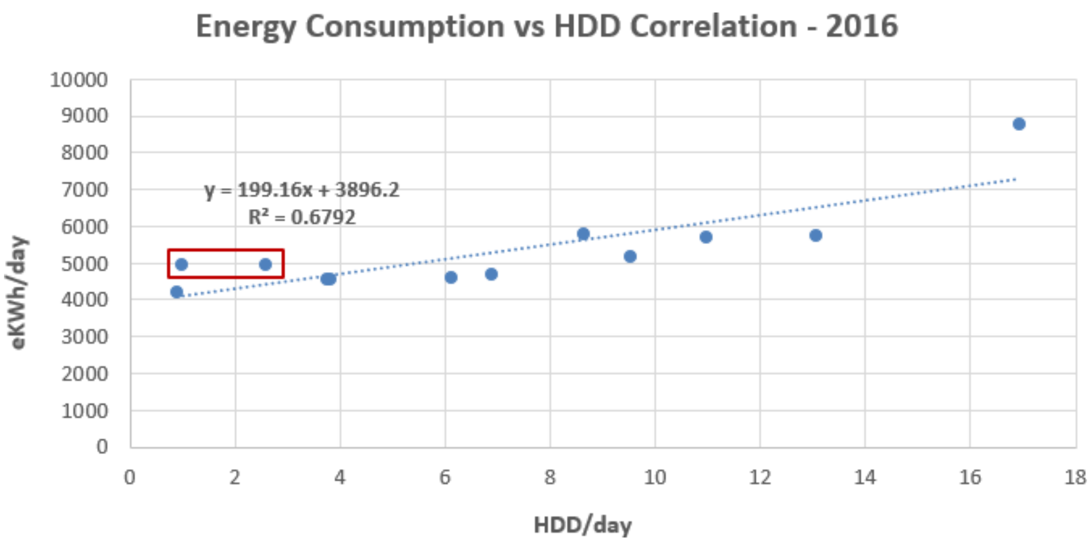


Figure 4.60: Effects of Weather on Building H for 2016

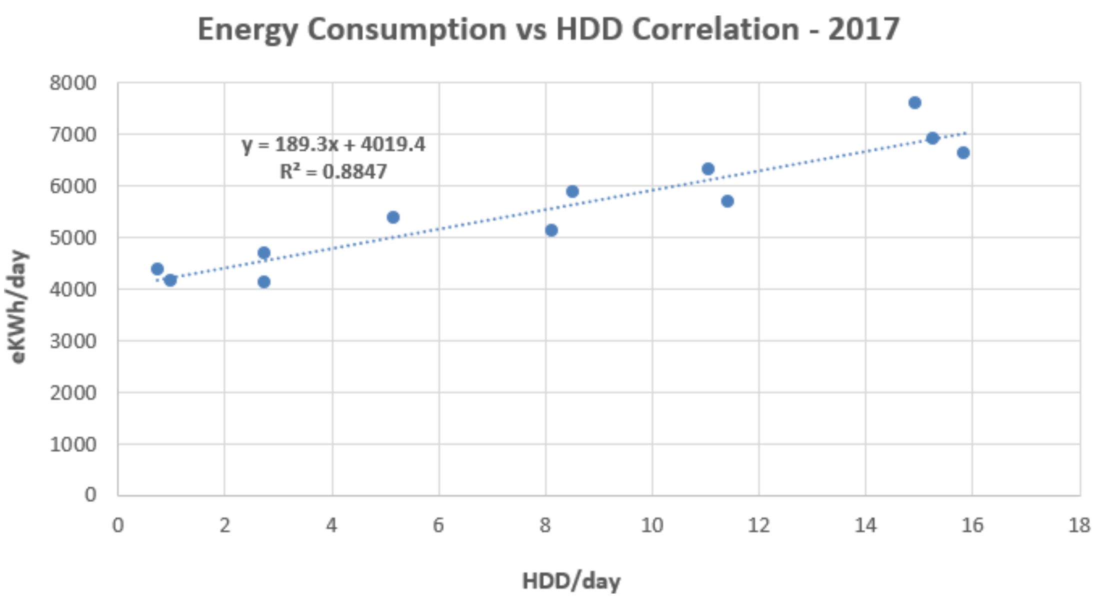


Figure 4.61: Effects of Weather on Building H for 2017

Monthly Energy Consumption Comparison

The monthly electricity usage comparison suggests that the most prominent deviation from the predictions for 2016 occurred in extreme weather months of February, June, July, and November featuring a ratio of 81.4%, 90.2%, 79.5% and 81%, respectively. For 2017, most deviations were observed in February and October with a difference quotient of 108% and 86.5%. It is recommended that the energy modelling of air source heat pumps should consider redesigning performance curves according to the practical operation and employ empirical curves.

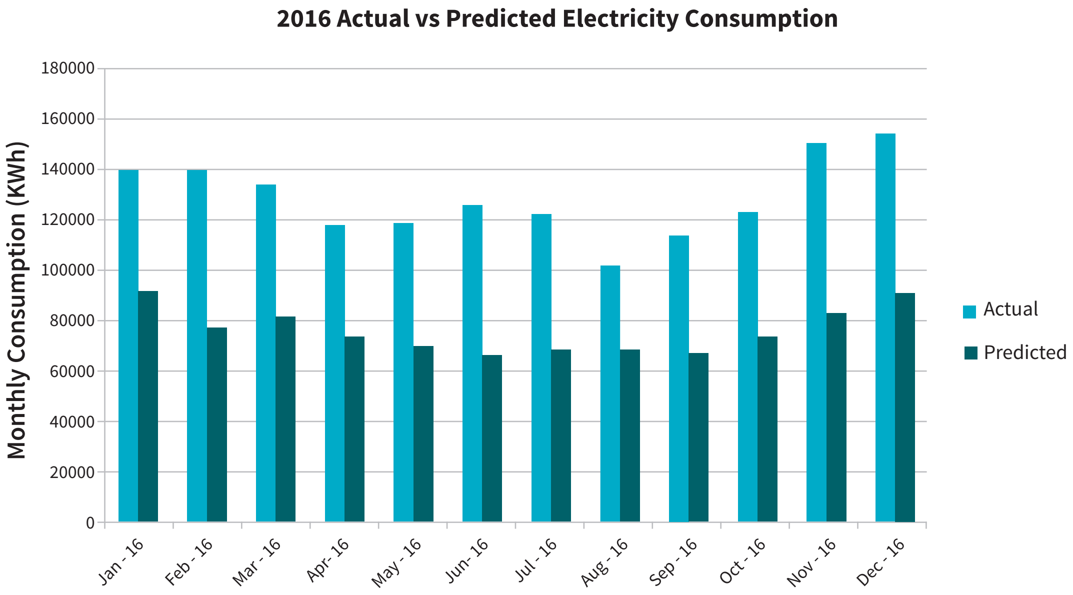


Figure 4.62: Electricity Consumption Comparison for 2016 of Building H

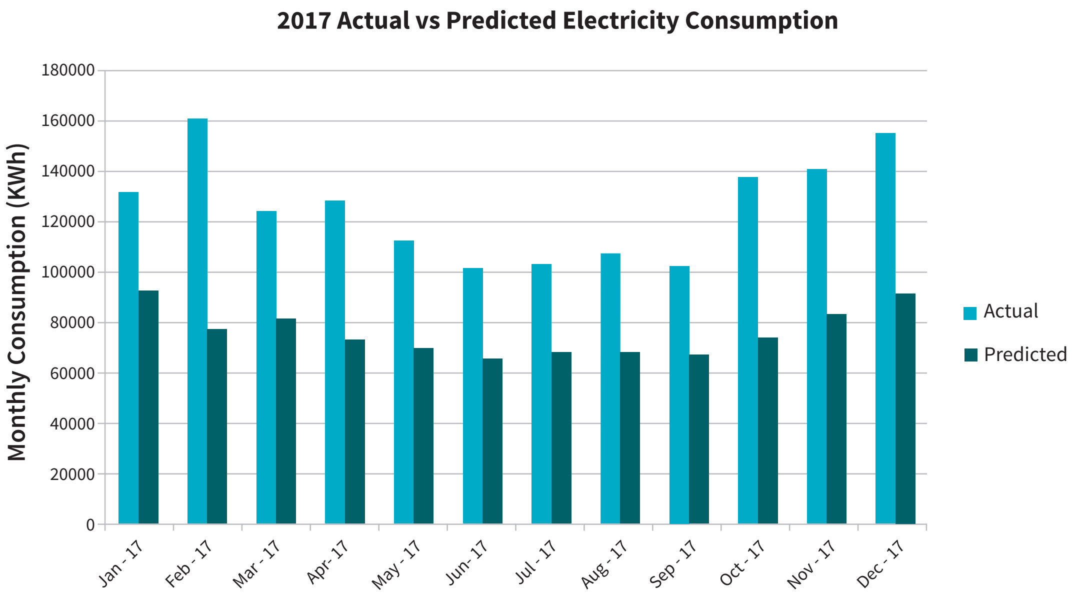


Figure 4.63: Electricity Consumption Comparison for 2017 of Building H

Figure 4.64 shows a jump in natural gas consumption for December 2016 and January 2017 that resulted from an increase in heating degree days and incapacity of ASHPs. The gas and electricity cost related to space heating should be calculated for cold months to determine the most economical to switch to gas-fired boilers rather than heat pumps. The lack of expected COP of the heat pump system, operating relevant fans, pumps and compressors under specific temperatures results in significant electricity wastage every year.

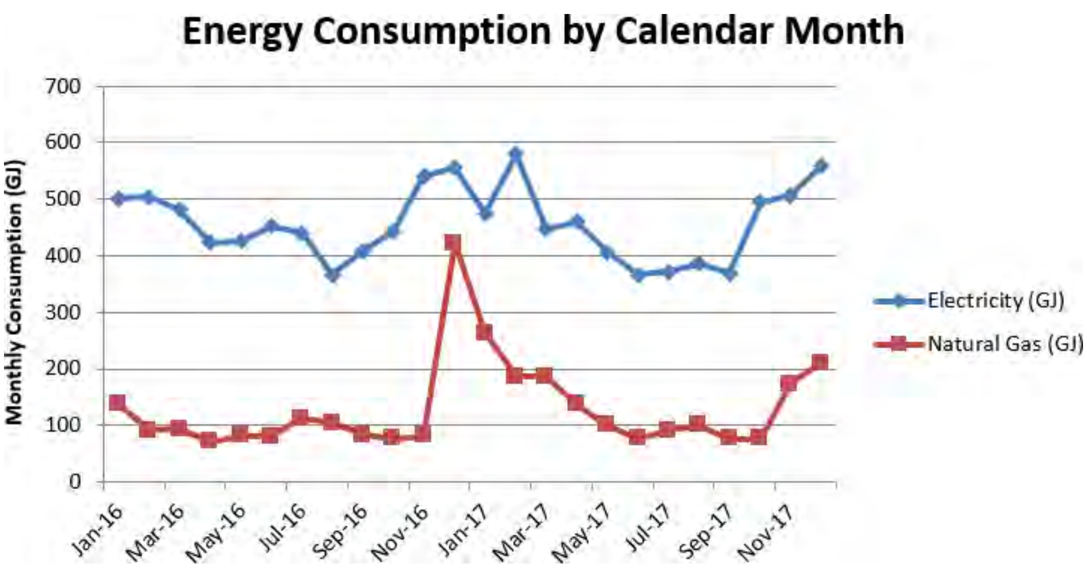


Figure 4.64: Monthly Utility Data by Types of Building H

Recommendations

- Evaluate the electricity and natural gas cost for space heating when the outside air temperature is low (for example below 5°C). Since the ASHP cannot function at its optimal status in winter, it might be more cost-effective to disable HP-1 and enable the boilers instead.
- Keep the overhaul record of HP-1 for reference and use for further maintenance and repair.
- Add a deadband to the control sequence of HP-1 to minimize its unnecessary operation during summer nights and shoulder seasons.
- Install sub-meters to monitor various end-uses and develop energy conservation methods for cases with large discrepancies from the designed model.
- Perform continuous commissioning for HP-1 which is recommended to improve its performance.

