Design versus Actual Energy Performance in Green Buildings

by

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B.Sc., Northeastern University, 2013

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ABSTRACT

The secondary energy use and GHG emissions have noticeably increased during recent decades in Canada; the residential sector accounted for the third largest portion of total energy use. The government and market turned to building highly efficient residential buildings for energy savings. However, premature technologies and designs brought countless issues from conception to operation stages resulting in performance discrepancies between the modelled results and field performance. This thesis looked into ten LEED Gold certified social houses in Victoria and Vancouver, BC to reveal their performance gaps, to investigate possible causes, to seek practical solutions and to summarize proper recommendations for the green building industry. It was accomplished by collecting LEED energy model and utility data for two years of each building, comparing their predicted and actual energy consumption, examining each site, discussing with facility managers and analyzing performance gaps. In addition, occupancy and building staff surveys served as robust support to the research. The assessment shows only two buildings realized their preliminary high-performance goals. Other buildings sustained an offset of energy consumption from the minimum of 22.1% to the maximum of 281.7% compared to their proposed models. The reasons for the discrepancy covered all the phases of a building's life from design to construction, to commissioning and to post-occupancy. The most common concerns were the unexpected inefficiency of air source heat pumps and unpredictable occupancy behaviours such as leaving windows open in winter. In consideration of these, the calibration of energy models according to refined performance curves of heat pumps and particular inputs for social housings would provide a more accurate prediction.

Together with improved designs, adequate commissioning and appropriate operation, performance gaps can be narrowed to a greater extent.

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Chapter 1

Introduction

The energy consumption of building construction and operation occupies an essential place in Canada's energy distribution. In 2013, the residential sector used around 17% of the total energy , of which space heating loads accounts for 53% and 62% in BC and Canada respectively[1]. Due to the continuously increasing population and environmental pollution across the world, the design of new sustainable buildings to reduce energy consumption is becoming the new direction in the construction industry. With the rising number of new green buildings being constructed, a rating system to assess the performance of a building is needed. The building performance assessment focuses on setting up a scheme to evaluate the cost of the construction and operation process, the impact on the environment, the energy saving's level and the satisfaction of the occupants.

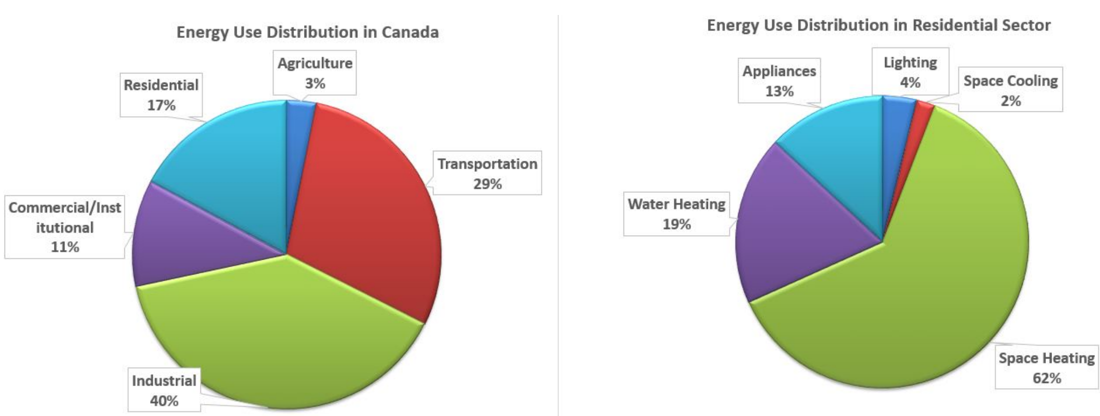


Figure 1.1: Energy Use Breakdown and Residential Sector Energy Use Breakdown in Canada[1]

LEED (Leadership in Energy and Environmental Design) is currently 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 & atmosphere, materials and resources, indoor environmental quality, innovation in design and regional priority. Each category gives one or more prerequisites for designers to satisfy to receive the initial assessment qualification of LEED-certified buildings. Designers then have the right to select the most applicable and felicitous points to earn for their projects under various credits. With total points of 100 LEED features four different levels of highly efficient buildings, which is LEED Certified (40∼49 points), LEED Silver (50∼59 points), LEED Gold (60∼79 points) and LEED Platinum (80 or more points)[3].

Passive House is another international-recognized certification system for energy-efficient buildings that was initially developed in Germany. The energy use intensity of Passive House certified buildings is usually 80∼90% lower than the conventional matched buildings, which is mostly attributed to the strict Passive House standards. The Passive House assessment requires a maximum of 15kWh/m^2 energy or 10 W/m^2 load each year to heat the space, a maximum of 120 kWh/m^2 energy use in total each year and a maximum of 0.6/h air tightness.[4]

As some of the energy performance of LEED-certified buildings did not behave as expected according to the post-occupancy evaluation, a more rigorous benchmark and standard for green buildings – Living Building Challenge (LBC) is developed[5]. The construction projects being assessed by LBC are required to provide the first occupancy year's energy consumption bill to demonstrate that the actual energy use does not exceed that at the design stage. Similar to the LEED rating system, LBC buildings are also authorized through specific categories, which are Place, Water, Energy, Health & Happiness, Materials, Equity and Beauty. LBC encourages three different certifications – Living Building certification, Petal certification and Net Zero Energy Building certification segregated by achieving different combinations of seven categories.

As people spend most of their time in buildings, the energy consumption decrease usually means an improvement in people's quality of life. Many studies have proved that most of energy efficient buildings use less energy than their conventional matched ones. An analysis conducted by National Research Canada[6] in 2009 announced that LEED buildings, in general, saved 18∼39% energy compared with the typical traditional matched buildings. Nevertheless, LEED-certified buildings that used more energy than the conventional matched ones accounted for 28∼35%. The principle of matched buildings defined by this paper contains similar age, activity type, floor area, and climate zone.

NBI analysis[7], probably the largest study, compared the median energy use intensity (EUI) of 100 LEED buildings to the mean EUI from CBECS database. For these LEED buildings, the total EUI was obtained by summing one full year's billing data. The result showed that the median EUI of LEED buildings was 33% lower than the mean EUI in CBECS database, but this study needs further analysis due to its limitations on sample size and sample matching level.

There might be a small discrepancy between the energy performances of green buildings assigned by different rating systems. It is delivered by the 20th International Passive House Conference 2016 that an average of 85% reduction in energy use for heating and cooling per square meter can be expected for buildings certified by Passive House standard, which is mostly contributed to the strict certification criteria of Passive House benchmark[8]. Also, buildings designated by the Living Building Challenge also present satisfied results due to its net-zero energy or net positive energy use prerequisite.

This study was inspired by a series of researches addressing the performance gap between designed and actual energy consumption in green buildings rated by various rating systems. The difference of rating systems, evaluation of building performances, investigation of possible causes and hidden issues of green buildings were reviewed as the foundation of the thesis. Ten LEED Gold buildings developed by BC Housing that were built five to ten years ago are the analysis samples. The post-turnover performance assessment of these buildings was implemented to verify if the primary design goals were realized. The examination of individual buildings was followed up to explore reasons for the performance discrepancy and summarize solutions to conquer the obstacles. Occupancy and building staff surveys were finally conducted to identify issues of case study buildings and provide guidance for future building development.

Chapter 2

Literature Review

2.1 Comparison of Different Green Rating Systems

In recent decades, the construction of energy efficient buildings is becoming mainstream in Canada. Despite the fact that most of the sustainable buildings have achieved the green building standards and performed a lot better than their conventional counterparts, certain buildings have not been acting as predicted at the design stage. Another problem gaining much attention currently is that higher level certified buildings may not perform better than lower level ones. It means that in some cases the actual energy performance of LEED Certified buildings perform better than LEED Silver buildings, LEED Silver buildings perform better than LEED Gold buildings and LEED Gold buildings better than LEED Platinum buildings. In consideration of this unexpected situation, a newer version of rating schemes has been modified every several years according to the changing construction technology and expectation.

2.1.1 LEED 2009 vs LEED v4

LEED v4 is the latest version of the LEED building rating system that took four years to develop from the previous version-LEED 2009. LEED v4 combined ten different rating systems in LEED 2009 into five, which are 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 Neighbourhood

Development (ND), LEED for Homes Design and Construction. It specified that multifamily buildings with four or more stories could use LEED BD+C instead of LEED HOMES as their certification target.

One of the widely-identified desiderata of LEED v4 is to improve the transparency in materials and resources. Although some LEED-certified green buildings achieved energy saving criteria, they are not as green as they appear to be due to substandard materials used in these buildings. One new prerequisite was set to help clarify the waste treatment and recycling rates. Three new credits are added to Building Product Disclosure and Optimization to track sources of raw materials, material ingredients and product life-cycle impacts. Another valuable development of LEED v4 involved in the imperatives of water and energy metering. In some previous LEED projects, the deficiency of post-occupancy metering data resulted in much worse field performance than predicted. The new interpolated strict prerequisites, to some extent, ensure better building performance in energy and water efficiency. Besides, the commissioning process is issued with higher significance in LEED v4 with more comprehensive prerequisite and credit specification, and the review of building envelope design is mandatory.[9]

2.1.2 Passive House VS LEED VS Living Building Challenge

Both LEED and Living Building Challenge standards are category assessment based. Apart from the energy performance rating that accounts for the most critical portion, there are still other items that need to be evaluated and ranked having a substantial impact on the certification authorization, such as site and material selection. In contrast, the Passive House standard only focuses on the total energy consumption, heating load and airtightness level. See Table 2.1 for the detailed difference.

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	% of the reduction in energy use compared modelled data to reference data (35/100 points)	Predicted energy consumption meets the certification criteria	A twelve-month post-occupancy meter data to prove net-zero energy use
Water Assessment	% of the reduction in water use compared modelled data to reference data (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)	Low thermal conductivity insulation materials required	Red list materials free, net positive waste
Indoor Environment	Indoor Air Quality Performance test at design stage (15/100 points)	Boundary conditions or calculation rules applied at the design stage	A nine-month post-occupancy Indoor Air Quality test

Table 2.1: General Comparison between LEED, PH and LBC

2.2 Performance Gaps between Actual and Designed Consumption

CMHC[10] performed a review study of the performance of a six-story multi-unit residential building in areas including energy, indoor environmental quality and environmental impacts. The design objective was designated to save 35% energy use based on the Canadian Model National Energy Code for Buildings and maintained a higher level of occupants' satisfaction at the same time. Refined heat recovery HVAC system and building insulation strategy were applied to the design and construction of the building. Separated subsystem metering was used to provide secondary end use and natural gas data for research and refinement in the future. To collect the performance data, distinct programs were generated to keep track of relevant elements such as energy use, HVAC systems and building insulations. According to the collected data, this building saved about 29.7% energy about the Model National Energy Code value and 54.3% energy in relation to the functionally equivalent reference buildings. Besides, this apartment performed much better than conventional buildings in water saving, HVAC system efficiency and reduction of thermal bridging.

iiSBE Canada[11] directed a project to investigate the differences between projected and actual performance in key performance indicators (KPI) of nine green buildings in Canada. The assessment of energy consumption in this research required a minimum of two years' energy billing report to provide a valuable reference for the comparison. Besides, interviews with building stakeholders such as designers, managers and occupants were also made to ensure an adequate understanding of building performance targets. However, the number of occupants seemed impossible to be strictly applied to the energy model used at the design phase, which might be one of the prominent elements that influenced the results. In this study, five of the green buildings' energy use intensity exceeded the projected value; one of them even used approximately 2.3% more energy than the conventional matched buildings. The report also pointed out that buildings with worse performances were more likely to receive lower satisfaction level in areas such as acoustic, lighting and thermal comfort.

K. Mahapatra and S. Olsson[12] investigated two residential apartments recognized by Passive House rating system in Sweden. The research suggested a concept of "specific energy use" that was used in the building code of Sweden, which described the actual energy consumption for the building operation without household end uses. About 90% of the building owners or tenants showed their satisfaction with the building performance including good indoor environmental quality and low cost of energy. In comparison to the projected energy model, the actual specific energy use was 10.43% more than the predicted value due to the more energy consumption on space heating. Nonetheless, the two green apartments saved around 3.7 kWh energy (total energy use including household end uses) per floor area annually, which performed better than the Passive House benchmark and typical reference buildings.

A survey[13] was conducted by C. Turner to study LEED building performance for the Cascadia Region Green Building Council. Eleven buildings with the operation of more than one year were included in this study, seven of them were non-residential buildings, and four were multi-family residential buildings. Most of the occupants showed a high satisfaction in overall indoor environmental quality in spite of some noise issues. Six buildings had less actual EUI than that of anticipated, three of them were residential buildings. On average, residential buildings used 86% of total energy compared to their initial designed model. The study also made a comparison between these LEED buildings EUI and Energy Star standard benchmark, all but two stayed below or within the range of Energy Star benchmark. In addition, six out of seven buildings actual water consumption exceeded their modelled value by an average of 133%.

The research[14] organized by USGBC and related institutions was set up in 2006 to explore the energy performance of 21 buildings certified by LEED from 2001 to 2005. Although these 21 samples only accounted for 7% of 300 LEED buildings of the year 2006, they served as the representations of major types of buildings and most of them were able to provide three years' utility billing data. Although the performances of these buildings were varied, eleven out of eighteen buildings showed an average of 27.4% energy saving compared to initial simulated values. Four of these eleven target achieved buildings were eligible to be awarded Energy Star certification. In this study, the federal buildings performed better than non-federal in real operation. The federal buildings saved 22% energy consumption compared to modelled outputs while the non-federal (exclude four laboratory buildings) exceeded 2% EUI in contrast.

A study[15] featured by using eQuest simulation software and real weather data to investigate the discrepancy between the actual and simulated performance of a five-story university building was conducted in 2013. The weather file and metering data including electricity and gas were collected from 2011 to 2013. In this study, the simulation was run on both annually and monthly basis to ensure a more accurate comparison result. The actual electricity use saved 6.4%, 0.7%, 19.5% energy in each year respectively (assessment for 2013 was from January to April). On the contrary, the actual gas consumption used more energy at 33%, 4.5% and 21.7% respectively. On this basis, the overall actual energy consumption lowered 3.9% in comparison to the eQuest modelled value. Concerning monthly data, most of the predictions were with a high accuracy except for a noticeable performance gap of 51.6% less energy use in May 2011. One of the reasons for the difference between electricity and gas consumption was the occupancy load. In the observation of 2012 collected data, the occupancy load was only 55% of that specified in the simulation.

Figure 2.1 summarizes the energy saving levels of reviewd buildings. 21 out of 38 buildings achieved the prediction. The performance offset of these buildings varies from about -200% to +80%.