4.9 Case Study: Building I

4.9.1 General Description

Building I is a nine-storey sustainable high-rise, residential social housing building located in Vancouver, British Columbia. The building provides housing for people experiencing homelessness and people at risk of homelessness, particularly those struggling with mental illness. The building has a total floor area of 5509m^2, excluding the unheated parking garage. It offers 96 residential suites, which include 12 specialized, accessible units and has a commercial kitchen serving one meal a day to tenants.

The curtain wall system on the main floor enables sunlight to reduce lighting energy requirements and provide heating in winter and shoulder seasons. Large windows installed in each unit contribute to the energy savings and help to increase the livability of the small unit spaces that are 20m^2 on average. It was occupied in 2011 and received LEED Gold building certification under LEED Canada-NC 1.0 in 2014.

4.9.2 Envelope and Construction

The exterior wall of the building has an average R-value of approximately 18, which is 14% higher than the reference building. The building used an SBS membrane to resist the extreme weather and extend the service life of the roof. On average, the R-value of the roof is 225% higher than the reference building. Occupancy sensors are equipped to save 39% of the lighting energy compared to the reference building model.

4.9.3 Mechanical System

The two energy recovery units, HRV-1 and HRV-2, operate continuously to deliver fresh conditioned air to Building I. The DDC system monitors the supply fan, exhaust fan, and pump status to monitor normal performance. Upon receiving a call for heating, the DDC system controls hydronic heating coils, the energy recovery core, and bypass dampers to maintain the supply air temperature at the set-point of 17°C. The DDC system modifies the supply and exhaust fan speed when the in-suite CO2 level increases. The make-up air unit, MUA-1, operates to maintain the discharge air (heated by gas) at 21°C in the commercial kitchens.

Once a call for heat is received, HP-1 to HP-3 activates to heat the hydronic loop. Subsequently, two boilers work on a lead/lag rotating basis to supply hot water to the radiant in-floor heating system and various hydronic coils. Any excess heated water is stored in the water tank, ST-1.

Table 4.26: Mechanical System Specifications of Building I

HVAC System Specifications	
Ventilation Air Handling Unit	HRV-1: 100% outdoor air ventilation with heat recovery serving residential suites HRV-2: 100% outdoor air ventilation with heat recovery serving shared zones, offices and the retail store
Space Heating System	In-floor radiant heating for suites Preconditioned air for the whole building Electric baseboard heating for service zones
Space Cooling System	Distributed fan-coil systems supplying cooling to shared spaces, offices and commercial retail units
Central Plant Specifications	
Heating Plant	Air-to-water heat pumps HP-1 to 3 serving the hot water loop Backup boilers B-1 and 2 offering auxiliary heating for the hydronic heating loop
Cooling Plant	Air-to-water heat pumps HP-1 to 3 serving the hydronic cooling loop A dry cooler DC-1 being added to the hydronic loop after HP-2 failure

4.9.4 Domestic Hot Water System

Upon receiving a call for heat from the DHW storage tank temperature sensors, the DDC system commands HX-2 to exchange heat with the storage tank ST-1 to maintain the water in DHWT-2 at set-point. If the call for heat from the DHW storage tank temperature sensors is sustained, the DDC system activates HX-1 to exchange heat with B-1 and B-2 for heating the DHWT-3 and 3A to supply water at set-point. The booster tank DHWT-1 operates to prevent the growth of Legionella before the hot water is supplied to the fixtures. If the supply water temperature exceeds the high limit thermostat set-point, HX-1 is disabled and a high limit alarm is activated in the DDC system.

Table 4.27: DHW System Specifications of Building I

DHW System	Storage tank ST-1 Heat exchangers HX-1 and 2 DHW preheat storage tank DHWT-2 DHW hot water storage tank DHWT-3 and 3A DHW electricity booster tank DHWT-1 Low flow fixtures

4.9.5 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

Total actual annual energy consumption for the 2016 and 2017 calendar year was 61.6% and 61.4%, respectively higher than the proposed building model. The results exceed the expected accuracy level of +15%. However, the actual energy consumption for both years is less than the reference building model with a ratio of 23%. The discrepancy in electricity and natural gas consumption is close to 46% and 48%, respectively, which is a result of various mechanical system issues in Building I.

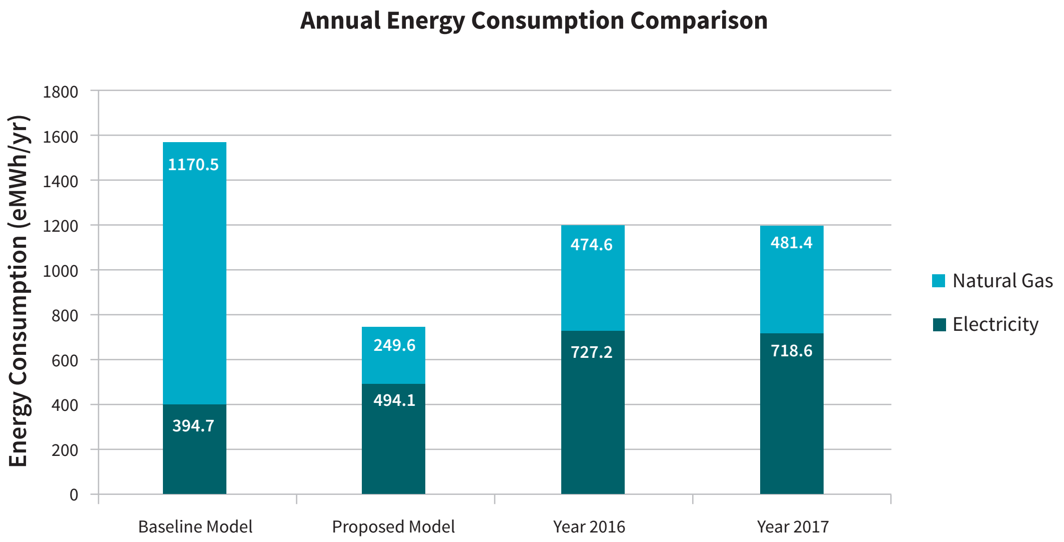


Figure 4.65: Annual Energy Consumption Comparison of Building I

Mechanical and Operation Deviations

The following mechanical and operational deviations were documented from the previous inspection report on mechanical issues and discussions with the building maintenance manager.

Failure of HP-1, 2 and 3

The air-to-water heat pump HP-2 failed to provide heating/cooling to the building since 2016 and was replaced by a dry cooler DC-1. Neither of the other two heat pumps, HP-1 and HP-3, were working properly and subsequently abandoned.

The predominant reason for the heat pump failure was that the equipment had limitations and couldn't reach design parameters. Heat pumps are not able to operate for maintaining the aimed loop temperature when the inlet air temperature is above 26.7°C in cooling mode. A three-way valve was installed and programmed to overcome this issue by recirculating the cooled water. However, the control strategy did not perform as planned due to the overly complex control sequences and the mechanical barrier of the equipment.

Gatekeeper DHW System

An issue with the gatekeeper tank was detected to have the same issue as described in the Building C case study.

Pump VSD Failure

Some variable-speed-drive pumps were not performing as designed. From the previous inspection report, the pressure differential sensor was not placed correctly and required relocation.

Radiant Floor Heating Respond Time Delay

The in-floor heating system had a long response time, up to several hours, to meet the heating demand from occupants. Since occupants had permission to adjust thermostats, they could adjust the temperature to a very high level. Once the room was heated through the radiant floor system, sometimes tenants opened windows to lower the room temperature and get fresh air.

DDC System

There was no historic data saved in the DDC system, making it impossible to identify the issues causing the performance discrepancy. The alarm/alert function was not working. The trend of log data could not be plotted, limiting the operators' ability to review the system performance or identify existing or potential operational issues.

Building Energy Performance Index Comparison

Considering that some dominant energy-saving design strategies such as air source heat pumps were not realized, EUI comparison between Building I and the peer benchmark buildings was performed to analyze the scenario.

Two gas-fired boilers provide both space heating and DHW heating for the entire building and a dry cooler is used to reject heat and cool the building. Both natural gas and electricity consumption was expected to be higher than the proposed case since boilers and dry coolers are not as efficient as heat pumps.

The building used about 148% more electricity and 30.4% more gas in 2016 and 2017 compared to the BEPI for the MURB building type. Over half of the gas and 25% of the electricity was saved against HCSA and AFS. The result is reasonable given that Building I is a social housing facility that offers supportive services as compared to conventional residential buildings.

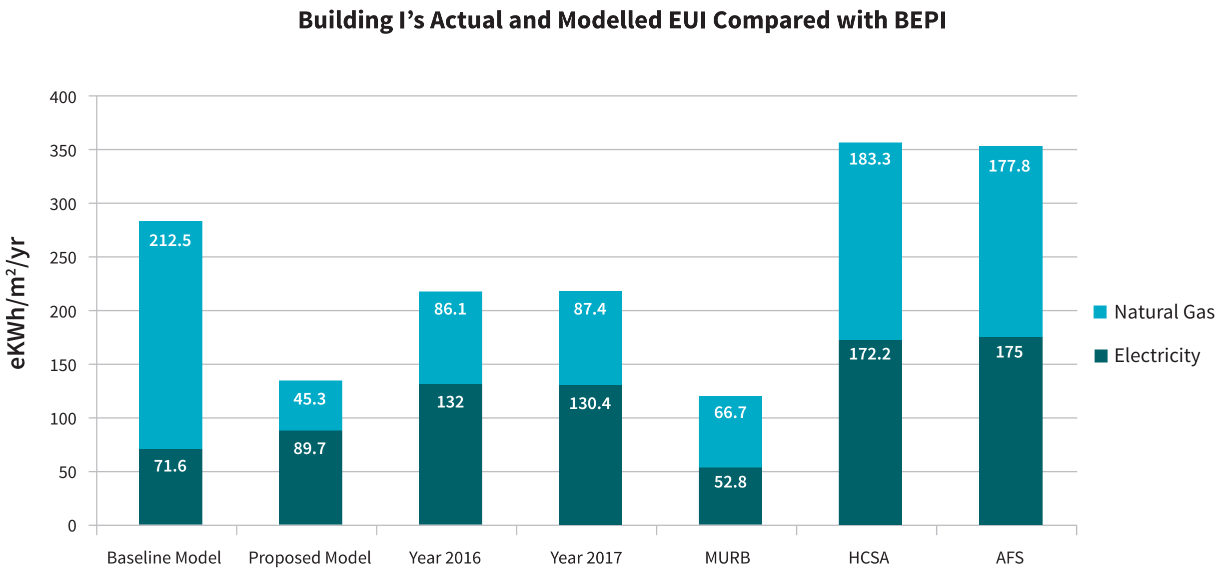


Figure 4.66: BEPI Comparison of Building I

Effects of Weather on Results

Regression analysis for 2016 and 2017 was performed to investigate the correlation between energy consumption and HDDs. For both years, the energy consumption was poorly correlated to HDDs with coefficients of 0.6 and 0.4. This is unusual because Vancouver is located in a heating-dominated climate. In this case, another regression analysis for the proposed building model was plotted. For both years, it showed a strong interconnection to HDD with coefficients of over 0.9. The weak correlation indicates that the building was not operating as designed.

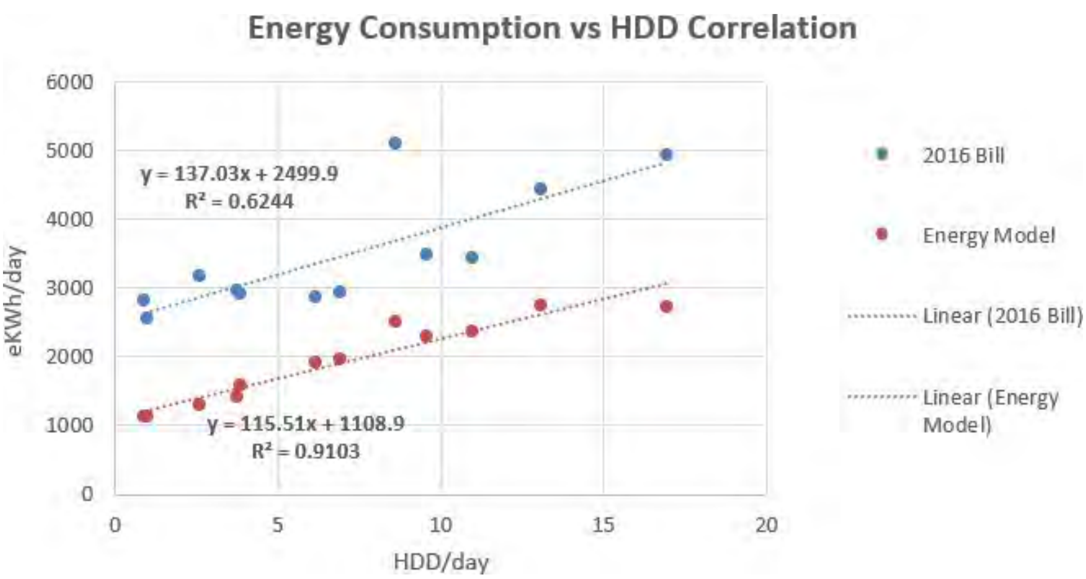


Figure 4.67: Effects of Weather on Building I for 2016

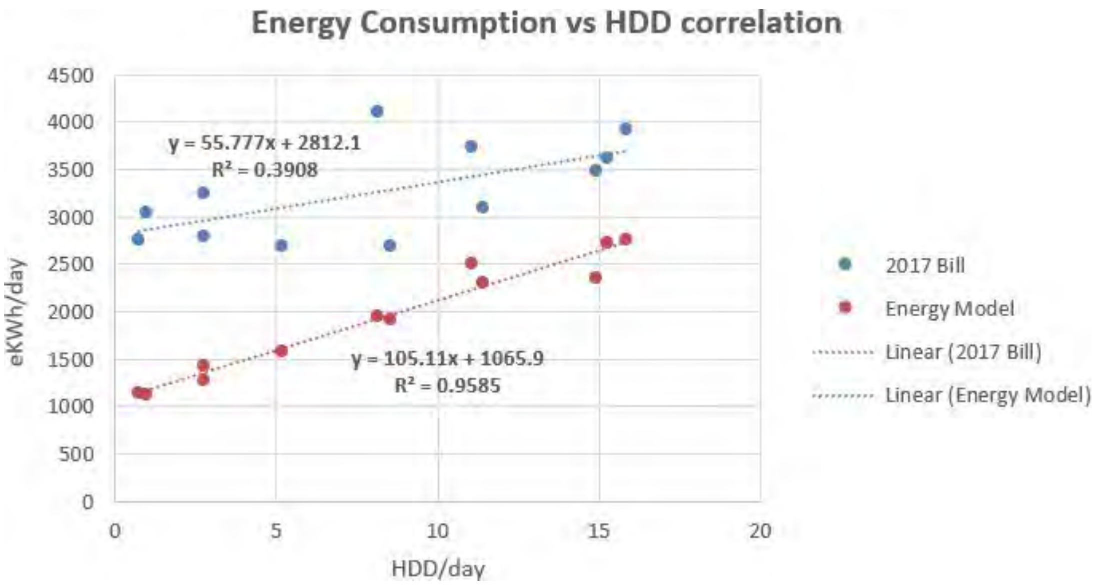


Figure 4.68: Effects of Weather on Building I for 2017

To determine the reason for this significant discrepancy, the monthly electricity and natural gas uses were plotted as shown in Figure 4.69. Considering that gas is the only source for space heating and service water heating, the higher gas consumption during winter months is expected. However, the electricity consumption should be theoretically lower than other months during the summer based on the proposed design, as shown in Figure 4.70.

A review of the utility bills revealed that the electricity usage swings between 200 and 250 equivalent GJ for the whole year. One of the primary reasons for the difference is that the dry cooler was not as efficient as ASHPs. Another strong argument would be the deviation related to the unpredictable behaviours of the occupants. The cooling energy, excessive plug loads, and lighting consumption contributed to the high electricity use in summer.

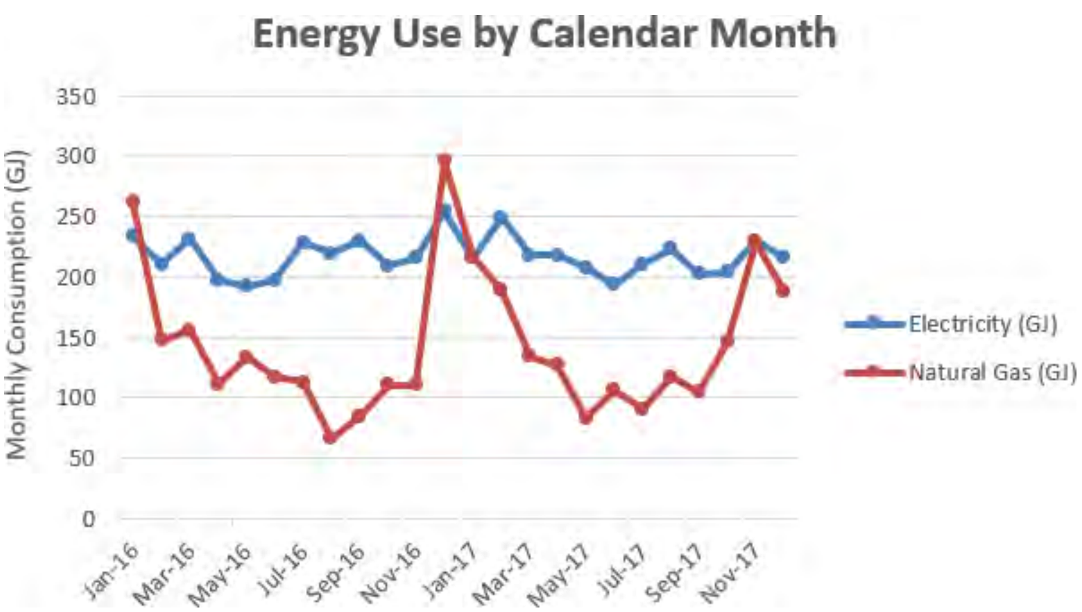


Figure 4.69: Monthly Utility Data by Types of Building I

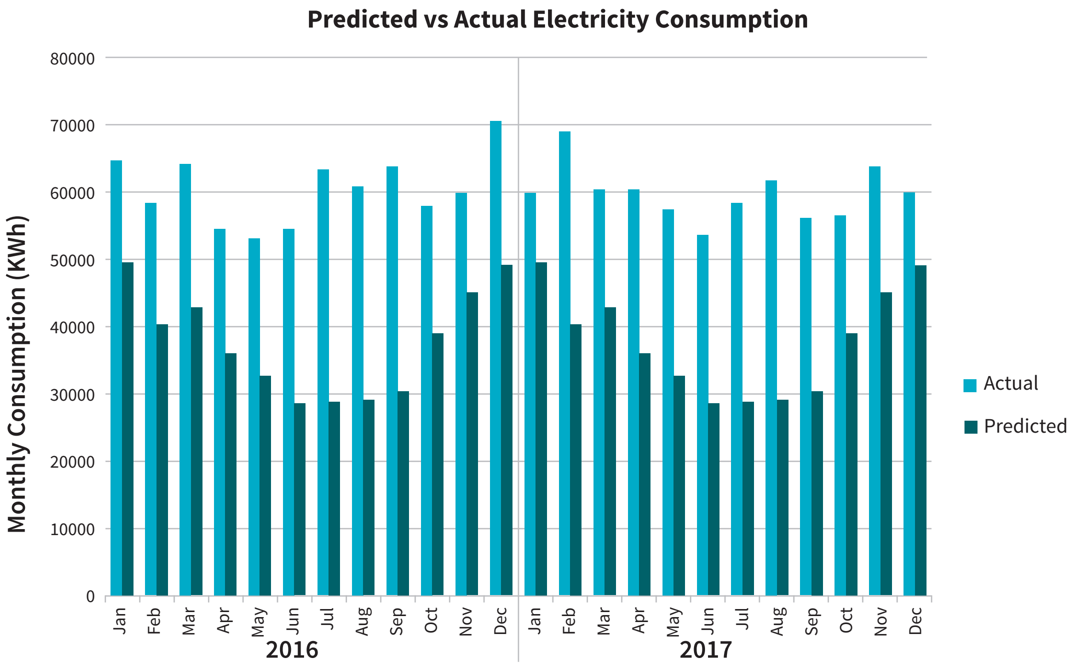


Figure 4.70: Electricity Consumption Comparison Between 2016 and 2017 of Building I

Recommendations

- Design of the ASHP system should be developed by experienced engineers who are knowledgeable in sustainable building design.
- Select an appropriate appliance. This is one of the critical factors for achieving the predicted energy target and normal operation of the building. The HP 1-3 and various pumps have limitations for achieving the outcome of the predicted design.
- Install sub-meters to track detailed end-uses to implement energy-saving measures.
- Continuous recommissioning of the building is necessary due to numerous mechanical failures.
- The DDC system needs to be updated to enable the alarm/alerting and plotting functions so that the operators can diagnose existing/potential issues of building performance.
- The boiler room on the top floor is very small and makes it near impossible to change the large equipment on the rooftop. The design of rooftop access needs to be carefully considered to accommodate future alterations that can need large equipment.