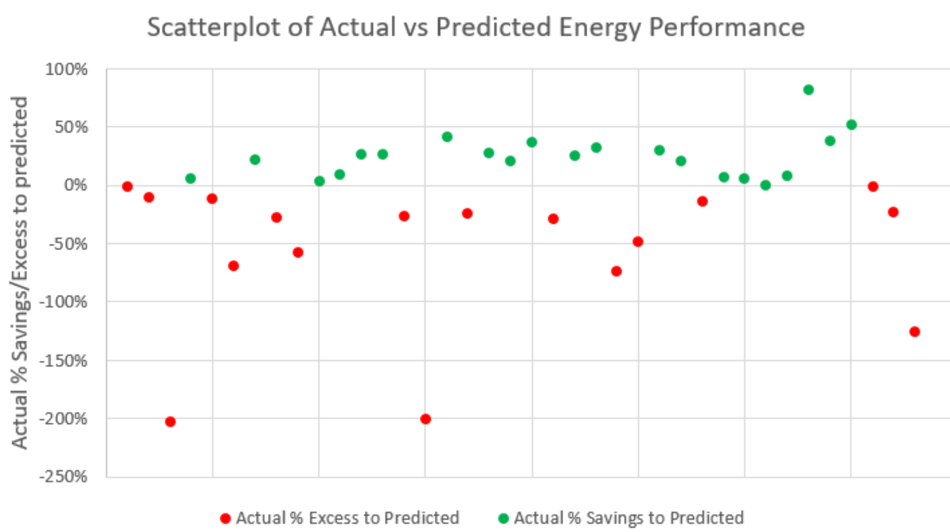


Figure 2.1: Summary of reviewd buildings' performance

The amelioration of occupancy satisfaction with IEQ (Indoor Environmental Quality) is another crucial factor of green buildings. In a survey[16] conducted by University of California, 15 LEED buildings along with 200 conventional buildings were assessed their IEQ in four categories - thermal comfort, indoor air quality, lighting and acoustic through questionnaires. Answers were classified as seven levels satisfaction, 3 points for very satisfied and -3 for very dissatisfied. In overall building comfort, thermal satisfaction and indoor air quality areas LEED buildings obtained higher average scores, which were 1.47 to 0.93, 0.36 to -0.16 and 1.14 to 0.52 respectively. In consideration of the young age of LEED buildings, they still performed better when they were compared with conventional buildings under 15 years; LEED buildings still received higher satisfaction. However, the performance of lighting and acoustics in LEED buildings were not superior to conventional ones. The same situation happened in another study[17] that was composed of 12 green and 12 conventional buildings. These buildings were paired according to significant properties including activity types, size, age and climate zone. The study was based on online surveys, interviews with operators and measurement of a few physical elements such as airspeed, temperature and small particles using the NICE Cart. The similar results of[16] and[17] were approved in other studies. The green residential high-rise building analyzed in[18] also received positive feedback in thermal comfort and indoor air quality. Moreover, the review study proceeded by Birt and Newsham[19] concluded that positive feedback was mostly given to thermal comfort and indoor air quality in green buildings but not to lighting and acoustic.

2.3 General Reasons for Performance Gaps

Narrowing the gaps between field performances and modelling outputs is a fundamental section of the construction industry. The gaps involve multiple reasons and can be classified as four main aspects-Design, Construction, Commissioning and Operation.

2.3.1 Design

The first dilemma of designing can be the diversified ideas from designers, consultants and owners of the building construction and operation[20]. W. Shen[21] introduced a user activity simulation and evaluation method (UASEM) that suggested a more effective way for engineers and occupants to communicate. This pre-occupancy evaluation can to some extent optimize the performance of green buildings, but other issues are existing in the designing process such as an insufficient estimate of the occupants, plug-loads and passive heating and cooling[22].

The design itself can frequently cause the underperformance of buildings. On the one hand, the green building industry tends to use sophisticated control systems to achieve higher energy efficiency. However, designers always had the assumption that these difficult-to-understand systems could be ideally operated after being occupied, which is a common problem at the modelling stage[22]. On the other hand, the Zero Carbon Hub[23] revealed that a whole design process is assigned as partitioned phases that are designated by different directors. For instance, initial exterior enclosure design that met both artistic and construction requirements may produce trouble for detailed subsequential design such as thermal bridge minimization and airtightness optimization. Thus, iterated communication between different design stages is recommended to ensure a performance-advanced model.

Another point needed to be kept in mind is the limitations of simulation software. The accurate modelling of certain items including weather data[25] and airflow[26] is hard to realize with today's technology. Moreover, a simulation is performed with very detailed boundary conditions, which might not be consistent with the practical data[27]. The discrepancy between theoretical and simulated values may lead both designers and owners to higher expectations at the design stage, but feel disappointed after living in.

Without the post-occupancy building operation data, the input parameters that were applied in the original energy model at the design stage is more likely to deliver inaccurate energy performance prediction. For instance, the research conducted by iiSBE[11] pointed out that the mismatch in occupancy number, occupancy behaviour and operation practices contributed a lot to the performance gaps. The uncertainties including lighting control, plug loads, HVAC system operation, temperature setpoints and operable windows control can significantly increase the actual energy use of a building[28]. Both the misestimate of timber usage in the building envelope and the miscalculation of other existed places with thermal bridging and heat loss led to a 70% higher energy loss than anticipated[29]. The unexpected occupancy densities and behaviours are very likely to cause the inaccurate modelling of heating systems and ultimately create performance gaps[30]. Efforts are recommended to be taken to calibrate the initial model by using actual performance data and thus provide a way to set up better models for future designs[28][27].

2.3.2 Construction

A common challenge existing in the construction phase is whether a building can be constructed as originally designed. The significant performance discrepancies may result from extremely small defects[20]. An unpredicted cost-cutting decision may lead to invisible debased construction quality change in such as insulation and airtightness system[22] and furthermore, affect the energy performance of a building. The Zero Carbon Hub[23] emphasized the importance of resource control and transparency in consideration of the possible performance changes issued from the replacement of specific product and material in real construction. An example of this is from Elm Tree Mews research[29], in which switching to another window supplier made 21% more energy loss in heat compared to the predicted value. With more and more complicated control systems utilized, installation work is experiencing further challenges. In Elm Tree Mews research, having difficulties to install the passive solar systems was a common issue such as leaking problems and positioning errors.

The performance gaps may also derive from a typical defective construction process of the building. The Zero Carbon Hub[23] summarized a series of issues needed to be carefully inspected during a construction process from understanding the fundamentals of sustainable buildings to effective as-built performance assessment. A flexible but indefinite production control has a chance to get some work reconstructed to ensure the installation such as cables, pipes and insulation to be appropriately performed, the process of which is neither efficient nor energy sustainable. Accordingly, the development of more detailed construction sequencing is approved to put the construction process on the path towards less cost and better performance. Furthermore, it is advantageous to establish more standardized processes for the same house types and mitigate the risk of building underperformance resulted from the work such as different designed routes of pipes and cables. The inspection process can also be brought about more efficiently and easily with the advanced standardization. Finally, as a critical part of a construction process, the as-constructed performance evaluation has not been held in the great account. For instance, the relatively simple and clear testing of airtightness is implemented superficially, making barriers for operatives to check the installation work. If appropriate support is considered to provide to input the measurement process, not only the quality of construction but also the improvement of design can be guaranteed.

2.3.3 Commissioning

There might have been opportunities to narrow the performance gap through building commisioning. Building commisioning defines a professional process that reviews building systems including mechanical systems, electrical systems and renewable energy systems along with their sub-systems and confirms the completion and effectiveness of these systems in comparison to the initial design target[31]. From an analysis[32] of 643 buildings, commisioning is proved to be a cost-effective method to achieve better energy performance. However, this paper pointed out that most of the improvements through commisioning were not noticeable immediately and as a result, owners were not willing to pay for the process.

A typical challenge in building commisioning is to ensure adequate verification of building systems and their associated sub-systems. However, as[33] mentioned, many energy-saving devices do not perform as they were originally designed due to incomplete commissioning applications. A similar condition was also revealed in ARUP's study[22], inadequately tested sub-metering systems during commisioning are more likely to provide worthless operation data. Retro-commissioning is introduced as the remedy for inadequate commisioning. An example showed that after a retro-commisioning of the cooling system, a 25% diminish in the cooling loads was achieved[34]. A great number of inadequate commisioning might stem from the insufficient time left to this process according to the study of[32], in which only around 25% buildings started commisioning at the design phase, and only approximately 30% starting from construction.

Natural Resources Canada recommended life-cycle commisioning rather than one-time commisioning[35] in consideration that despite, in some cases, commissioning has been completed to meet the Owner's Project Requirements, performance gaps might still exist in real operation. The IFMA Foundation demonstrated that even buildings with completed commisioning and well-maintained devices might usually have a 10 15% downgraded performance after several years' operation[36]. The seasonal commisioning was suggested by Arup[22] and Carbon Trust[37] to mitigate the impact of changing the weather on building performance. For instance, to verify the operation of the heating system at its peak season, Bideford College re-commisioned the systems in winter to ensure the optimal performance of the building. The re-commisioning was also suggested by[38] as long as there exists ageing equipment, drifting sensors and other possible factors changing building functions. In this case, the continuous commisioning is indispensable to keep a building operating at high efficiency[39]. As the framework of continuous commisioning 'Soft Landings', featured a process not only performed during construction but after the project completion as well and it was recommended for buildings seeking better performance in spite of the existence of imperfections[37][40].

2.3.4 Operation

One of the most significant factors that can produce problems in building performance is the imprecise control of building systems. The lack of appropriate metering system disables to provide accurate performance data for building operators or managers. It appears to be more robust for them to understand the operation of the building better and moreover, it becomes almost impossible to adjust the control systems for higher efficiency. It has been proved by [41] that buildings with energy consumption metering systems upgraded an average of 10% in performance compared to the upgrade of 4% 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 the significant saving within two years in both electrical and gas use – 13% and 48% reduction respectively. However, after installing the monitoring system, the examination of possible metering errors should be applied to ensure the effective use of the metering data[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 control due to its complex systems. As mentioned in the study[41], experienced operators had the capability to find the optimal control strategy according to the monitoring data and improved the building performance to the maximum extent compared to new green building operators. The insufficient understanding of the building system from both managers and inhabitants may give rise to the underperformance of the building[22][29][33][20]. For example, the inappropriate control of HVAC and lighting systems brought about 200% more energy outputs than prediction[13]. As a consequence, developing the professional skills of operators makes a great potential to save the actual energy expenditure in buildings.

There is increasing evidence that occupant behaviour has an enormous impact on building performance deviation. Occupant preference on building system controls such as temperature set points and operable windows is one of the most significant operational factors that affect heating and cooling energy consumption of a residential building[43][30]. The study of[44] pointed out that the voluntarily controlled operational hours of heating systems contribute even more to the energy usage than temperature setpoints. For non-domestic buildings that occupants cannot control heating and cooling systems directly, the opening and closing of windows are more likely to drive the energy waste[45][46][47]. Furthermore, the uncertainty of occupancy numbers can largely influence the energy expenditure of a building[22][33].

2.4 Hidden Issues of Green Buildings

2.4.1 Green Roof

Green roofs are widely used nowadays to reduce rain runoff, save cooling energy usage in summer and mitigate urban heat island in sustainable building designs[48]. They can be categorized into two types based on different media soil depth and plant species – extensive and intensive roofs[49]. In the meanwhile, related issues have been questioned and studied to optimize the performance of green roofs. One of the most significant challenges is to select a proper weight growing medium. Intensive green roofs are usually very heavy that may place a burden on building structure and thus, are rarely used[50]. From CMHC's research[51], 75mm depth of growing medium performed as well as 150mm depth in both rainwater management and thermal effectiveness. The inappropriate use of heavier weight green roofing system may cause the potential structure problem and lead to higher maintenance cost[52]. Furthermore, there exists a controversy that green roofs may lead to more space heating consumption in winter[53]. With vegetation and growing medium, green roofing systems are relatively more complex and challenging to detect leaks in drainage, insulation and membrane layers[54]. Besides, the materials used for drainage, filter, protection and membrane layers are typically polymers that can cause extra energy consumption and pollution throughout their fabrication process[53][55]. This might be another concern although some pollution can be offset by the long-term use of green roofs, greener materials are recommended to be applied to achieve the real sustainability[56].

2.4.2 Material

The ultimate goals of green building are to be constructed environmental-friendly and operated sustainably at high efficiency. To mitigate the pollution generated by conventional materials, the use of renewable materials has been a trend and obligation based on green building rating systems' suggestions[9]. However, the lack of knowledge about new materials can lead to the inappropriate selection of materials that introduces potential risks to building endurance and performance[57]. The new OSB-core resin door is formaldehyde free but easily damaged by compression, which makes it a short-lived non-green product[58]. Also, some of them were only partially tested in the laboratory to ensure basic properties compliance such as thermal and acoustics, and this complex analysis may cause further failures in building performance[59]. A study[60] conducted a review of renewable insulation materials and identified that the study of unconventional materials is rarely comprehensive at this stage. For example, the data of certain properties such as thermal dynamic, fire safety, earthquake resistance and water absorption need to be further explored. Another big concern is the indoor mould and moisture problem related to materials. It has been demonstrated in[61] that microbial growth can be found in various building materials and some are even generated during production processes[62]. Nevertheless, little research data can be accessed on the relationship between green materials and fungal growth[63], and the long-time testing which is essential is unavailable[64]. Also, although green building schemes suggest using low emitting materials for building the structure, some of the recycled materials existed in furniture are evidenced having higher emitting of VOC (volatile organic compounds) that is detrimental for occupant's health[65].

2.4.3 Water

The design of water systems in green buildings is generally targeted to have a minimum of 20% less water usage than conventional designs[66]. However, this specification indirectly leads to a longer water conservation period and may affect the water quality and ultimately, has a negative impact on occupant's health[67]. According to the fact sheet prepared by[68], longer water age can damage plumbing pieces with accumulated corrosion and influence human health with more generation of microorganisms. This view has also been confirmed by[66], in which three green water systems were compared to one conventional system. The results demonstrated that water in green plumbing systems could be preserved for 2.7 days to 6.7 months, whereas water conserved in a conventional system can stay for only one day. Besides, the pathogen genetic level existing in water of green buildings was tested much higher than conventional ones.

2.5 EnergyPlus as the LEED Building Modelling Software

CaGBC has approved several energy modelling software to predict the performance of buildings that are pursuing LEED certification, among which EnergyPlus is a widely accepted and used simulation tool. It has been 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 BETest) [69].

A benchmark of 400 residential buildings in Brunei Darussalam was set up by using EnergyPlus[70]. The necessary building geometry information such as buildings envelope and materials were collected by surveys and interviews with related individuals. In addition, the climate data offered by the local Meteorological Department was used in the energy modelling process. The detailed operation schedule was furthest specified according to the investigation results. The predicted energy consumption stays approximately the same as the actual utility bills in spite of some small fluctuation due to various occupant behaviours. However, 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 of the required 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 with represented climate features (cold, medium, warm) were selected, 42 simulations were applied to each location, and the simulated results were approved by comparing with issued measurements. In this study, lighting has been identified as a potential saving component, and furthermore, the building orientation and insulation factors may contribute a lot to reduce energy use in relatively cold regions.

Fumo et al.[72] proposed a simplified methodology 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 utilized predetermined coefficients that were derived from running multifarious EnergyPlus Benchmark Models with detailed weather data. The results were validated by comparing with a number of presumptive buildings and received an accepted error within 10%. The study was then improved in[73] by using modified EnergyPlus Benchmark building energy consumption profile based on monthly electrical and fuel energy bills, and significant degradation of error rate was detected.