4.10 Case Study: Building J

4.10.1 General Description

Building J is a four-storey mid-rise, low-carbon, supportive, residential housing building located in New Westminster, British Columbia. The wood-frame building has a total floor area of 1,591m^2 and offers 24 units out of which 11 units are for transitional housing and 13 units are permanent, independent suites.

Public transit, including SkyTrain station and bus loop, and a centralized shopping center with grocery stores and restaurants, are within a 10-minute walk from Building J. The main floor has a lounge, library, multi-purpose room, and a kitchen for tenant use for their social events.

Large operable windows with blinds are installed in the lobby for daylight, natural air exchange, and saving energy during the daytime. It was occupied in 2011 and received LEED Gold certification under LEED Canada-NC 1.0 in 2012.

4.10.2 Mechanical System and DHW System

At the planning stage, heating and cooling for the building were designed to be supplied by the central air source heat pump HP-1. When the OAT falls below 0°C, HP-1 is disabled instead of firing the boiler B-1. The OAT heating/cooling changeover set-point is 16°C without deadband. The make-up air unit AHU-1 is programmed to serve supply air at the temperature of 28°C when the OAT is lower than -5°C. The air is supplied at 13°C when the OAT is higher than 12°C. The radiant loop is programmed to serve supply water at a temperature of 40°C when the OAT is lower than -5°C, and 25°C when the OAT is higher than 13°C.

Table 4.28: Mechanical and DHW System Specifications of Building I

HVAC System Specifications	
Ventilation Air Handling Unit	AHU-1: Rooftop air handler with hydronic heating and cooling serving corridors on the second, third and fourth floor Heat pump units: Distributed heat pump units serving common area on the first floor
Space Heating System	Radiant floor heating in suites Distributed heat pump units heating general space on the first floor
Space Cooling System	Distributed heat pump units cooling general space on the first floor
Central Plant Specifications	
Heating Plant	The air-to-water heat pump (HP-1) with auxiliary natural gas boiler B-1 heating serving radiant floor and hydronic heating coils
Cooling Plant	Condensing units of HP-1 serving hydronic cooling coils
Domestic Hot Water System Specifications	
DHW	Preheated by an air-to-water heat pump (HP-1) through heat exchanger HX-1 Three electricity-powered DHW storage tanks ST-1 to 3 Low flow fixtures in washrooms

4.10.3 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

There was no natural gas utility bill available for January and February 2016. The annual energy consumption analysis was based on 10-months of data from 2016. On comparing annual energy consumption between actual performance and the predicted model, the results suggest that both years used around 90% more energy than the proposed model and over 10% more energy than the baseline model. The significant difference in natural gas use is understandable given that the ASHP system was not working for more than three years.

The full-capacity gas-fired boiler was the only heating source for the whole building. However, the boiler had some leaks, as seen on a previous inspection report, which reduced the heating efficiency and led to gas wastage. A dry cooler was added to the cooling system for providing cooled water to AHU-1. Another contributing factor for the energy consumption discrepancy could be occupant behaviour, tenants leaving windows open in winter and lights on when not in use.

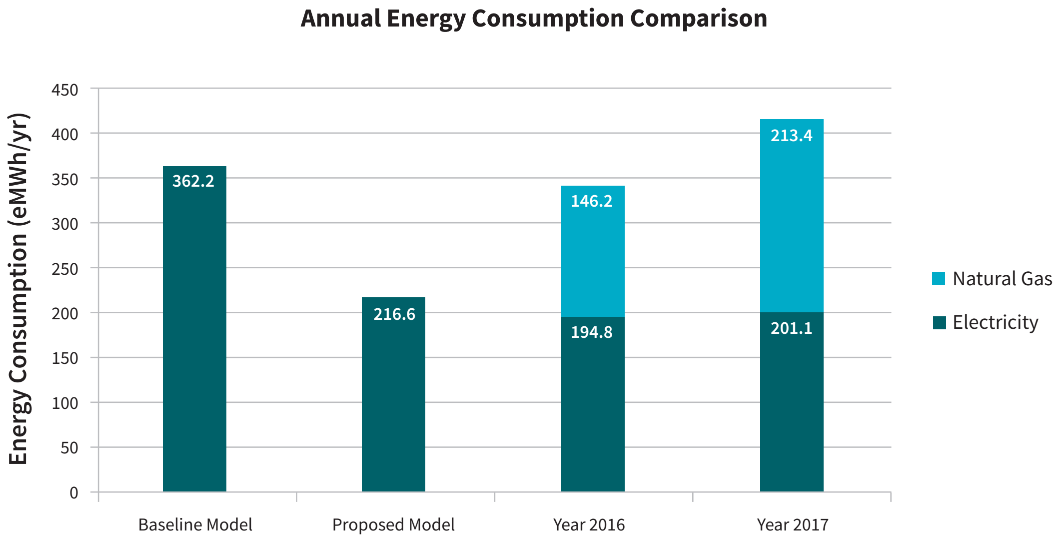


Figure 4.71: Annual Energy Consumption Comparison of Building J

Building Energy Performance Index Comparison

Both reference and proposed building models demonstrated a higher EUI compared with BEPI for MURBs, which confirms the unique housing type of Building J. Although the post-occupancy energy consumption exceeded what was predicted, it still maintained around 25% less energy use than the peer HCSA and AFS buildings.

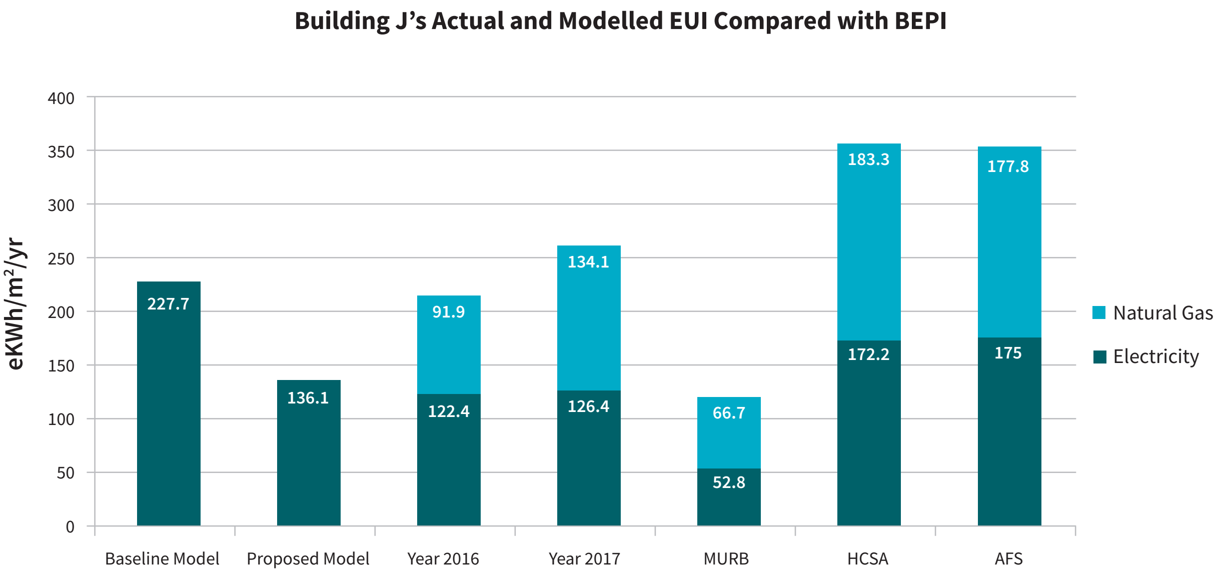


Figure 4.72: BEPI Comparison of Building J

Effects of Weather on Results

The regression analysis for both years illustrated weak correlations between energy consumption and HDD with R^2 of 0.56 and 0.27 for 2016 and 2017, respectively. For 2016, the correlation was plotted from March to December.

In Figure 4.73, the two points in a blue rectangle show that November had only half of the HDDs compared to December but consumed almost the same amount of energy. Furthermore, the yellow rectangle suggests that November and March, with approximately the same HDDs, had a significant difference in energy consumption. It can be deduced that some equipment issues may have occurred during November 2016.

For 2017, three groups of noticeably unusual consumption data are highlighted in the red, orange, and green rectangles in Figure 4.74. The two points in the red rectangle represent June and September, which have the same HDD yet highly different energy consumption. The orange rectangle indicates that September had fewer HDDs, but energy consumption was almost the same as January. Even though December, shown in the green rectangle, had the second most HDDs, the total monthly energy consumption was considerably lower than most of the other months.

Mechanical issues related to the heating/cooling system and occupant behaviours had more significant effects on energy consumption than the weather for Building J.

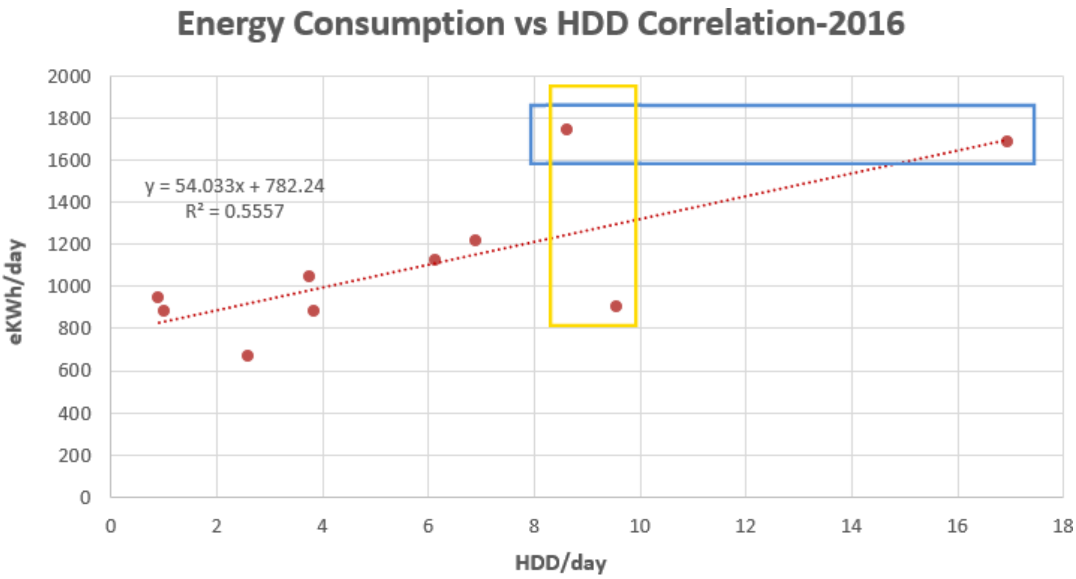


Figure 4.73: Effects of Weather on Building J for 2016

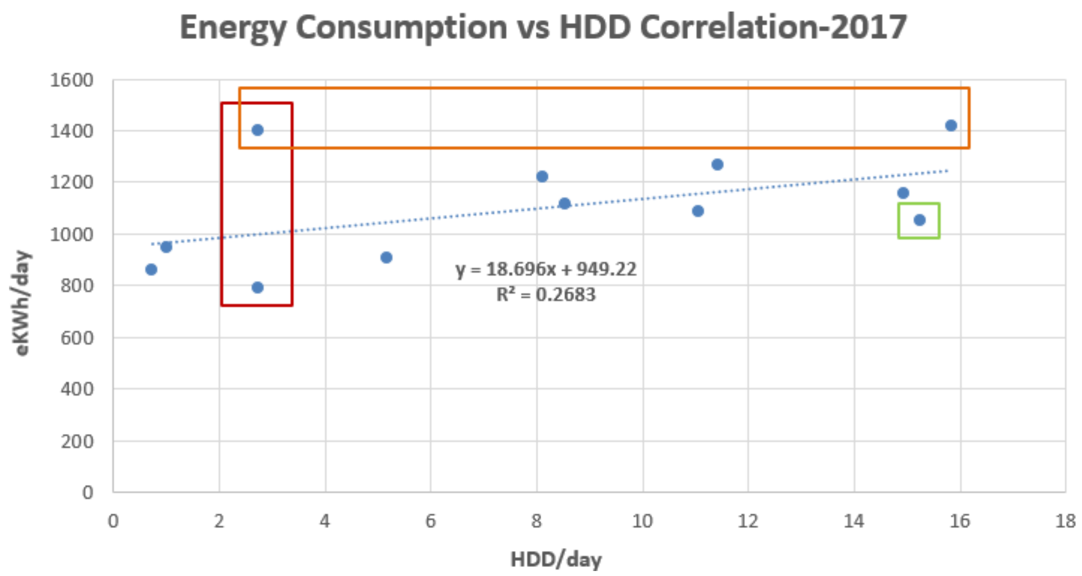


Figure 4.74: Effects of Weather on Building J for 2017

Monthly Electricity Consumption Comparison

After plotting the electricity consumption for 2016 and 2017, the month of August is observed to have the highest electricity consumption due to the use of additional fans in residential units and frequent use of the air conditioner in common spaces. The biggest discrepancies appear in May, July, October and November with an average consumption variation of 3,760KWh. Specific trends in the data for hydro consumption are not observed for Building J, which can be the result of mechanical equipment issues and occupant behaviour.

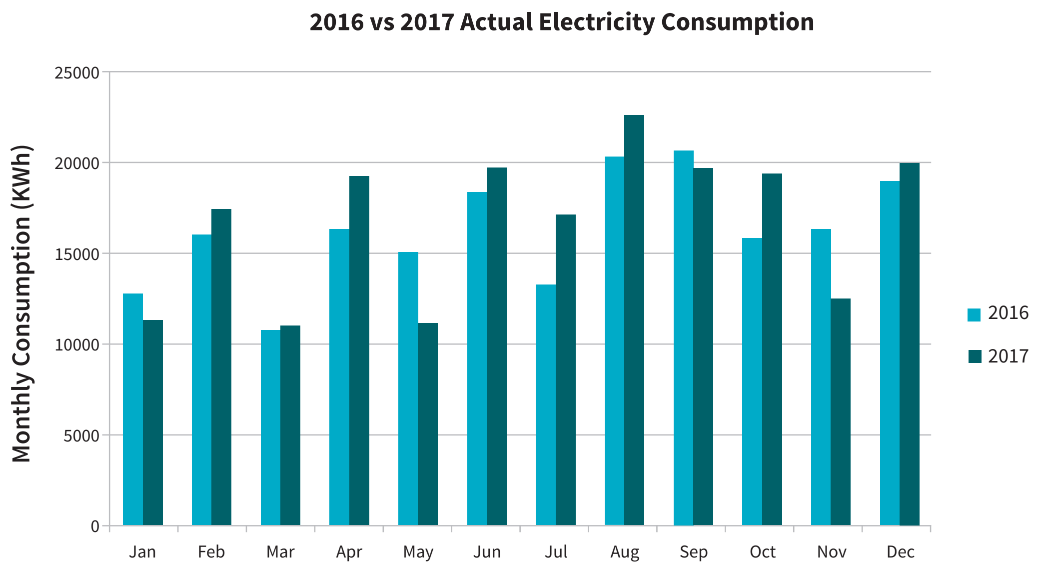


Figure 4.75: Electricity Consumption Comparison Between 2016 and 2017 of Building J

Recommendations

- Employ building maintenance managers who have advanced skill sets and the ability to operate complex mechanical systems.
- Add sensors on the boiler and alarms in the DDC system to detect leaks and save natural gas as a result.

4.11 Summary and Discussion of Case Studies

4.11.1 Summary of 10 Buildings

Based on the case studies described, buildings performed differently from one another because of diverse architectural and engineering design variations, as well as unique building issues related to design, construction, commissioning and operation. A summary of the findings from individual case studies is outlined in this section. The summary emphasizes the interrelationship between performance gaps and designed EUI, floor area, type of central plant and M&V credit categorically.

The designed (modelled) EUI for each building varied widely from 80.3 to 164.9 eKWh/m^2/yr. Figure 4.76 shows a summary of whether or not these buildings achieved the design target. On the chart, each building has four bars to illustrate: 1) the reference baseline model, 2) the proposed model, 3) 2016 energy consumption, and 4) 2017 energy consumption results from left to right.

Two of the buildings – Building E and F – overperformed compared to their proposed models, while other buildings did not reach their high-performance goal. All of the buildings, except for Building C, H, and J, realized significant energy savings, especially in the reduction of fossil fuels when compared to their baseline building models.

The aim of reducing natural gas follows BC Housing's High-Performance GHG Strategy goals of keeping the total energy use to a maximum of 10% from fossil fuels. For Building C, H, and J, possible non-regulated loads excluded in the energy model cannot explain the large discrepancy.

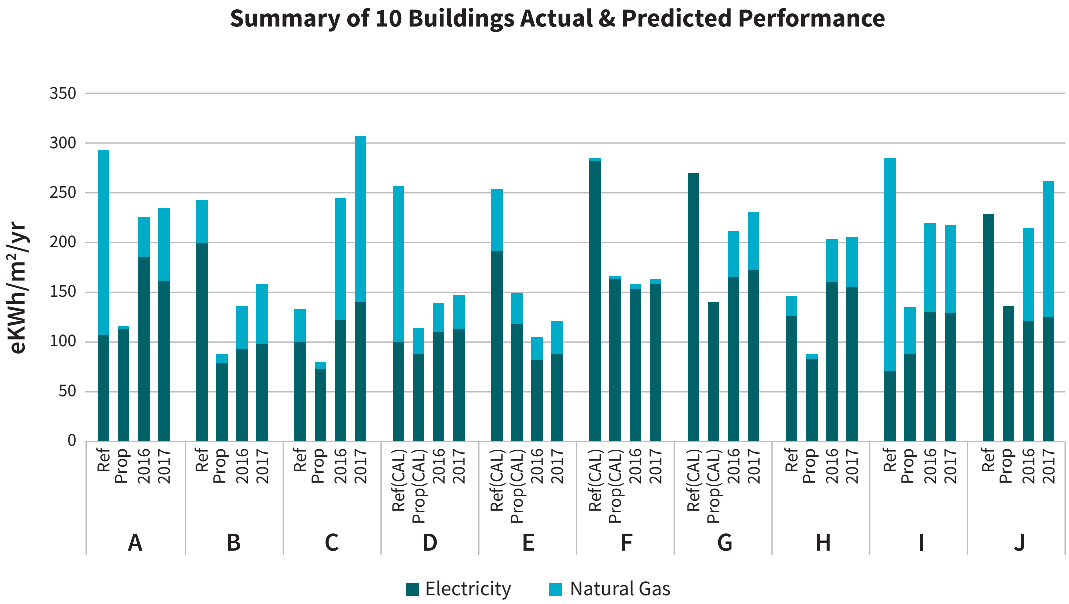


Figure 4.76: Summary of Annual Energy Consumption Comparison

Figure 4.77 examines if energy consumption discrepancy is influenced by the size of a building. After getting rid of the two exception points of Building C (with an over 200% gap), the performance gap percentage fluctuated among various sizes. This indicates a weak interrelationship to the building floor area.

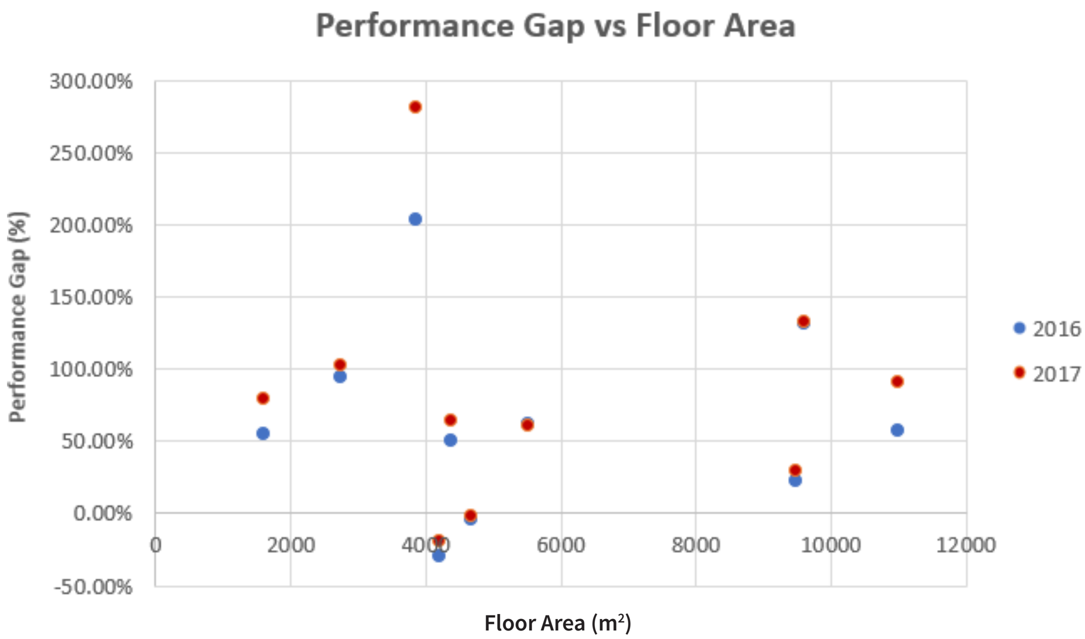


Figure 4.77: Summary of Performance Gap vs Floor Area

Table 4.29 summarizes the core equipment of the central plant, the total performance gap for both years and the M&V credit application. As shown in Figure 4.76, the building without an efficient central plant for the mechanical system resulted in the highest variation from the prediction.