Another research processed using EnergyPlus was 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 system with a variety of related parameters such as power generation unit (PGU) and heat exchanger. The results indicated a significant reduction in primary energy use when adjusting CHP elements and demonstrated the ability of EnergyPlus in building energy modeling.

EnergyPlus is highly applicable to numerous specific component explorations of buildings from envelopes to complex operation systems due 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 then strongly validated with the real operation of the building. Another example is that 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. Besides, the thermal and energy study of buildings with double skin façade were largely simulated using EnergyPlus[77][78][79][80][81].

In comparison, HOT2000, which is developed by Natural Resources Canada (NRCan), acts as a leading energy modelling tool for residential buildings in Canada[82]. For instance, HOT2000 was used as the building simulation program for benchmarking 72 residential homes in Manitoba[83], for the analysis of energy consumption and GHG emissions of 2 green homes in Toronto[84] and for developing authoritative parameter setting packages that may use 20% less energy than OBC SB-12 standard[85]. However, HOT2000 is not approved as the simulation tool for LEED Canada.

2.6 Research Objectives

Through reviewing papers on green building performance along with causes for performance gaps, several findings could be concluded as below:

- Most energy efficient buildings except those with serious operational or design issues performed better than their conventional peer buildings. However, around half of the sustainable buildings did not achieve their energy performance expectations.

- In general, occupants felt satisfied with their Indoor Environment Quality of green buildings, yet acoustic issues appeared to be a noteworthy problem.

- The performance gap may be narrowed a lot if using post-occupancy feedback to calibrate design models.

- The precise control of construction and commissioning process is necessary to reach the high-performance target. Besides, the advanced commissioning process – continuous commissioning is a feasible approach to the optimal operation of building systems all around the year.

- Proper energy metering contributed a lot to energy efficiency improvement.

- An effective way to actual energy savings was paved through professional training for building operators.

Based on the fact that some green buildings can not perform as design, BC Housing introduced this project to explore performace gaps between the prediction and field performance of 10 BC Housing's multi-unit green residential buildings. Based on lessons learned from the literature review, the objectives of this study are outlined as follows:

- Examine if the involved buildings perform as predicted by energy models.

- Investigate the cause for performance gaps and summarize the contributing factors of the performance variation.

- Explore the cost-effectiveness methods to achieve better performance.

- Explore general parameters that can be modified according to the actual building performance to help predict energy use in social housing buildings.

Chapter 3

Methodology

In order to fulfill the research objectives, 10 LEED-Gold certified social housing buildings less than 8 years old were selected for the evaluation and analysis of their energy performance. Comparisons between actual and designed performance of these buildings were carried out. The involved buildings also compared to their baseline models and conventional benchmarks to identify their superior energy efficiency. With the examination of individual buildings, observations and solutions for each building were implemented and then summarised to diagnose common issues and recommendations for energy efficient social housings.

3.1 Data Collection

Comparisons between actual and predicted energy performance were accomplished by collecting monthly utility bills over a two-year period and energy modelling information of both baseline and proposed models. Monthly utility bills of electricity and natural gas for the year 2016 and 2017 for each building were collected from either building management organizations or power suppliers including BC Hydro, Fortis BC and the city of New Westminster. There were no estimated data over the period of these 24 months. LEED Canada NC v1.1 compliance energy model information for the proposed case was accumulated. Building locations, service features, envelopes, materials, mechanical systems and types of occupants were gathered from building management societies and energy modellers. Both baseline and proposed energy models for all buildings were established upon the MNECB standards and compiled with per MNECB Code Supplement except for building H which used ASHRAE 90.1-1999 as the primary building code requirements. All buildings were modelled using EE4 software version 1.7 exclusive of building H using eQuest V3.64. The table below summarises how detailed the building energy modelling data is available.

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

Table 3.1: Energy Modelling Data-Monthly/Annually

The comparison of annual energy consumption including electricity and natural gas in terms of eMWh/yr was first performed. The building performance regarding EUI of eKWh/m^2/yr was then examined in contrast with BEPI buildings. The data source for benchmarking is originated from Natural Resource Canada's Comprehensive Energy Use Database with the latest update in 2015. In consideration that social housings included in this research are more than conventional residential apartments, a total of three types of benchmark buildings – Multi-unit Residential Building, Health Care and Social Assistance, Accommodation and Food Service – were selected from NRCan's database to satisfy the characteristics for each building.

Building Type	**Electricity** ($eKWh/m^2/yr$	**Natural Gas** ($eKWh/m^2/yr$)
MURB	52.8	66.7
HCSA	172.2	183.8
AFS	175	177.8

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

3.2 Simulation Process

Building A was selected to perform a simulation using OpenStudio and EnergyPlus. All the inputs were gathered from shop drawings and the previous submitted LEED energy models.

The geometry of the building including roofs, doors and windows were created in SketchUp, and the neighbouring properties and trees were simplified with only surfaces that might have an effect on shading. The OpenStudio plug-in is available in SketchUp which makes it possible to save the model in OpenStudio at the same time. Thermal zones allocation were completed at the geometry generation stage as well. The specification of the building envelope was input by using "material" and "construction" function in OpenStudio.

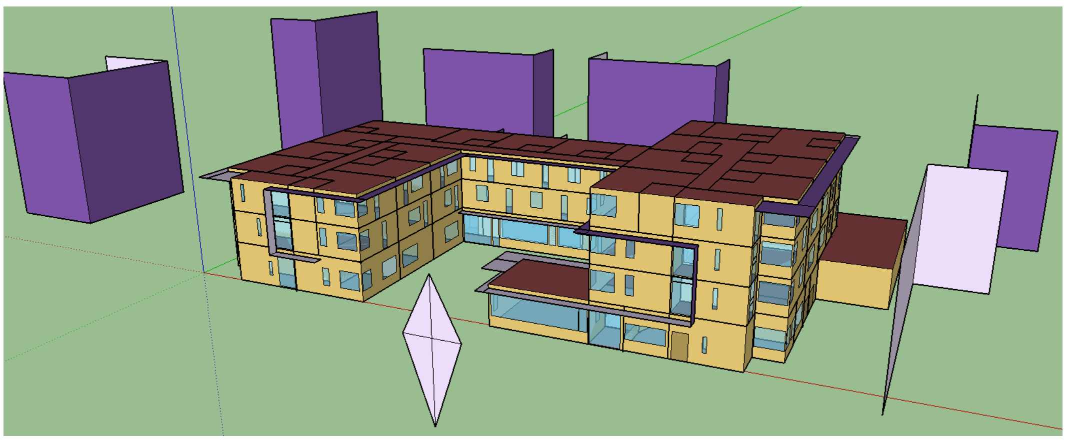


Figure 3.1: Geometry and Shading of Building A

After creating the geometry model, detailed information on internal gains (interior lighting, electrical equipment and people) for each zone were specified based on the LEED energy model. The end-use loads were calculated according to the scheduling of internal load items. Users define the total load for each category in each zone, and "Fraction" is usually used as the schedule type of lighting, equipment and occupancy describing the percentage use or vacancy rate of 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 setpoint for residential suites. Based on the occupancy survey, interviews and DDC system records, heating setpoints for units were adjusted to 23°C instead of 21.1°C.

The modelling of the mechanical system was based on the LEED energy proposed model and parameters were obtained from shop drawings. The only difference is that the air source heat pump was removed and only kept a boiler in the heating loop. This variation is to find out if the performance gap comes from the inefficiency of the air source heat pump when the outdoor temperature is low. Detailed clarification and modelling of the mechanical system for building A can be found in Section 4.1.

3.3 Exploration of Possible Causes

3.3.1 Effect of Weather

The weather file applied to the energy model is 30-year average weather data based on the Canadian Weather for Energy Calculations (CWEC) weather file. The actual weather condition for the year 2016 and 2017 might be different from the weather data applied during the simulation process. The Measurement and Verfication process of LEED buildings usually consider the influnce of heating degree days and calibrate the energy model according to the comparison results. Accordingly, the effect of weather on performance gaps needs to be reviewed to verify if it would be the potential cause for the discrepancy.

[2]Heating degree days (HDD) and Cooling degree days (CDD) are defined as an assessment tool to estimate the amount of heating or cooling energy needed for a building to achieve thermal comfort. The value of HDD and CDD specifies the summed up number of degrees required to heat or cool a building to the temperature boundary point for a particular period. The temperature limit for heating and cooling is 18°C. The equation for calculating one day's HDD is showed as (3.1):

$$HDD\ for\ one\ day = 18 - \frac{\sum_{i=1}^{24} T_i}{24} \tag{3.1}$$

Where T_i is hourly outdoor air dry bulb temperature of a day.

If the HDD result equals 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. For the HDD calculation of a whole month, the principle is to add up every day's HDD value together, and the result is the total degrees calling for heating for this month.

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

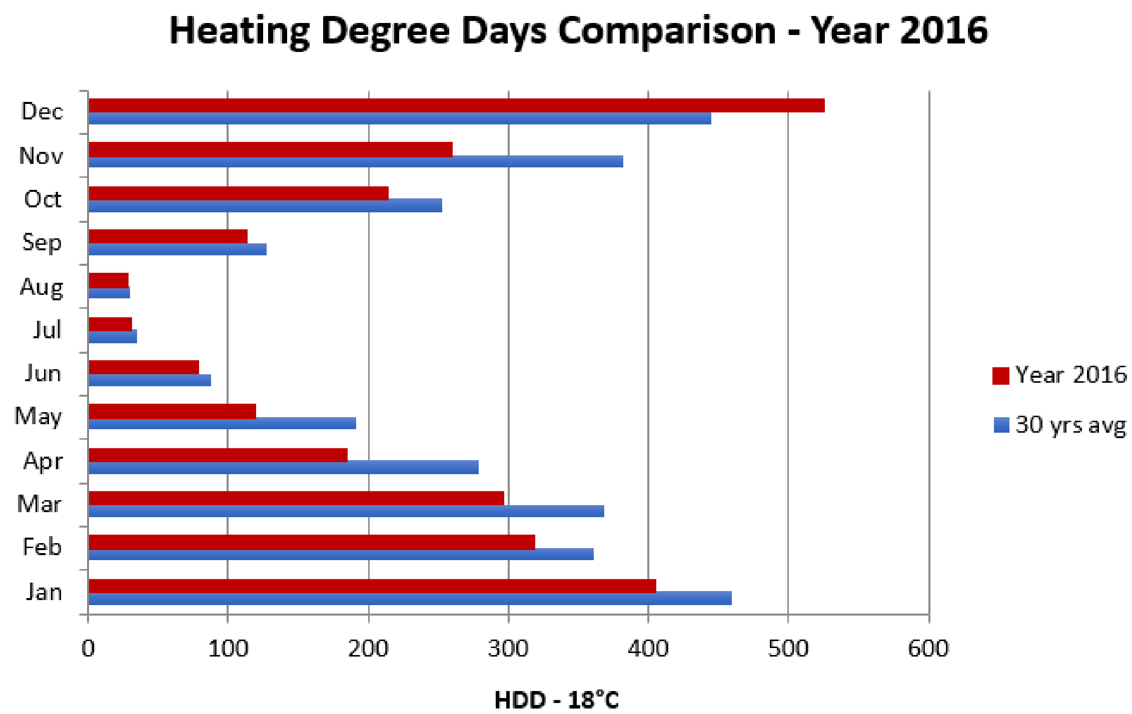


Figure 3.2: 30-year Average HDD vs 2016 HDD

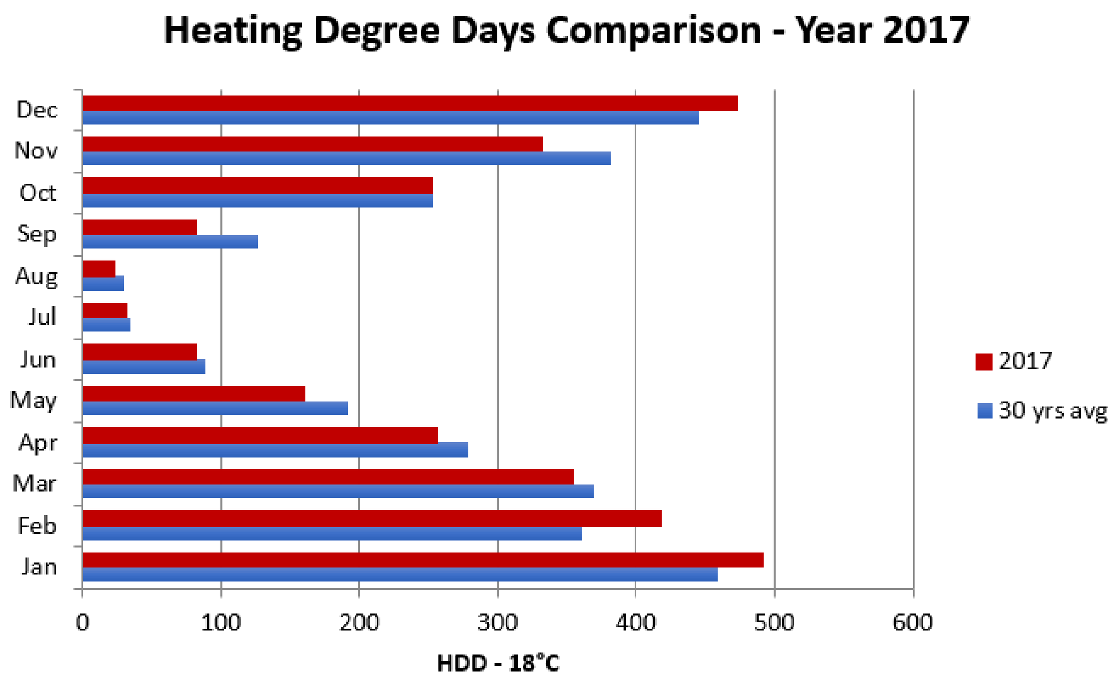


Figure 3.3: 30-year Average HDD vs 2017 HDD

For the year 2016, HDD is 14.9% less than the 30-year average. From the figure 3.2 above, all of the heating months had less HDD except December which was the only month figuring 18% more HDD than the average. For the year 2017, HDD is 2.2% less than the 30-year average. From the figure 3.3 above, the coldest months January, February and December possessed a total of 9.2% more HDD than that used in the energy model. Other typical heating months in 2017 including October, November, March and April counted 6.9% less HDD.

Regression analysis for buildings with huge performance gaps was performed to check the correlation level between HDD and energy consumption. The intercept of the linear equation theoretically represents the baseload energy consumption. The correlation coefficient R^2 represents how accurate the prediction is when getting the energy consumption according to the HDD. The coefficient R^2 floates 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].