Buildings adopting ASHP systems were likely to face more challenges in achieving their design targets. Building D to G employed M&V methods to evaluate post-occupancy building performance. Out of these four buildings, Building E and F completed the required continuous 3-year verification process. Building D and G terminated their M&V plan due to the unsolved inaccuracy of sub-metered data.

It can be concluded that appropriate M&V methods are effective for energy conservation. Furthermore, based on the case studies, the GSHP systems had fewer issues compared to the ASHP systems.

Table 4.29: Summary of the Building System, Performance Gap and M&V

Building #	Central Plant	Total Performance Gap% (2016)	Total Performance Gap% (2017)
Building A	ASHP	+94.3%	+102.9%
Building B	ASHP	+54.7%	+79.4%
Building C	N/A	+203.7%	+281.7%
Building D	NEU	+22.1%	+29.3%
Building E	GSHP	-29.3%	-19.2%
Building F	GSHP	-4.4%	-1.5%
Building G	GSHP	+50.8%	+64.4%
Building H	ASHP	+131.1%	+132.2%
Building I	ASHP	+61.6%	+61.3%
Building J	ASHP	+57.4%(incomplete)	+91.4%

4.12 Lessons Learned from Case Studies of 10 Buildings

Establish the Design Strategy

The first challenge to overcome in the design of sustainable buildings is ensuring collaboration amongst stakeholders. It is important to align the aesthetics principles suggested by architects and high-performance targets proposed by mechanical engineers to meet post-occupancy performance targets. The design can proceed without settling the disputes between the involved parties leading to overly complex mechanical system designs.

Consequently, complicated building systems create challenges for control engineers to design an appropriate control system. As a result, higher costs are incurred at the planning stage or in the form of maintenance costs, once the building is occupied.

Lifecycle assessments for energy and cost must be considered at the design stage. Based on the discussion above, the lifecycle assessment is likely to play a key role in building consensus between architects and contractors if low energy consumption and low cost are shared goals.

The mechanical design principle of all the 10 buildings was generally the same. All the buildings used highly efficient core equipment – heat recovery ventilation units, ASHPs, GSHPs, and solar panels to generate heating/cooling energy. However, each design was different in terms of equipment specifications such as the size of the equipment, water flow calculations, pump pressure and other characteristics.

A review of evaluation reports suggested that designers created new designs each time, rather than using a successful design from the past as a reference and modifying it to improve overall performance. Each new design created the risk for new issues during the operations phase and challenges with addressing the observed issues. As an example from the case studies, the failure of solar panels and the unreasonable physical size of the mechanical room highlight this issue.

Furthermore, designers rarely considered maintenance costs of the building in the operations phase, potentially contributing to a higher life-cycle cost. Buildings using M&V methods were more likely to achieve their energy performance goals.

At the beginning of the planning stage, it is recommended that M&V should be included in the whole building design. M&V specialists should be included in the design team meetings, early in the process since it is costly to add sub-metering points after the mechanical and electrical systems have been designed.

Improve the Accuracy of Modelling

The recommendation to improve the energy modelling process does not suggest errors in the energy model. Each model was validated and reviewed by experienced energy consultants to ensure accuracy. However, most of the modelling results included in this research cannot represent the actual energy performance of these buildings. The primary reason is that the energy model did not consider every non-regulated plug load. It is necessary to include all spaces and all metered energy in the simulation to achieve a precise post-occupancy evaluation. Other causes for the discrepancy can be classified into two categories, which are occupant related and weather-related.

The most typical representation of weather-related inaccuracies was the performance curves applied in the ASHP modelling. In some cases, the performance data provided by manufacturers was unreliable. The unforeseen low energy efficiency of ASHPs during freezing days led to increased natural gas consumption. Thus, manufacturers are encouraged to test as much performance data as possible during real operation, for at least an entire winter season, and share actual performance curves with energy modellers.

Occupant related factors stem from the unique schedules and behaviours of many social housing occupants. As a result, the calibration process can be very challenging because of this uncertainty. One feasible approach is to recalibrate existing LEED social housing buildings based on real-life monitoring data. Through quantitative recalibrations of this particular type of residential building, a set of standard inputs, unique to social housing units, can be created for realistic energy performance simulation.

Extend the Commissioning Period

The commissioning process is intended to confirm that various mechanical systems are operating as planned, the equipment has been correctly installed, and active control sequences and systems perform as designed. Hiring an experienced commissioning agent is crucial for completing a detailed examination.

As outlined in the case studies, a large number of issues were discovered once the buildings were occupied. For example, failure of solar energy systems, improper locations of VSD pump pressure sensors, and erroneous control of 3-way valves were discovered post-occupancy. The commissioning engineer can help to prevent such issues to an extent. Additionally, installing a sub-metering system to monitor various real-time end uses can assist the commissioning agent to locate and analyze issues.

In general, the commissioning process occurs before the building is handed over. This leads to an assessment of the building when the building is unoccupied. It can be seen from the case studies and literature reviews outlined in this report that occupant behaviours have a significant impact on building performance. Consequently, continuous commissioning is recommended.

Continuous commissioning repeats the testing process to examine the control sequences of the building system. It allows building performance to be optimized while satisfying the thermal comfort of tenants. The efficiency loss due to seasonal changes, improper operation, and wear and tear on equipment can be largely reduced or eliminated by employing continuous commissioning. It is recommended to keep track of any maintenance records, repairs and commissioning phases as reference for future building retrofits and overhauls.

Strengthen Facility Management's Capability

The on-site visits to the buildings in this report suggest that operators are not always up to date with the latest renewable building system technologies or have adequate background knowledge in the technical aspects of facility management. Some maintenance managers were not familiar with DDC systems and relied on remote supervision by contractors. Control contractors may not always be interested in the operations or maintenance of the building and hence contribute to overall energy wastage and increased service costs.

It is essential to train operators to understand the initial design objectives, the renewable systems, and to familiarize themselves with the control strategies. Additionally, detailed mechanical drawings and O&M manuals should be visible and accessible.

Update the DDC system

All of the DDC systems should be updated and capable of storing hourly data, generating trend graphs, and delivering alarms and alerts to verify current and potential operating issues. Monitoring data should be saved in the system for at least two years and available for easy export. This can act as reference information for future retrofits and research. Regular checks of the DDC system to ensure the graphs generated are consistent with monitoring data are necessary.

5 Conclusions

This study investigated the performance discrepancy between modelling outputs and field energy consumption of 10 LEED Gold social housing buildings, located in Victoria and Vancouver, British Columbia. A comparative study of different green building rating systems, including Passive House, Living Building Challenge, LEED 2009 and LEED v4 was completed to better understand the benefits and limitations of each program.

The literature review examined performance differences from previous research, summarized possible causes from conception to operation stage, and categorized hidden issues in highly-efficient buildings. Based on the literature review and individual examination of building sites, solutions and recommendations for social housing multi-unit residential buildings (MURBs) were developed. Developing solutions and recommendations for bridging the performance gap was the primary motivation for this study. The analysis was completed by collecting 2016 and 2017 monthly electricity and natural gas bills from building management organizations or energy suppliers (including BC Hydro and Fortis BC) and comparing them to known energy models.

Buildings were also compared with NRCan's database benchmarking buildings to quantify the superiority of their energy savings, as compared to other conventional peer buildings. The effect of the weather was also investigated to eliminate potential deficiencies in the analysis. The investigation of individual buildings and reviews of prior inspection reports supported the verification of problematic mechanical systems, control strategies, and defective operating techniques.

The evaluation suggests that only two out of ten buildings outperformed compared to the predicted model results. In contrast, three buildings consumed more energy than their baseline buildings. Extra natural gas usage was typical for most of the examined buildings. Although the design intent rigorously followed BC Housing's fossil fuel combustion criteria to minimize natural gas usage, the outcomes illustrate the limitations of these planned approaches. It is important to highlight that large amounts of natural gas were saved as compared to baseline buildings.

Air source heat pumps were observed to be the most common barrier to energy efficiency, given their low coefficient of performance (COP) during cold days. Two buildings abandoned their ASHP systems and the other three buildings, which were equipped with an air source heat pump (ASHP) system, experienced extremely high natural gas consumption as a result of the inefficiency of heat pumps in winter. Ground source heat pumps performed much better in such scenarios.

Almost all buildings served by heat recovery ventilation (HRV) systems did not benefit from free cooling during summer nights. This is attributable to the control strategies of providing heating when the outdoor air temperature (OAT) is lower than 18°C. The slow response of the radiant floor heating system was found to be another reason for the performance gap. Tenants often had little patience for waiting several hours to allow their suites to warm up, which usually led to a higher than necessary adjustment to thermostats (up to 28°C and even 30°C).

Poor design of solar panel systems and their connection to other systems led to unexpected loss of this source of renewable energy. Other small defects such as installation and positioning errors reinforced the discrepancy.

It is essential to simplify the design of mechanical systems and control strategies to ensure that energy targets are achievable. Uncertainties at the construction and operation stages may increase as the complexity of the systems increases, which is likely to add energy penalties. Future maintenance costs and service availability must be considered during the preliminary design phase. The service availability refers to whether the equipment is easily accessible and whether the cost to service the equipment is affordable.

Effective communication within the team to finalize designs and budgets can be attained by using the Integrated Project Delivery (IPD) method which gathers stakeholders together to establish a stable framework to ensure the project's success. [91]

Advanced data collection methods can be a practical approach to improving building performance. Data collection should consist of sub-metered consumption data as well as service and retrofit costs, which are valuable for both troubleshooting and property management. Furthermore, it is recommended that all properties should have access to the full set of building system drawings and descriptions on site. Organizations can share utility data and acquire cost-effective methods for energy saving from other successful projects.

Various performance gaps observed were a result of mechanical issues as well as from limitations of energy modelling. The unique parameter inputs for social housing type buildings, based on occupant behaviours, needs to be considered during modelling. Heat pumps need to be tested in real operation to modify performance curves that are used in energy models. The energy model needs to contain as much non-regulated load as possible to provide convenience and precision for the post-occupancy evaluation.

In summary, a successful green building project requires reliable and simple designs, precise energy modelling, careful construction detailing, adequate commissioning, qualified operation and continuous commissioning.

Future research should focus on 1) calibrating energy models based on BC Building Codes and LEED v4 standards to improve the modelling guidelines, and 2) exploring building design, construction and commissioning processes, including consulting with contractors for a more detailed analysis of the performance gaps between predicted results and field performance.

Appendix A

A.1 Occupant Satisfaction Survey

Thank you for participating in the Occupant Satisfaction Survey.

1. How long have you lived in Building A?

2. Please indicate your age:
   ◯ Below 30 ◯ 31-50 ◯ 51- 64 ◯ Above 65

3. Please indicate your gender:
   ◯ Female ◯ Male ◯ Prefer not to answer

4. Which floor are you living on?
   ◯ 1 ◯ 2 ◯ 3 ◯ 4

5. What is your window's orientation?
   ◯ North ◯ South ◯ East ◯ West ◯ Don't know

6. How often do you open windows in winter **daytime**?
   ◯ Everyday ◯ 3 to 5 days per week ◯ Depending on weather ◯ Never

7. How often do you open windows in winter **nighttime**?
   ◯ Everyday ◯ 3 to 5 days per week ◯ Depending on weather ◯ Never

8. Is your room hot in summer?
   ◯ Yes* ◯ No
   *If yes, please answer the following questions 8.1, 8.2 and 8.3

8.1 Is your room too hot **every summer**?
◯ Yes ◯ No

8.2 Are you using other equipment for cooling such as fans?
◯ Yes ◯ No

8.3 How comfortable do you feel after using additional fans?
Not comfortable ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Very comfortable

9. Is your room too cold in winter?

◯ Yes* ◯ No

* If yes, please answer the following questions 9.1, 9.2, 9.3

9.1 Is your room too cold **every winter**?

◯ Yes ◯ No

9.2 Are you using other equipment for heating such as electric heaters?

◯ Yes ◯ No

9.3 How comfortable do you feel after using additional heaters?

Not comfortable ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Very comfortable

10. How satisfied are you with the in-floor heating in winter?

Not satisfied ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Very satisfied

11. Is the ventilations sufficient in summer?

◯ Yes ◯ No

12. Do you feel any air leakage during winter nighttime?

◯ Yes ◯ No

13. How satisfied are you with the thermal comfort of your room?

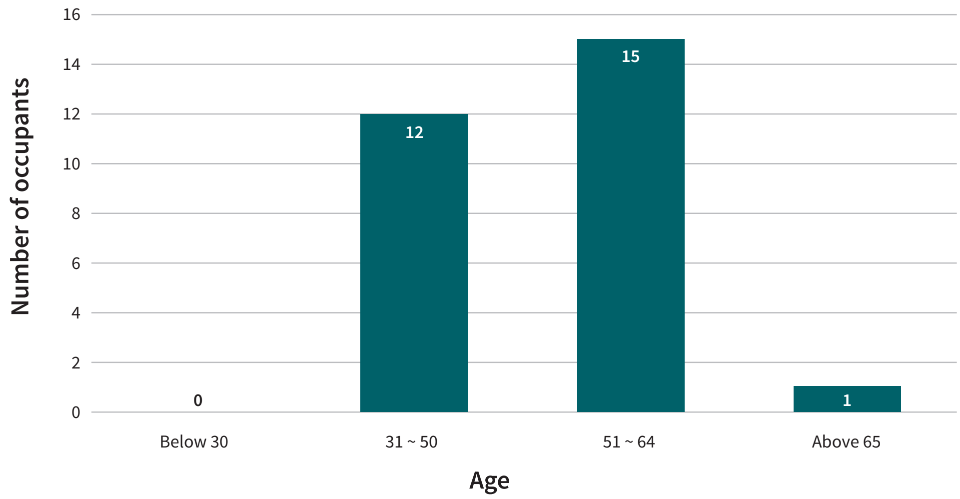
Not satisfied ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Very satisfied

14. How satisfied are you with the acoustic privacy of your place?

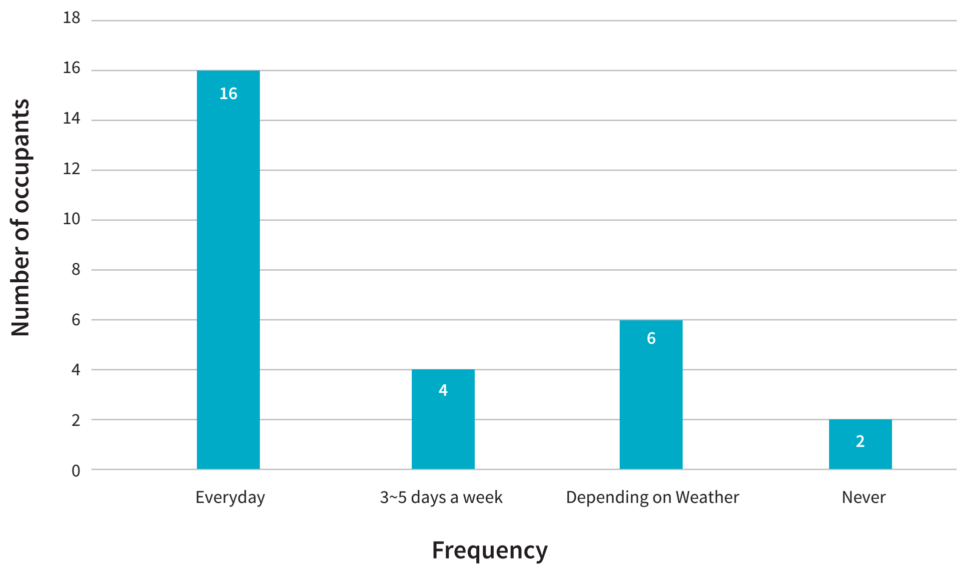
Not satisfied ◯ 1 ◯ 2 ◯ 3 ◯ 4 ◯ 5 Very satisfied

A.2 Occupant Satisfaction Survey Summary

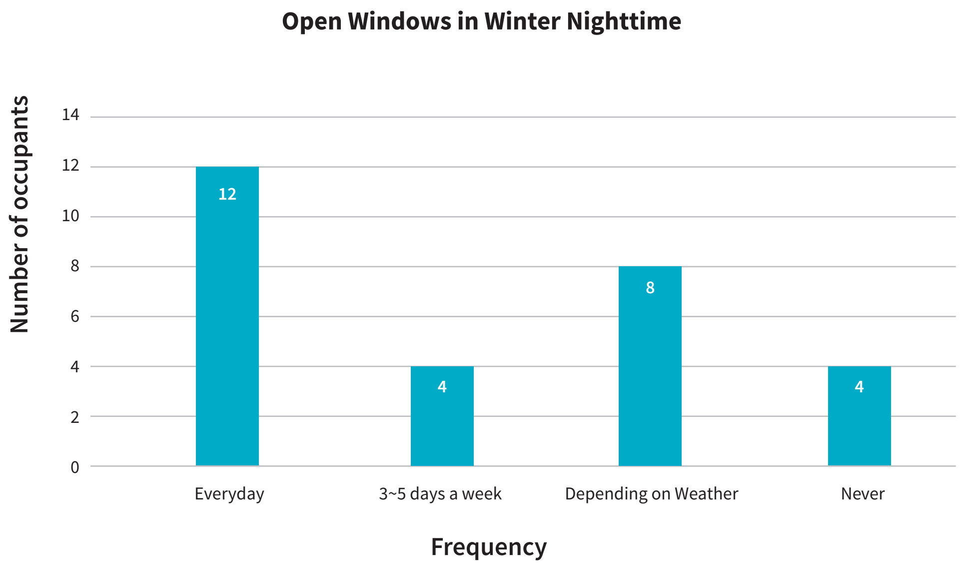
28/49 suite occupants participated in the survey



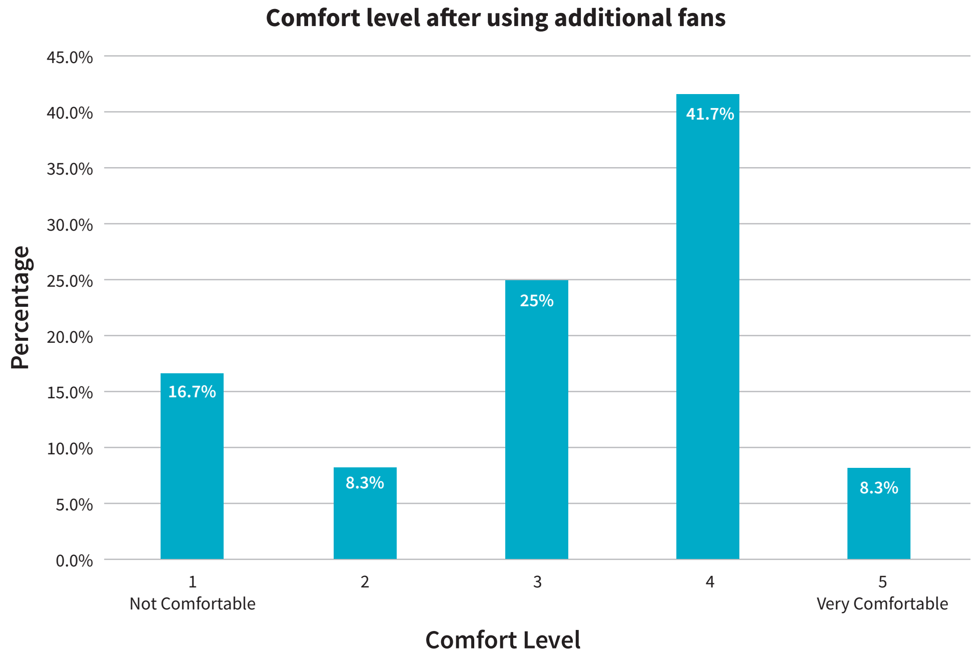
Open Windows in Winter Daytime



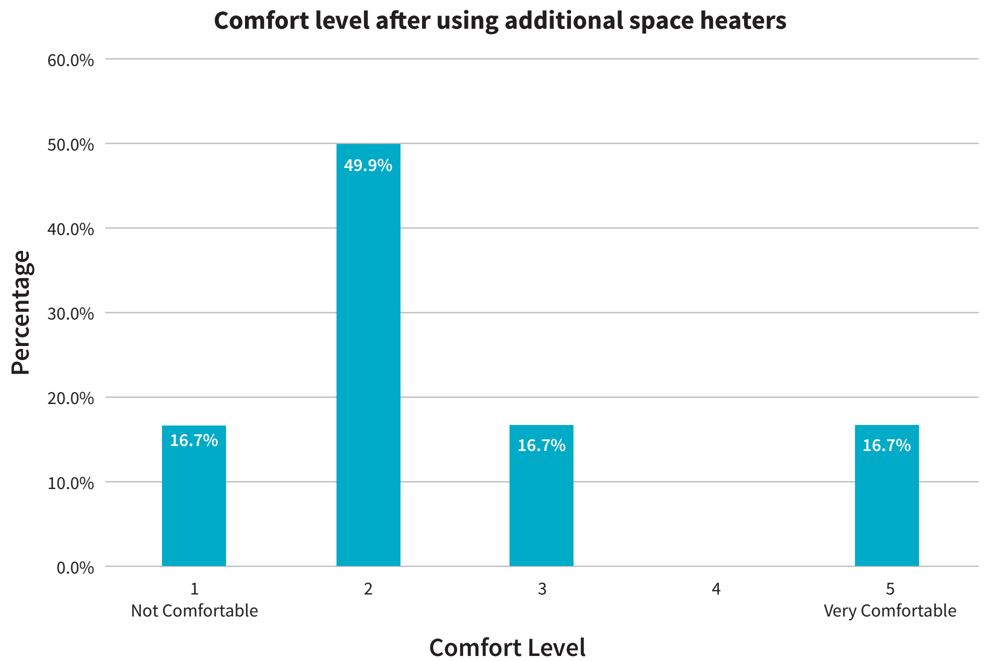
Frequency	Everyday	3~5 days	Weather	Never
Percentage	57.1%	14.3%	21.4%	7.1%