3.3.2 Examine Individual Sites

The examination of the individual site was followed up after the comparison of designed and actual building performance. The primary purpose of site visits is to identify mechanical system issues, control sequence conflicts, operational challenges, BMS effectiveness and occupancy behaviour offsets. The same questions were expected to answer by facility managers and listed below:

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

3.3.3 Questionnaire Survey Design

From the literature review of general causes for performance gaps, occupancy behaviours have an increased impact on the unanticipated energy use. In order to better understand these low energy social housings performance, one of the buildings was selected to participate in the "occupant satisfaction survey" based on the tenants ability to complete the survey, which was under the direction and supervision of BC Housing. The survey focuses on exploring the thermal/ventilation comfort of occupants and their behaving manners possibly contributing to the energy penalty. Besides simply providing yes/no answers to the questions, the satisfaction/comfort levels were included in the survey. 28 out of 49 tenants participated in the survey. A full copy of the occupant satisfaction survey was attached to Appendix A.

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

Chapter 4

Results and Discussions

4.1 Case Study: Building A

4.1.1 General Description

Building A is a three/four–storey LEED Gold mid-rise residential building located in Victoria, BC. All the Model National Energy Code for Buildings (MNECB) mandatory requirements have been met. It was occupied since 2011 and approved as a LEED building in 2013 under LEED Canada-NC 1.0. It has a total conditioned floor area of $2740m^2$. The building accommodates 38 bachelors, six one-bedroom suites with amenity rooms, parking and bicycle storage spots. The orientation of the building is 45°C North which makes good use of solar gain. Large windows were applied to common spaces of the main floor to provide sufficient sunlight during the daytime.

4.1.2 Envelope and Construction

The U-shaped Building A enclosure possesses a high perimeter envelope. It can offer a larger quantity of fresh air for natural ventilation and sufficient daylighting for suites. The wood-framed building reduces the energy consumption in consideration of the life-cycle analysis since less energy was consumed during extracting and fabricating. The off-site premanufacturing of the frame decreases the total construction time. The glazing to wall ratio is as low as 27%, which grants a better thermal performance without affecting the in-suite livability.

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 ($hr \cdot ft^2 \cdot^\circ F/Btu$)	Type 1: Concrete built-up roofing with wood framing Type 2: Concrete built-up roofing with glass fibre insulation and wood framing Type 3: green roof On average, R=29.7
Wall ($hr \cdot ft^2 \cdot^\circ F/Btu$)	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 ($hr \cdot ft^2 \cdot^\circ F/Btu$)	U assembly=0.39
Whole Building ($hr \cdot ft^2 \cdot^\circ F/Btu$)	On average, R=8.6
Lighting Fixture	Suspended in space
Lighting Power Density (W/ft^2)	0.99
Plug Loads (W/ft^2)	Based on space function
Outside Air Rate (cfm/ft^2)	0.15

Table 4.1: Envelope and Internal Loads Specifications of Building A

4.1.3 Mechanical System

- Air Handling Unit Loop

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

The 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 2-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 will be damped to be equal to 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 which extend to

Temperature Setpoint	Heating setpoint: 21°C Cooling setpoint: 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

Table 4.2: HVAC System Specifications of Building A

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 will operate continuously during occupied periods. The supply fan will modulate the speed and air volume to satisfy the supply air static pressure requirement, which then controls the return fan speed in proportion to the supply fan.

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 setpoint temperature is altered in keeping with the average zone cooling demand, which can be achieved in OS and EnergyPlus by using a Setpoint 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; 4) unoccupied cooling mode has been out of

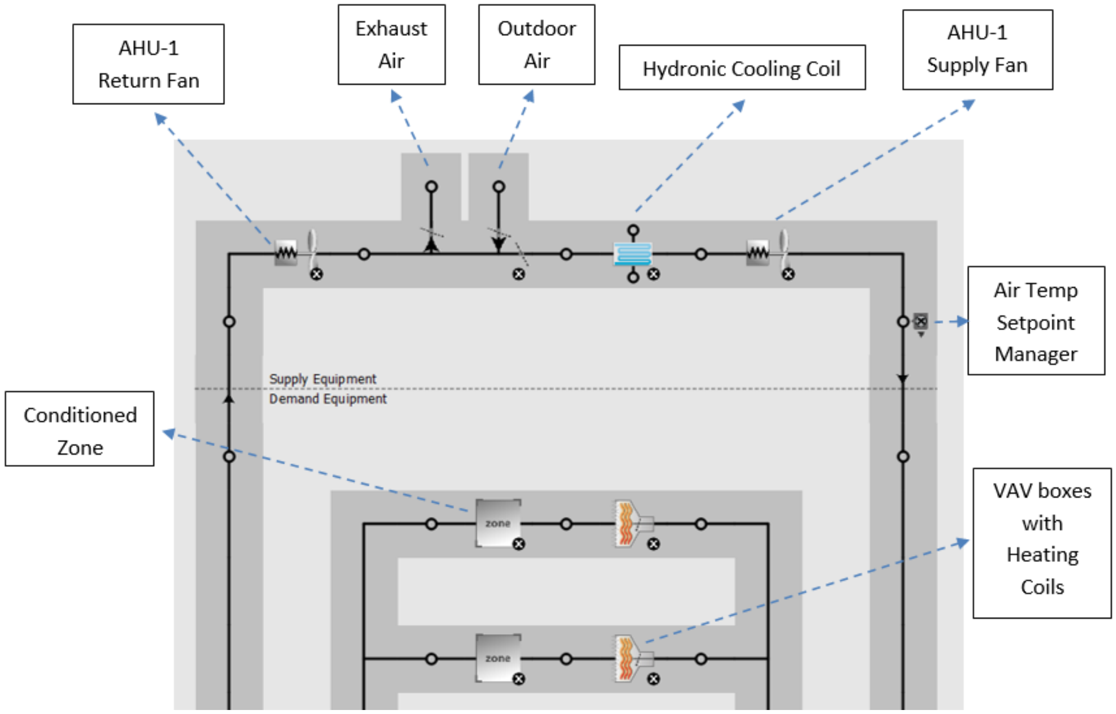


Figure 4.1: Air System for the Main Floor

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 air flow control damper, a heating coil and a heating water control valve. It operates upon the VAV's DDC system which monitors the air flow rate, room temperature and supply air temperature. A 30 minutes' early morning warm-up will be enabled before the operation of the building during heating days. The full run of the AHU system will be set up with the heating coil control valve tempering to maintain the supply air temperature at setpoint. Activation of the unoccupied heating mode will be enabled if any two space temperatures fall below the recommended unoccupied heating temperature. Accordingly, the air flow from the VAV boxes will be set to its maximum and the heating control valve will be 100% open. In the case that the room temperature exceeds the unoccupied heating setpoint by 2°C, the VAV boxes will modulate the air flow at its minimum volume and the heating control valve will be fully closed.

- Energy Recovery Ventilation Loop

The other levels and the suites on the main floor are conditioned directly by two ERV (energy recovery ventilation) 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 thereupon reduces the heating and cooling energy consumption of a building. Besides, the pollutants and small particles in the outdoor air can be removed after passing through the filtration component of the ERV unit, and purified air will be sent to the conditioned zones to provide a high-quality indoor air environment. The ERV system operated in this building can deliver not only sensible but latent energy as well by transferring water vapour from one airstream to another directly. Conditions of possible frost are negligible since the average winter temperature in Victoria is higher than the minimum operating temperature -23.3°C of the ERV unit. Additionally, as indicated in the manufacturing sheet, the infrequent extreme weather will not affect the normal operation or performance of the component.

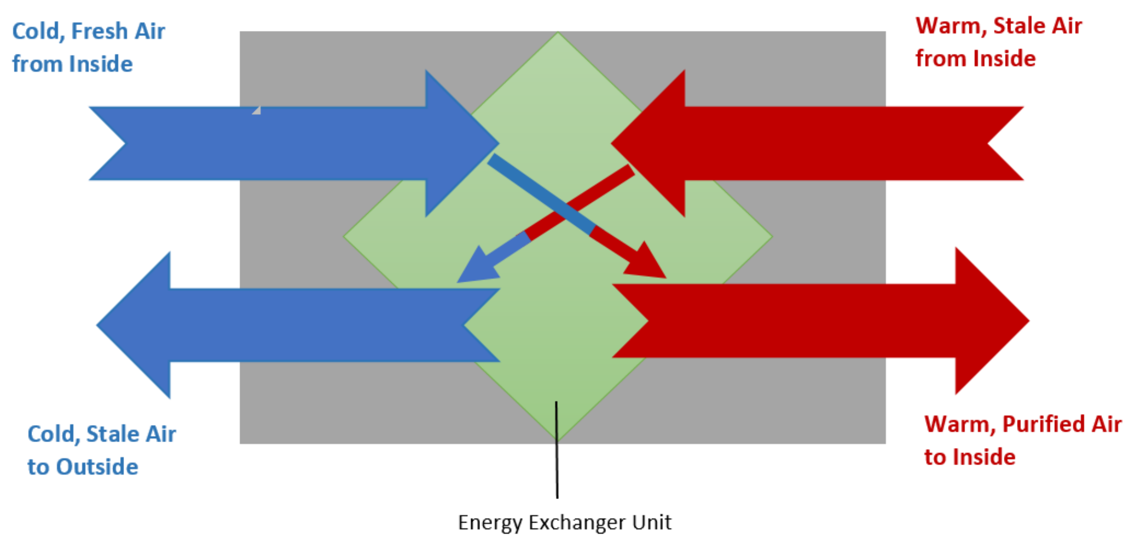


Figure 4.2: Schematic of a Typical ERV System

Each ERV air loop contains a return fan and a supply fan to drive air to outside and inside respectively. Exhaust air is drawn through the individual ceiling mounted exhaust air grilles and then it travels through ducts to the exhaust air inlet of the ERV unit. After exchanging energy with outdoor air, exhaust air will be sent to outside by the exhaust fan. At the same time, fresh air will pass through the air filter, the heat recovery core and then will be ducted to each conditioned zone. Continuous running of the unit guarantees consecutive oxygenated and clean air being served through single duct ceiling diffusers to these living units and corridors.

Cooling is provided by the cooling coil which is placed on the supply equipment side, and average cooling demand of multi-zone is defined 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 supply more individually preferred comfort but not just the satisfaction with the ambient temperature. Moreover, it has a chance to reduce the cooling load when the outside temperature is not too much higher than the cooling setpoint. The increased flow of air has a positive effect on the cooling of a zone.

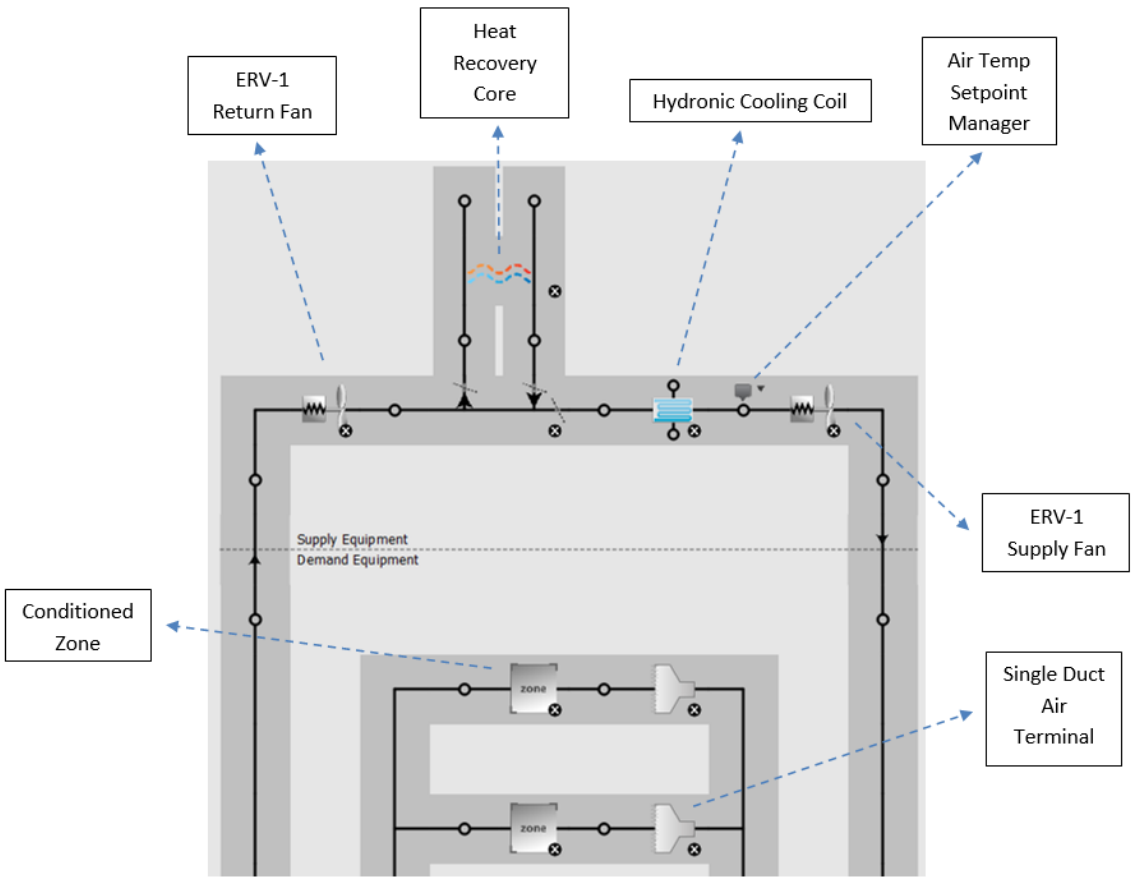


Figure 4.3: ERV Loop for Residential Suites

- Infloor 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 of respective zone. When the temperature sensor installed in the suite indicates the room temperature lower than the setpoint, a need for heating will be transmitted to the DDC system. In line with the control command, the zone control valve will be opened allowing the heating fluid to circulate in the floor heat piping loop. Once the room temperature achieves the heating setpoint, the valve will be closed until the room temperature drops again.

4.1.4 Central Plant

It is essential to maximize the energy efficiency of the HVAC equipment and minimize the electricity or other primary energy in order to design a low energy building. In this case, an air to water heat pump placed on the rooftop is used to provide cooling/heating water circulated in fan coil systems and floor radiant heating loops.

The circulated fluid always enters the heat pump first and then might flow through a boiler that is added to the plant loop as an additional heating resource. It happens when the leaving water temperature from the heat pump is lower than the setpoint, extra energy for the water heating process will be provided by the boiler. Upon setpoint being attained the boiler is disabled first and then 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 upon a drop in loop pressure. The ASHP can operate under low-temperature ambiance 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, water control valves, and water circulation pumps open/closed on the basis of monitoring parameters including leaving water temperature from heat pump/boiler, supply/return water temperature to/from radiant floors and AHU heating/cooling coils. The heating water system will start if more than two zones ask for heat and close if all zone temperatures are higher than their setpoints. During the heating supply period, the control valve will be 100% open to keep the radiant floor system at its normal operation. The DDC system also monitors all of the equipment alarm contacts to keep the mechanical system working accordingly. In order to investigate if the ASHP was efficient enough, the simulation of building A in this project removed the heat pump and kept only a boiler as shown in figure 4.4.