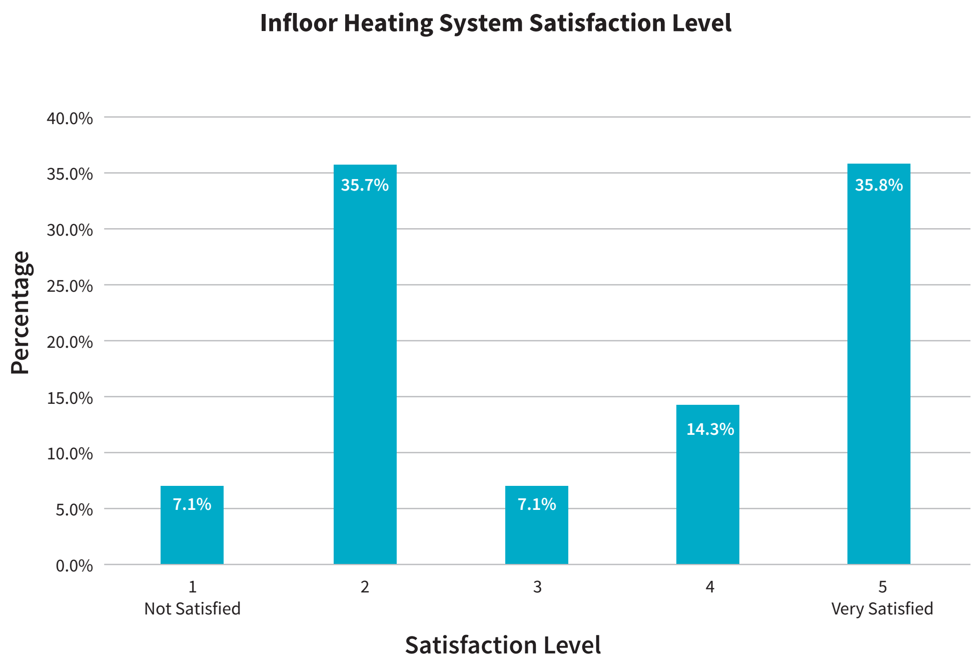
Frequency	Everyday	3~5 days	Weather	Never
Percentage	42.9%	14.3%	28.6%	14.3%

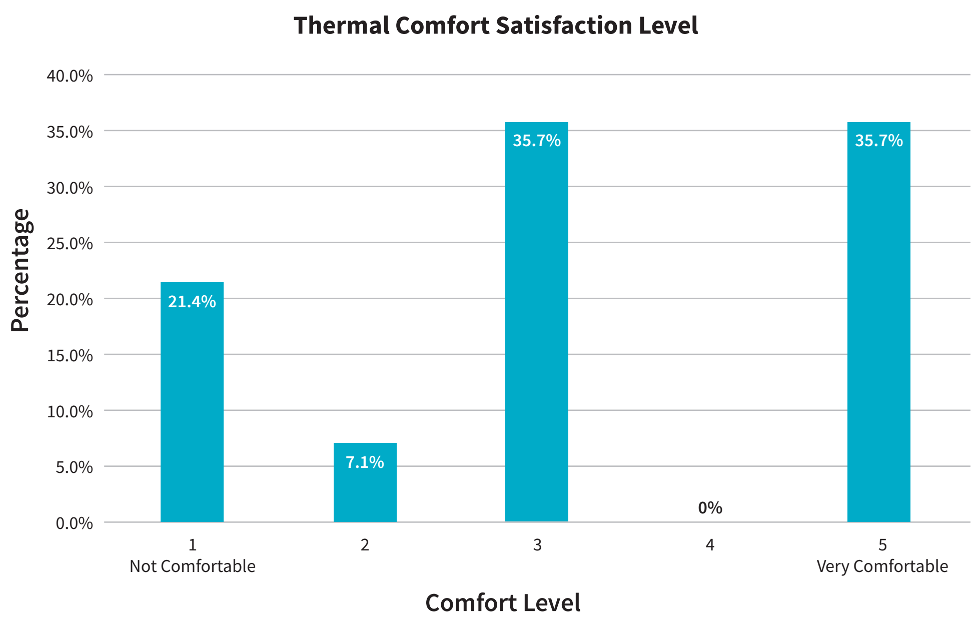


Twenty-four out of 28 (85.7%) occupants use additional fans in summer; some occupants use more than one fan.

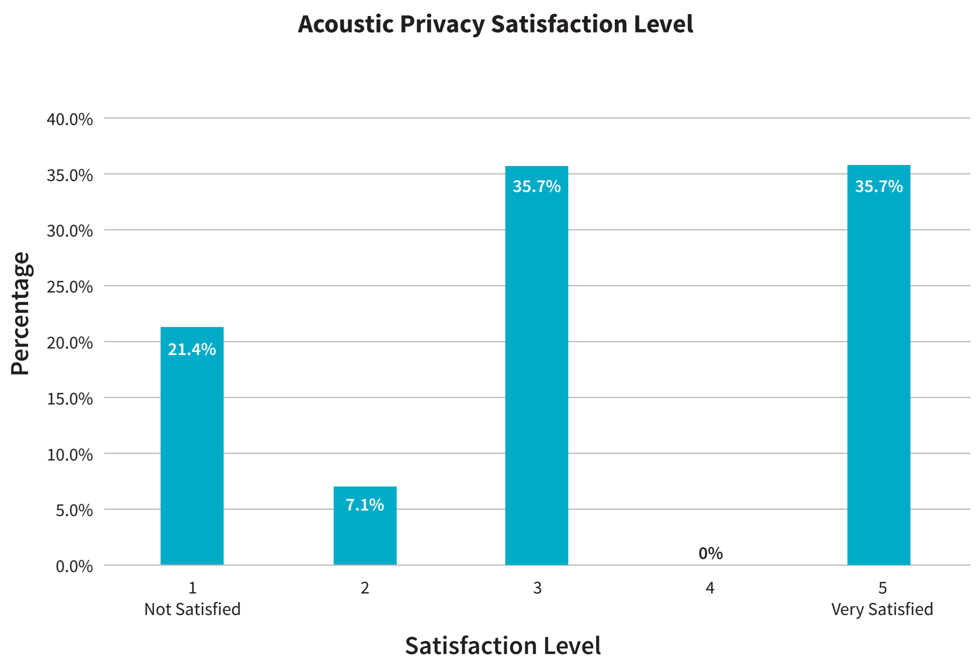


Twelve out of 28 (42.9%) occupants use additional heaters in winter.





Sixteen out of 28 (57%) occupants complained ventilation was not sufficient in summer. Twelve out of 28 (43%) occupants have felt air leaks on winter nights.



Acoustic Privacy Satisfaction Level
Percentage
40.0%
35.0%
30.0%
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
21.4%
7.1%
35.7%
0%
35.7%
1
Not Satisfied
2
3
4
5
Very Satisfied
Satisfaction Level

Appendix B

B.1 Facility Manager Survey

Thank you for participating in the Building Performance Survey

1. How long have you worked as the maintenance manager for this building?

2. Please indicate what new technologies were applied to the building (even if the system is not working now):
   A. Solar energy system
   B. Heat recovery ventilation
   C. Radiant in-floor heating system
   D. Air source heat pump system
   E. Geothermal loop (ground source heat pump)
   F. Neighbourhood Energy Utility (NEU) system
   G. Others (specify)

3. Are there any specific issues with the building? You are welcome to add your comments to the blank area below:
   A. None
   B. Overheating issues during the summer
   C. Too warm in summer in certain areas
   D. Too cold in winter in certain areas
   E. Poor quality of specific equipment
   F. Poor installation of specific equipment
   G. High maintenance fee
   H. Other (specify)

4. What factors contribute to the performance gap of the building? You are welcome to add your comments to the blank area below.
   A. Overly complex
   B. Thoughtless design
   C. Inefficiency of specific equipment
   D. Poor quality of specific equipment
   E. Poor installation of specific equipment
   F. Control/programming issues with DDC system
   G. Unexpected occupancy behaviours (for example, open windows in winter, extra fan/heater use)
   H. Ineffective commissioning
   I. Others (specify)

5. Which equipment is more likely to break down or more frequently needs service? You are welcome to add your comments to the blank area below.
   A. Air source heat pump
   B. Ground source heat pump
   C. Water-to-water heat pump
   D. Decompressor
   E. Distributed air conditioners
   F. Heat exchanger
   G. Boiler
   H. DHW water heating tank
   I. Solar system
   J. Pump
   K. Fan
   L. Valve
   M. Pipe
   N. Make-up air handling unit
   O. Heat recovery ventilation unit
   P. Radiant in-floor heating system
   Q. In-suite thermostat
   R. Sensor
   S. VFD/VSD
   T. Glycol feed station
   U. Others (specify)

6. Do you have any difficulty in operating or maintaining new technologies (for example, the complexity of controlling the system, poor design led to barriers in adjusting, repairing and maintaining)? Please feel free to comment below:

7. Do you have any further suggestions or recommendations for future green building design? Please feel free to comment below:

Appendix C

C.1 Energy Modelling Results of Building A

	January	February	March	April	May	June
Electricity (GJ)	69.9	63.1	70.0	67.3	69.8	67.5
Natural Gas (GJ)	104.9	74.2	65.9	35.5	11.9	3.4
Total (GJ)	174.8	137.3	135.9	102.8	81.7	70.9
	July	**August**	**September**	**October**	**November**	**December**
Electricity (GJ)	129.2	129.9	94.4	69.7	67.7	69.8
Natural Gas (GJ)	0	0	6.4	32.2	67.1	99.1
Total (GJ)	129.2	129.9	100.8	101.9	134.8	168.9

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