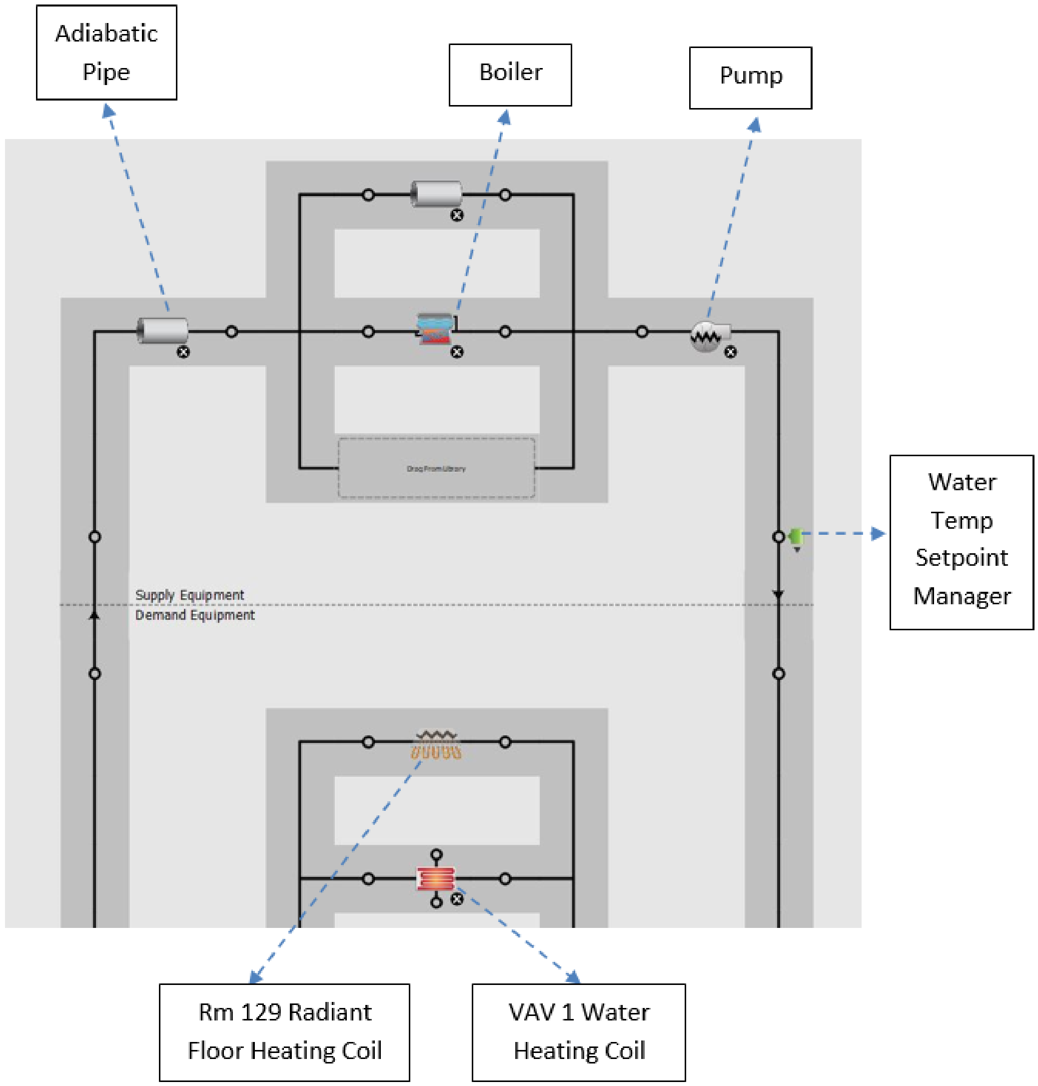


Figure 4.4: Modified Heating Plant of Building A (no ASHP)

4.1.5 Domestic Hot Water System

An array of solar panels is mounted on the rooftop at a particular angle to produce renewable energy for the building. On a call for domestic hot water, the solar water heating system works first to satisfy the water setpoint. A pump is then activated to circulate the water in and out of the heat exchanger and up to the solar panels.

The solar heated water flows into two preheat storage tanks which are systematically heated to maintain the storage water at 54°C to prevent Legionella. Additionally, an electric water heater is connected to the storage tank that 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 setpoint at 60°C. In the meantime, two recirculating pumps run continuously to supply hot and tempered water to the whole building.

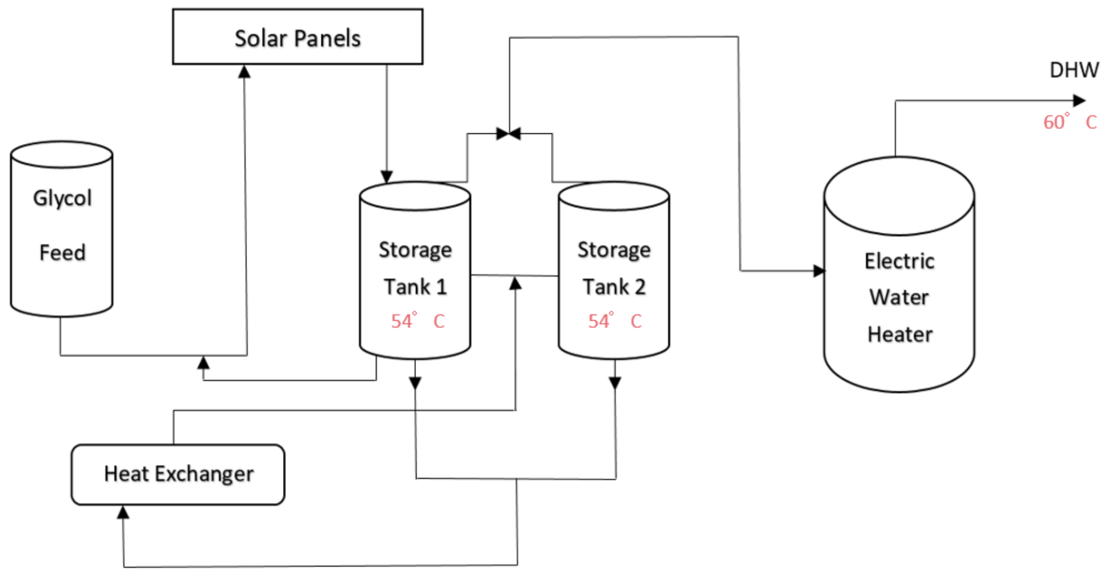


Figure 4.5: Domestic Hot Water System of Building A

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

The heat exchanger will start to work 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; 3) central plant supply water temperature is higher than 36°C. While it will be commanded to stop if preheat tank temperature is greater than 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 every day. The solar panel is then activated/deactivated at the sunrise/sunset time respectively. If the solar loop pump does not work properly (as expressed by amperage), or the running of the pump is unable to follow the DDC system command, an alarm will annunciate.

4.1.6 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

Building A consumed 94.2% and 102.7% more energy respectively in 2016 and 2017 than the proposed model, yet avoided 23% and 19.6% energy usage annually compared to the baseline building as shown in figure 4.6. The hydro data shows 62.1% and 41.3% more consumption than the prediction which partially results from the exclusion of non-regulated loads such as elevator and parkade lighting at the design stage. However, the big discrepancy cannot be explained merely by the non-regulated consumption. The inefficiency of the solar system and air source heat pump might contribute a lot to the performance gap. More electricity will be used to heat the domestic water without sufficient renewable solar energy as anticipated. The ASHP on the rooftop will cycle much more time during cold days due to its deficient operation, and associated pumps and fans will keep operating at the same time. It can be proved by the extra 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 of the equipment functioned during 2016 and 2017, the sustainable design features did not perform as predicted.

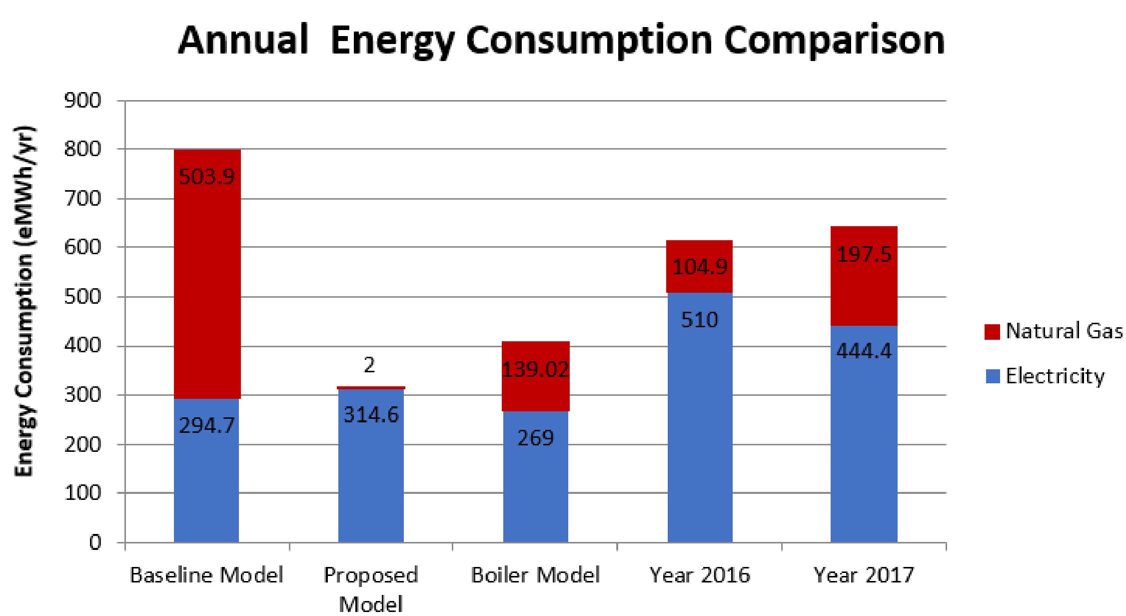


Figure 4.6: Annual Energy Consumption Comparison of Building A

In order to investigate how the ASHP performed in the real world, the monthly natural gas use comparison between the boiler model and year 2016 and 2017 was conducted. From figure 4.7, it seems like that during January and February of 2016 the ASHP was working as expected. However, February with fewer HDDs than January consumed more natural gas than January. The abnormal presence might be a clue that the ASHP started to have some issues. HDDs from March to November in 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, no matter the actual weather was warmer or colder than the weather file used in the modelling. Furthermore, the space heating demand during summertime should be zero but not as predicted.

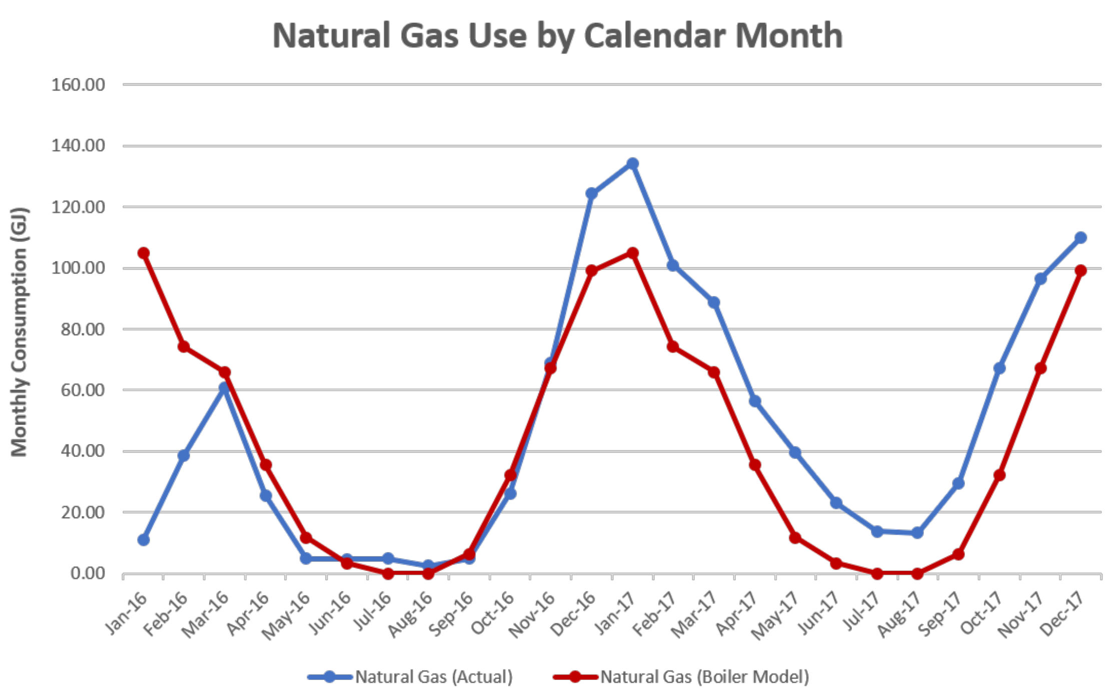


Figure 4.7: Monthly Natural Gas Use Comparison between the Boiler Model and Actual Consumption

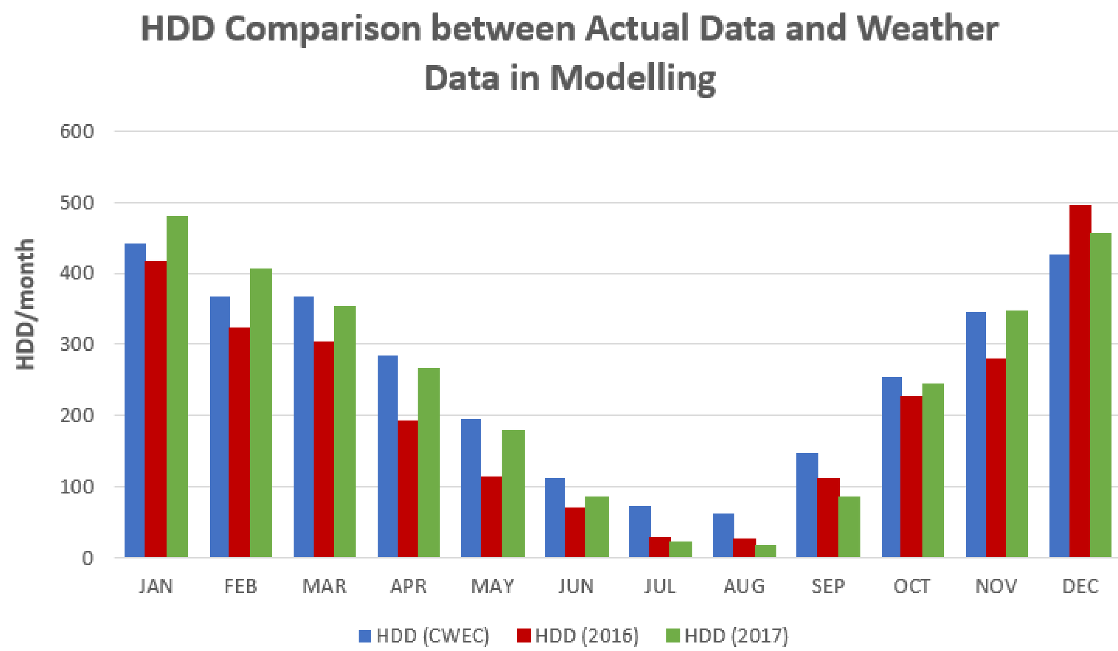


Figure 4.8: Monthly HDD Comparison between Actual Data and 30-yr Average Data

Another possible reason would be the unpredicted occupant behaviour according to the occupant satisfaction survey and boiler model results. Tenants kept opening windows during winter months for direct fresh air, which increased heating burden for the ASHP loop. From the occupancy satisfaction survey, 42.9% of participated tenants use additional heaters in winter, and 85.7% of them rely on extra fans in summer for sufficient ventilation and cooling.

The rules of LEED v1 may partially attribute to the difference of electricity results as it excluded some non-regulated loads if they did not contribute to space heating gains such as elevators, parking fans and so on. Furthermore, all of the energy use of non-regulated plug loads is based on rough estimates and code defaults. Actual use can vary substantially depending on actual operations and what ends up being plugged in.

Building Energy Performance Index Comparison

From the annual energy usage comparison above, building A performed far away from the anticipation. It is essential to compare the EUI of building A with benchmark buildings. Two building types were selected from NRCan's database including Multi-unit Residential Building (MURB) and Health Care and Social Assistance (HCSA).

Building A is other than a typical apartment with 24/7 on-site staff and various supportive assistance. Accordingly, it should be classified as a particular social housing type with accommodations and social assistance.

The comparison uses a building's annual EUI per floor area as the measurement criterion. The actual EUI of both years is 87.8% and 96.1% greater than benchmark MURBs yet 36.9% and 34.1% less compared to HCSAs. The electricity consumption in 2016 is 8.1% more than HCSAs with the save of 78.9% natural gas. It essentially follows the trend of reducing fossil fuels firing as designed for the proposed model despite more energy being consumed.

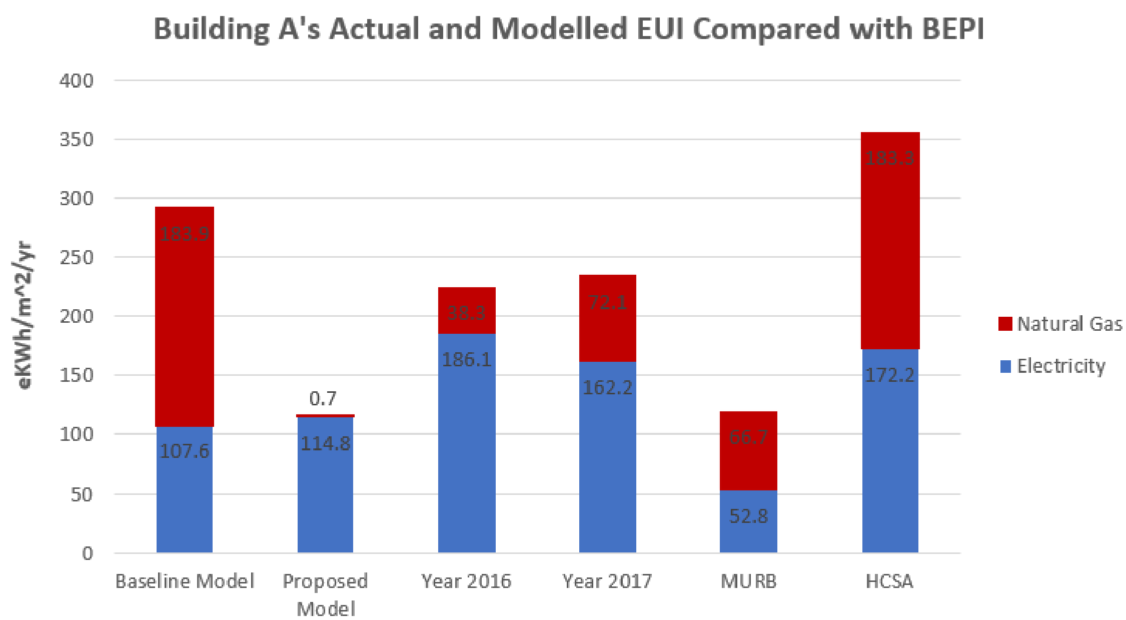


Figure 4.9: BEPI comparison of Building A

Effects of Weather on Results

With 14% less HDD for the year 2016, the less energy consumption for space heating is expected. However, the utility data demonstrated much more electricity and natural gas consumed than the prediction. A regression analysis was performed to check the correlation level between HDD and energy consumption since the extremely high gas consumption is not consistent with the presumption. The correlation coefficient is 0.88 for building A of the year 2016 which indicates a close relationship between the high energy consumption and particular weather condition. From figure 4.11, the natural gas firing appears more frequently during cold months especially in December which confirms the inefficiency of the ASHP under extreme weather. Furthermore, the continuous gas consumption is evidence that excessive heating supply existed during summer nights when outdoor air temperature fell below a certain value. It is recommended to review control sequences to avoid any unnecessary heating operation. From the comparison in Chapter 3 Methodology, it cannot be merely summarized that less heating energy would be used for the year 2017. Compared to the utility data, building A consumed much more energy than the prediction. Regression analysis indicates the high energy consumption strongly correlated to HDD with more gas firing.

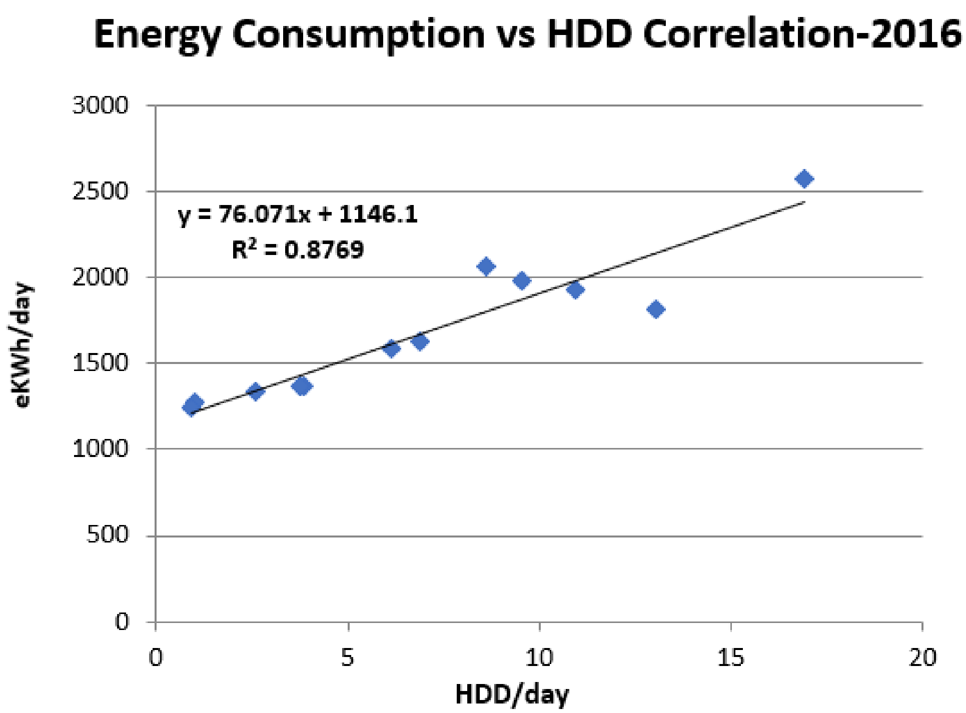


Figure 4.10: Effects of Weather on building A for 2016

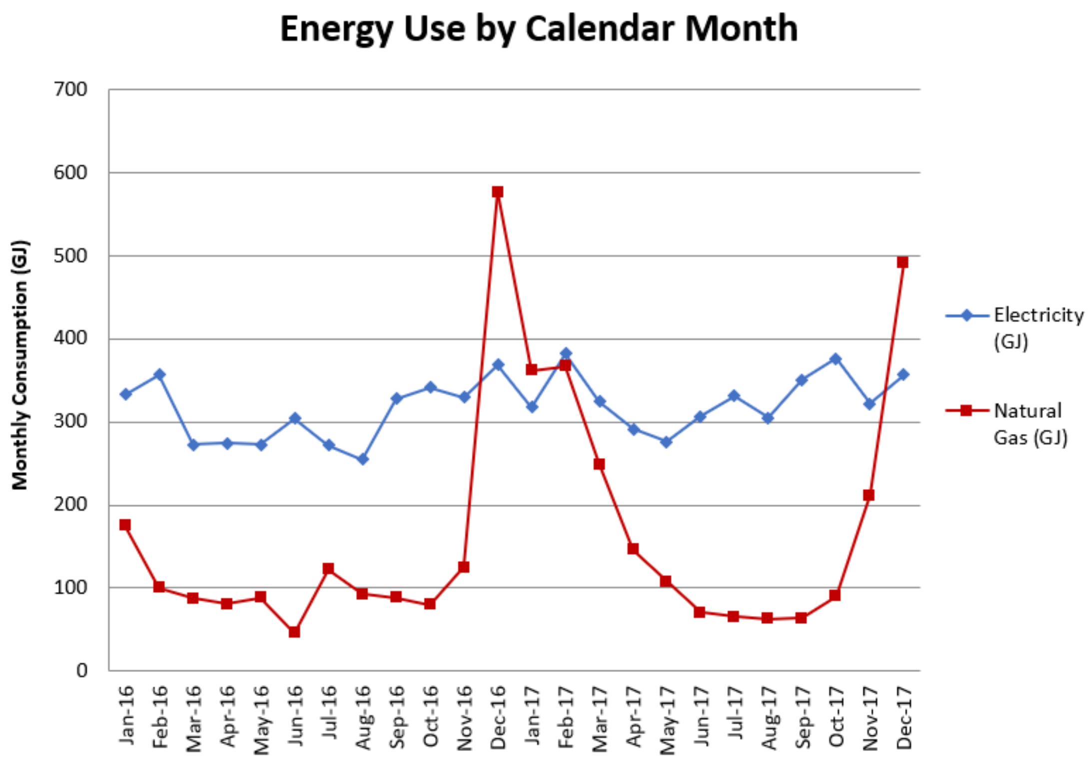


Figure 4.11: Monthly Utility Data by Types of Building A

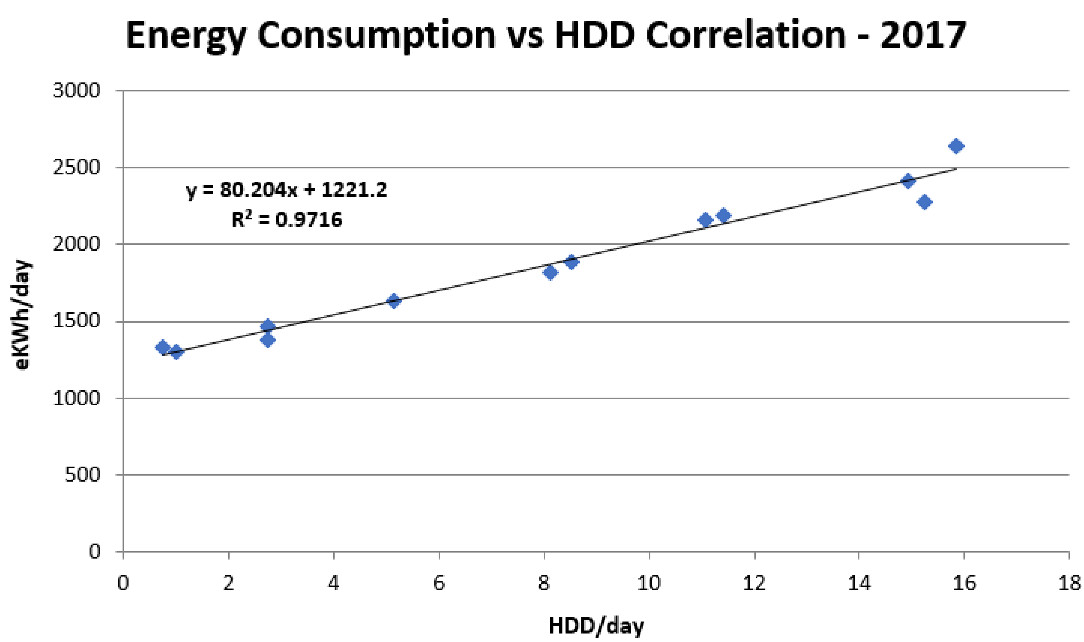


Figure 4.12: Effects of Weather on building A for 2017

Monthly Electricity Consumption Comparison

Figure 4.13 and 4.14 present the monthly gap between actual performance and proposed design in electricity for the year 2016 and 2017 respectively. The biggest discrepancy for 2016 appeared in January, February, May and October featuring an average of 72.2% and for 2017 the involved months are April and May with an average of 67%. Typical heating and shoulder months are more likely to produce unexpected electricity usage which generally results from the occupant behaviours. Other drivers from the discussion with the facility manager and inspection reports are in-suite temperature sensor issues, control valves fail, DHW tank contactor overheating or fail, heat pump low-pressure alarm, glycol feeder leakage which can affect the heating/cooling system efficiency.

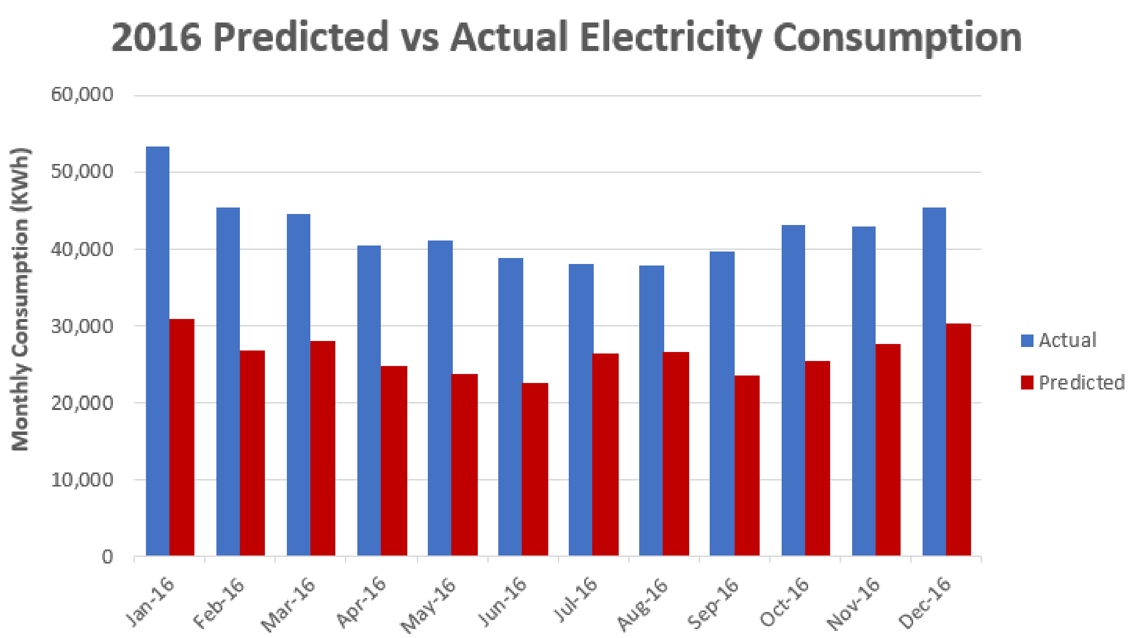


Figure 4.13: Electricity Consumption Comparison for 2016 of Building A

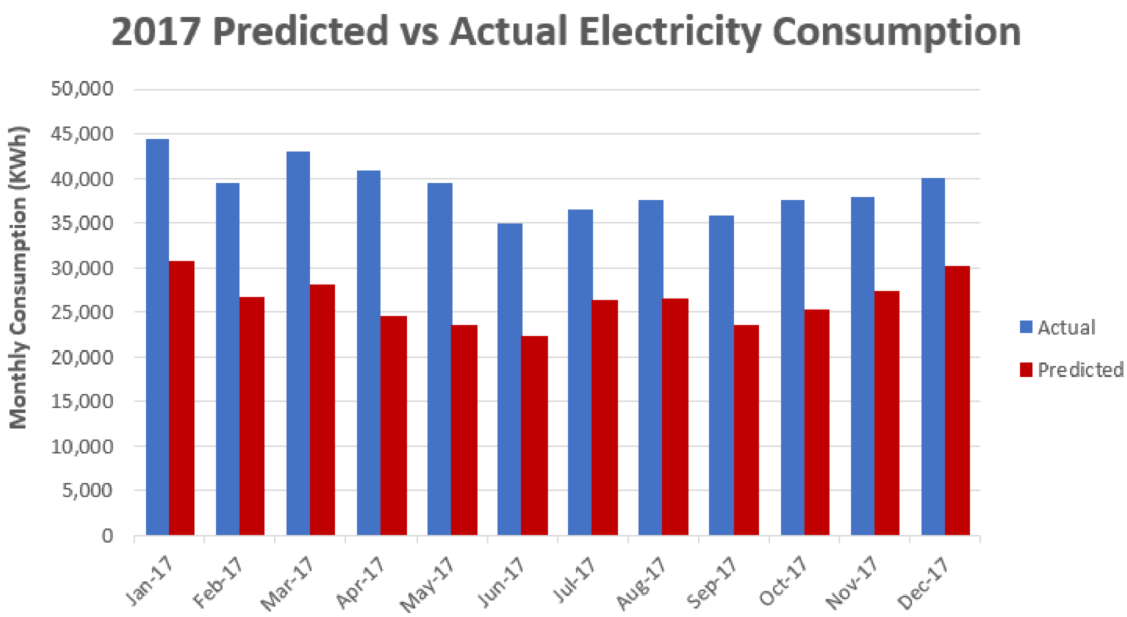


Figure 4.14: Electricity Consumption Comparison for 2017 of Building A

Recommendations

- Examine the ASHP system to find out the reason for its inefficiency and reduce the related energy penalty.
- Check the operation of the solar energy system to ensure its optimal performance.
- Review and adjust the control sequences of the DDC system to avoid unnecessary heating energy used during summer nights.
- Install sub-meters to monitor various end-uses such as heating/cooling equipment and lighting for easily and quickly addressing mechanical and control issues.
- Seasonal commissioning is essential to optimize the building performance by regulating the associated heating/cooling accessories.
- Future energy models are recommended to calibrate 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 sustainable high-rise residential social housing located in Vancouver, BC. The site was formerly a small hotel containing only 24 rooms. After redevelopment, the building with a floor area of $10989m^2$ (excluding parking area) can accommodate 106 studios, 41 one/two/three-bedroom suites with amenity rooms, parking and bicycle storage spots. It has three leased retail stores on the first floor and non-profit society office on the second floor. Children's play room is connected to the outdoor playground along with a garden. With large windows (the height is almost floor to ceiling size) mounted on the wall, amenity rooms receive abundant natural light in the day and thus, lower the heating season energy consumption to a certain degree. It was occupied since 2015 and is in process of targeting the LEED Gold building under LEED Canada-NC 1.0.

4.2.2 Envelope and Construction

In consideration of both safety and effectiveness, building B of ten-storey high was designed to be built with stable and long-lasting concrete walls along with high thermal resistance insulation. It has much higher R-values in exterior walls and roofs to ensure less heat loss and thus, save energy. The fenestration accounts for more than 30% of the exterior wall which brings sufficient sunlight for tenants to save lighting in daytime and heating demand in winter, especially for lobbies and lounges, large floor-to-ceiling windows were installed. Windows in suites are operable to provide natural ventilation and free-cooling for occupants. Materials used for the building tried its best to follow the basic LEED material principles which are durable, recyclable and regional manufactured.

Exterior Wall ($hr \cdot ft^2 \cdot^\circ F/Btu$)	*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 ($hr \cdot ft^2 \cdot^\circ F/Btu$)	R=30 (254% higher than the baseline)
Overall Glazing U-Value ($Btu/hr \cdot ft^2 \cdot^\circ F$)	*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 space function
Infiltration (cfm/ft^2)	0.05

Table 4.3: Envelope and Internal Loads Specifications of Building B

4.2.3 Mechanical System

The air handling units with heat recovery wheels AHU-1 and AHU-2 operate continuously to supply preconditioned air to suites, corridors and common places. Upon receiving a call for heating or cooling, the DDC system will start the hydronic coil circulating pump and modulate the coil control valve at a specific position to provide conditioned air at setpoint. The DDC system controls the supplied air temperature between 13 and 22°C according to the room temperature sensors. The fans used in the system are variable speed drove to economize energy cost.

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 indoor air temperature. The DDC system disables heat recovery wheels when free cooling is available, which means the AHU is in cooling mode while the outdoor air temperature is lower than the inside. The common space supply and exhaust air dampers are closed during the blank period.

Besides obtaining heated air from the AHU system, the suites also receive heat supply through an in-floor radiant heating system. The zone control valve for radiant floor heating is operated based on the command from the DDC system.

To minimize energy consumption including natural gas burning, 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 in heating mode, AHP-1 functions as the primary heating source. If it operates at its full load and still cannot satisfy the heating demand, the DDC system will start to cycle the boiler to provide additional heat to the building. The heat pump prepares low-temperature hot water for radiant floors, hydronic coils and distributed water-to-air heat pumps. In cooling seasons, it produces chilled water for 2-pipe fan coils and water source heat pumps.

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

HVAC System Specifications	
Temperature Setpoint	Heating setpoint: 22 Cooling setpoint: 24
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: 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

Table 4.4: Mechanical System Specifications of Building B

4.2.4 Domestic Hot Water System

Building B installed low flow fixtures for toilets, faucets and shower heads which helps to save approximately 40% water usage compared to its baseline model. Another air source heat pump AHP-2 is used to preheat the domestic hot water. Upon a request for hot water, the gas-fired condensing boilers are engaged to heat DHW to its setpoint.

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

Table 4.5: DHW System Specifications of Building B

4.2.5 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

Monthly electricity and natural gas consumption data for building B has been collected and reviewed. Total annual energy consumption given by utility bills for 2016 and 2017 calendar year is 54.8% and 79.6% respectively greater than the predicted energy for the proposed design. The results are beyond the aimed plus or minus 15% range of accuracy level. However, the actual energy used for 2016 and 2017 calendar year is 43.8% and 34.8% less than the baseline model.

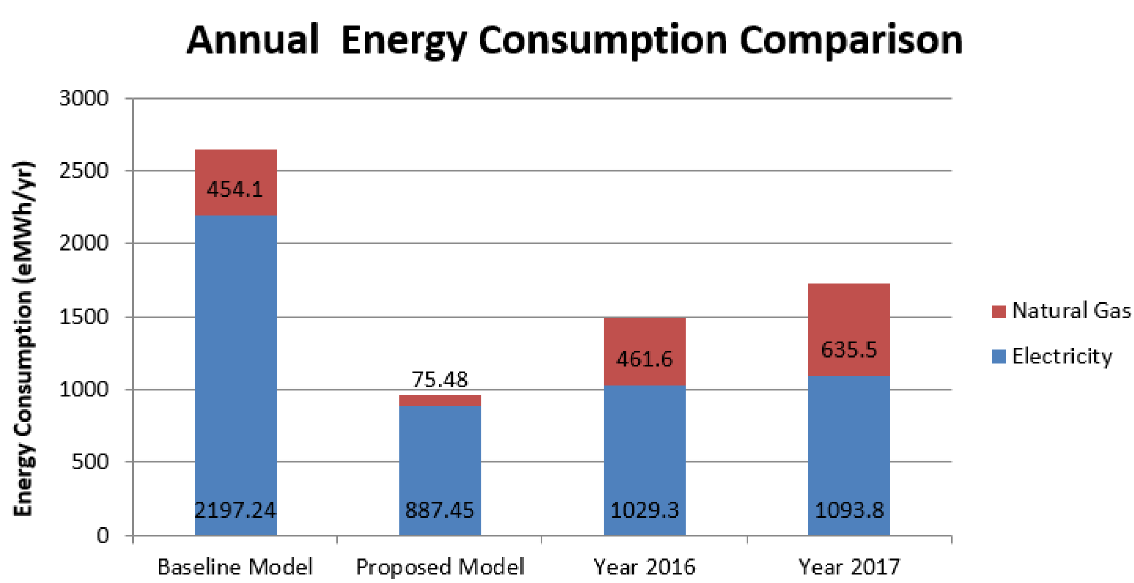


Figure 4.15: Annual Energy Consumption Comparison of Building B

The discrepancy between the modelled and measured results regarding natural gas consumption has a much more significant impact on the total energy performance gap than electricity as shown in table 4. The considerable discrepancy in natural gas indicates the backup boiler for space heating and condensing boilers for DHW firing much more than expected. From the discussion with building facility manager, all of the equipment functioned properly, and regular maintenance was accomplished well even if the daily inspection by operators may sometimes not be performed. One of the possible reasons for the inconsistency would be the low-efficiency issues of the heat pump in winter, which is a common problem for air source heat pumps in Vancouver. Another cause would be that the building was not used by the residents in a manner that the modelling anticipated: Windows were open all winter; doors were left propped open to the hallways; ovens were kept on even not in use; people covered their ducts and vents and left their taps running. There was a whole range of behaviours that were nearly impossible to correct since occupants living in supportive housing do not need to pay utility bills.

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

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

Building Energy Performance Index Comparison

The comparison between building B and benchmark buildings was performed to justify the outcome of the sustainable design. The building 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 offering meals, different types of amenity spaces such as children playing room. One more building type of Accommodation and Food Service (AFS) was selected from NRCan's database to ensure more rigorous analysis. The baseline model appears 101.9% more energy used than the benchmark of typical MURBs but 32.1% and 31.6% less than HCSA and AFS respectively. Although the building performed far away in reality from the proposed model, it consumed only 13.6% and 31.6% more energy than the benchmark Building Energy Performance Index (BEPI) for the building type MURBs during the year 2016 and 2017 but around 60% less energy saved when compared to HCSA and AFS. In general, the building utilized much less natural gas compared to all the three types of benchmark buildings.

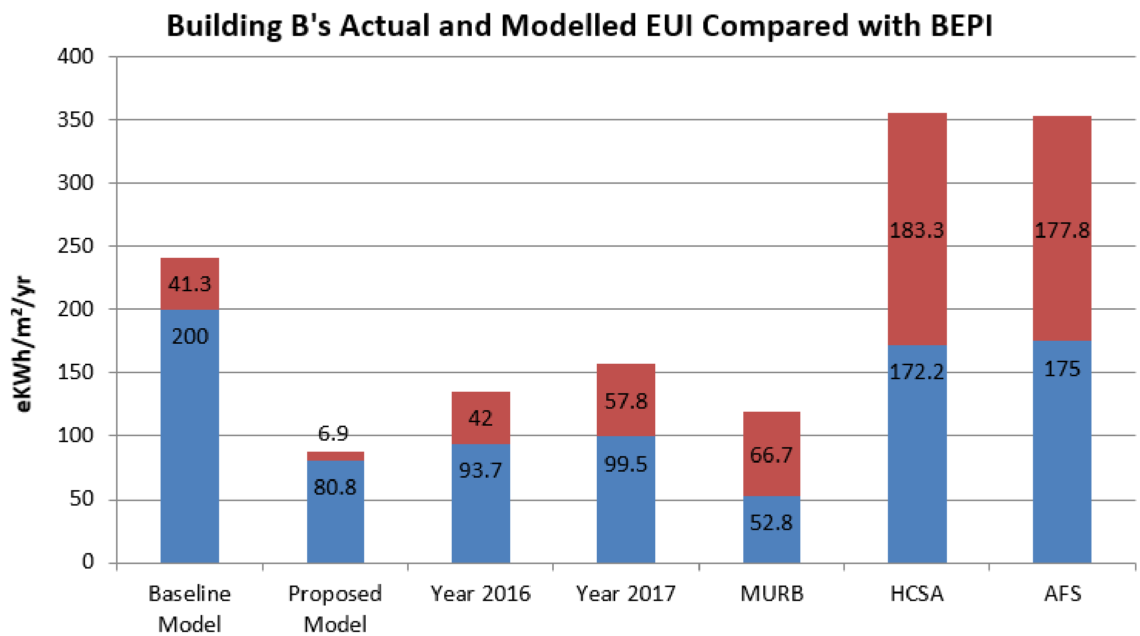


Figure 4.16: BEPI Comparison of Building B

Effects of Weather on Results

A regression analysis was performed to check the correlation level between HDD and energy consumption since the extremely high gas consumption is not consistent with the presumption. With an R^2 of 0.5831, it indicates a poor correlation between energy consumption and HDD for the year 2016, which means the extremely high natural gas consumption was not brought by space heating but probably by DHW preheating issues. Even excluding the abnormal point, the coefficient is still low with a value of 0.5181. It may also be as a result of operaional issues and wear and tear on equipment. Another possible explanation would be occupancy behaviours subjected as mentioned previously. Furthermore, the energy model may need to be calibrated regarding the inputs contributed to space heating and peak load for DHW.

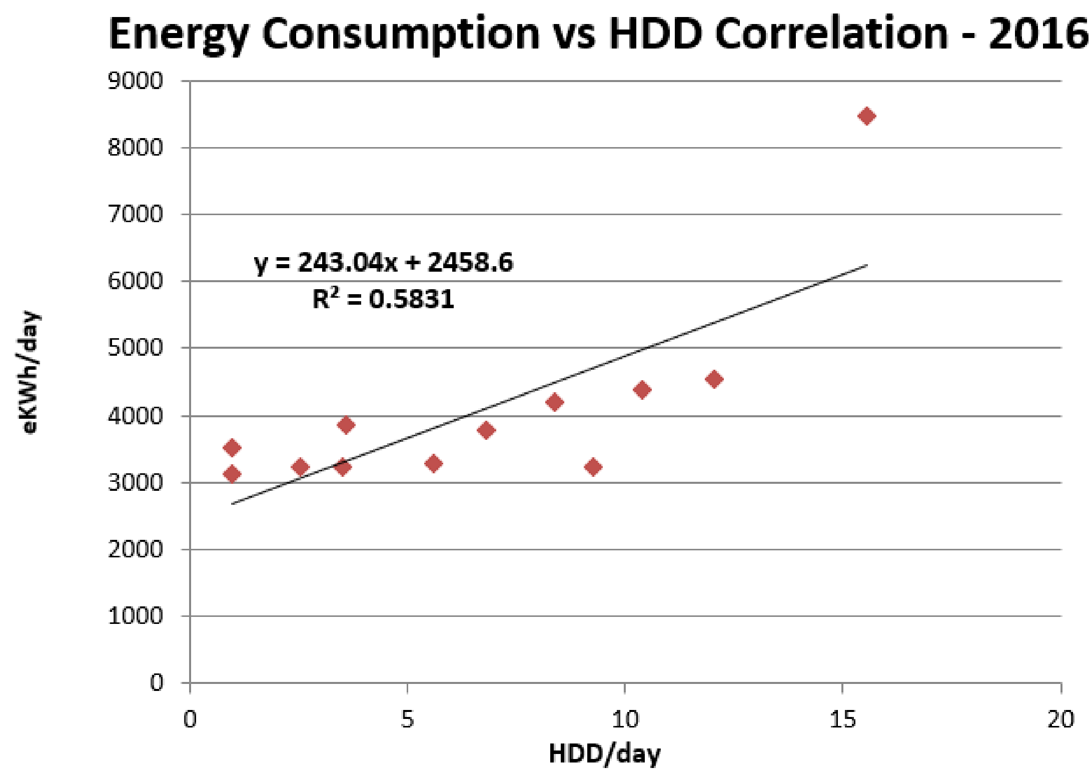


Figure 4.17: Effects of Weather on building B for 2016

Compared to the utility data, building B consumed 23.3% more electricity and 741.9% more natural gas than the prediction. Regression analysis is then necessary to evaluate the interdependence between HDD and energy consumption. As shown in figure 4 below, the baseload energy consumption for the year 2017 was 2790.1eKWh/day, 13.5% higher compared with that for the year 2016. The greater baseload energy consumption might occur with the colder climate in 2017 which resulted in more electricity consumption in pumps and fans.

With an R^2 of 0.7857, it indicates a good correlation between energy consumption and HDD for the year 2017. However, it cannot explain the excessively high natural gas consumption demonstrating 741.9% more being used. The building uses an air source heat pump for heating supply and a gas-fired boiler as back up. The inefficienct operation of AHP-1 during very cold days may contribute to one portion of the unexpected natural gas use. Moreover, the demand for DHW may increase with the colder winter, which could result in more gas consumption than 2016. The occupant behavious factor and equipment operation issues cannot yet be neglected at this time.

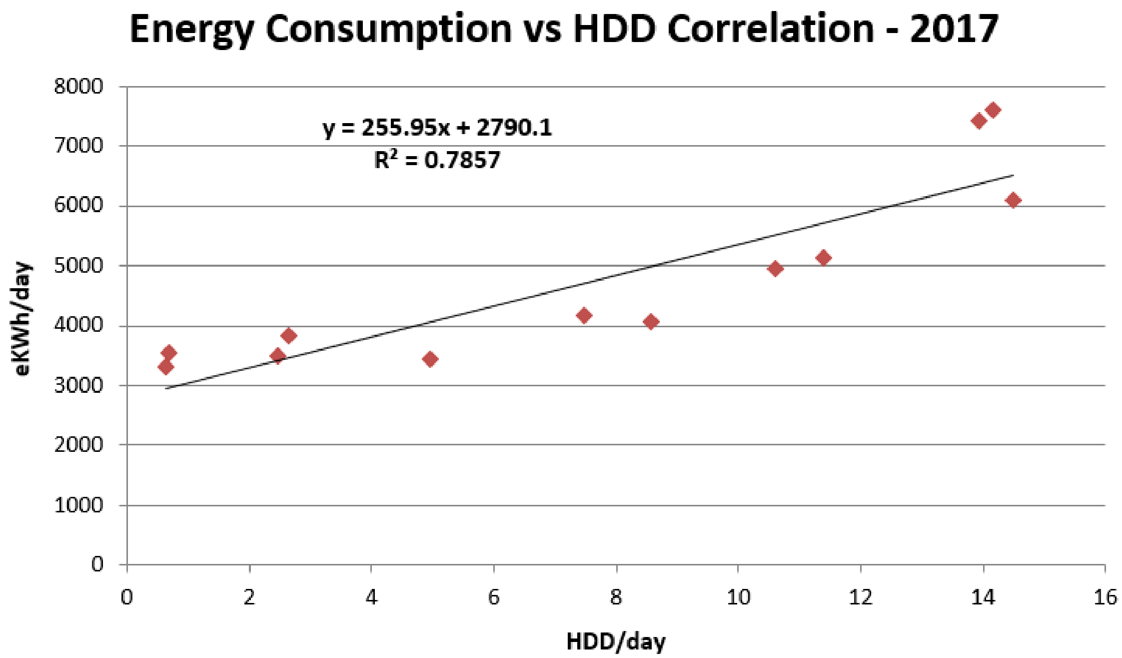


Figure 4.18: Effects of Weather on building B for 2017

Monthly Energy Consumption Comparison

Figure 4.19 and 4.20 present the comparison between monthly modelled results and hydro bills for the year 2016 and 2017 respectively. For both years, actual electricity consumption for building B keeps constantly greater than the prediction. The greatest discrepancy appeared in the same period for the year 2016 and 2017, which was in 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 the disparity since other cold months did not display such a big difference. The energy model may need further assessment concerning the inputs for these three months.

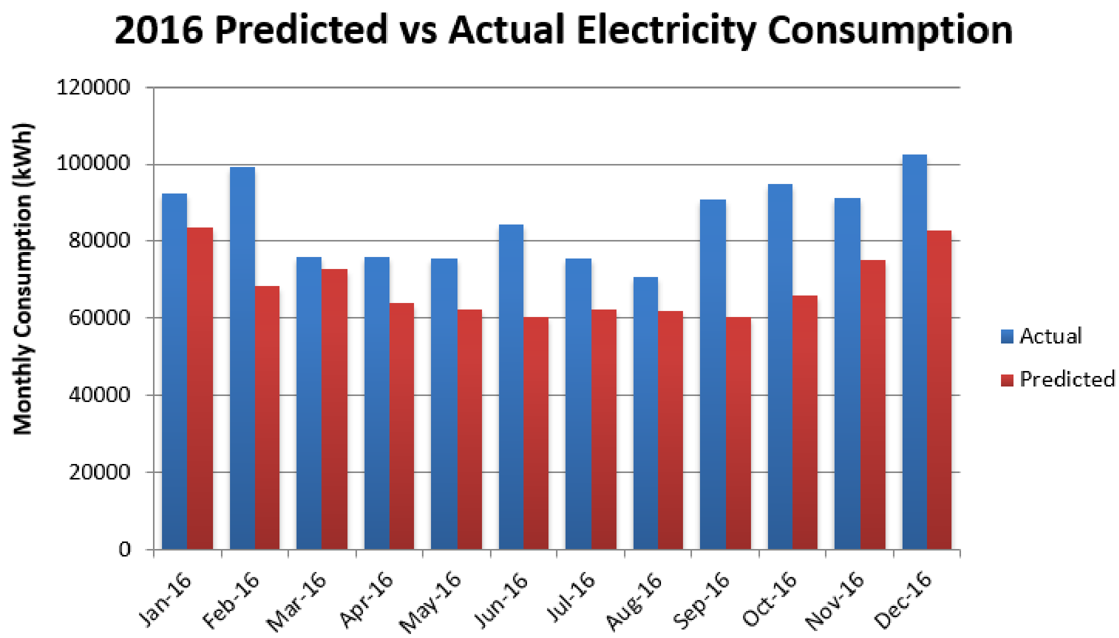


Figure 4.19: Electricity Consumption Comparison for 2016 of Building B

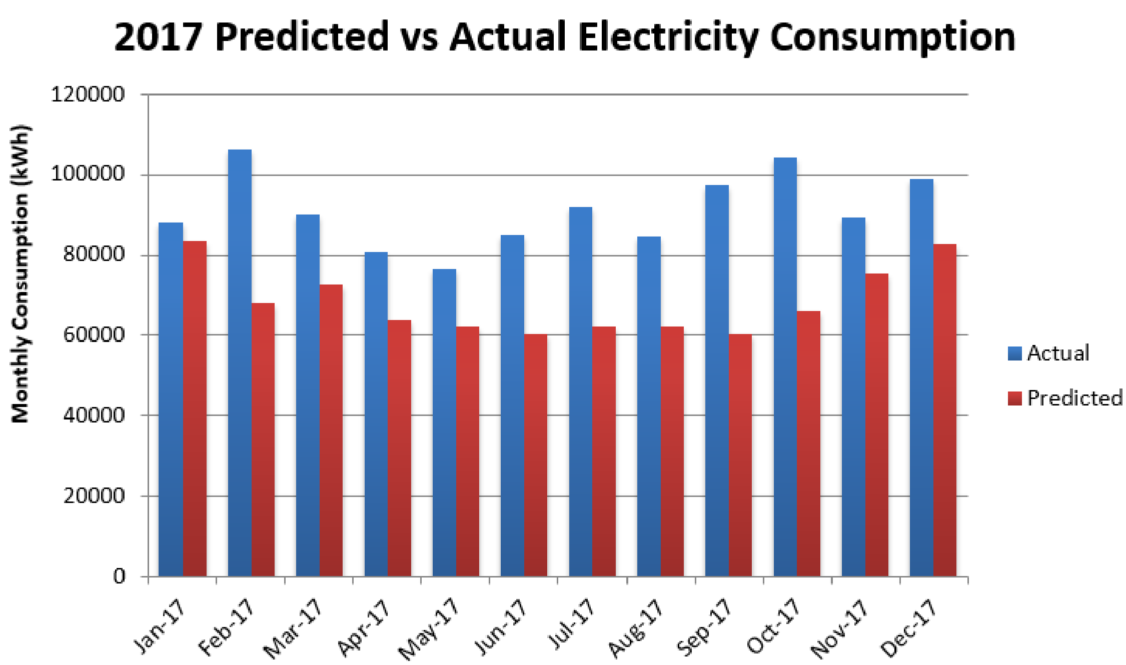


Figure 4.20: Electricity Consumption Comparison for 2017 of Building B

Figure 4.21 shows the electricity and natural gas consumption by calendar month between the year 2016 and 2017. As can be seen on the graph, the natural gas consumption increased rapidly during winter time from November to March each year. It can be explained by the inefficiency of the air source heat pump under the cold circumstance. It is necessary to modify the performance curves when modelling the building using air source heat pumps to get more accurate results.

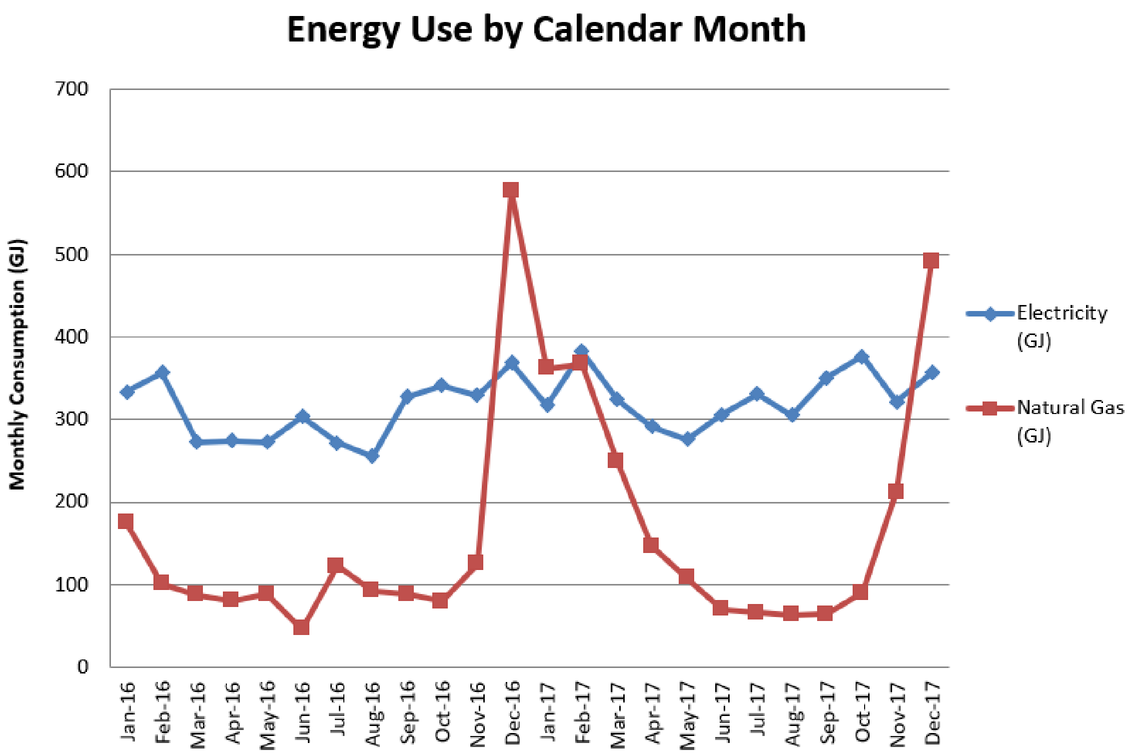


Figure 4.21: Monthly Utility Data by Types of Building B

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 occupants comfort.
- Review the control settings of the DDC system to ensure no unnecessry heating during summer time.

- Future energy modelling process is recommended to refer to experienced performance curves for ASHPs in real operation rather than the manufacturer shop drawings.

4.3 Case Study: Building C

4.3.1 General Description

Building C is a four – storey sustainable mid-rise residential social housing located in Vancouver, BC, within 400 metres of 4 bus routes. The building was designed to provide accommodation for low-income people with physical and/or mental health issues. The site has a total floor area of $3852m^2$ including $412m^2$ of commercial retail units on the first floor. 51 lodges are available in total, 47 among which are single room occupancy (SRO) and 4 out of 51 are wheelchair accessible arranged for the handicapped. A broad lounge equipped with a television and several computers on level one has direct access to the outside garden. With extra large windows installed in common spaces, the shared areas take advantage of the generous daylight during daytime to save lighting energy consumption and save heating in cold days. The building was redeveloped on a previous contaminated site (gas station) and effective remediation has been performed. It was occupied since 2011 and has received the 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 both exterior walls and roofs to economize the cost of energy use. The roof of the building makes use of white SBS membrane which helps to reflect the sunlight in summer daytime and grants a long life circle. The application of high R-value envelope can scale down the heat island effect to a certain extent. The insulation including metal panels and brick masonry work for breaking the heat bridge.[87] 15.29% of construction materials consist of recycled ingredients, and 25.07% of materials were extracted and manufactured regionally.

Exterior Wall ($hr \cdot ft^2 \cdot^\circ F/Btu$)	Overall R=15
Roof ($hr \cdot ft^2 \cdot^\circ F/Btu$)	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 space function

Table 4.7: Envelope and Internal Loads Specifications of Building C

Mechanical System

HVAC System Specifications	
Temperature Setpoint	Heating setpoint: 21°C Cooling setpoint: 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 exhause 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

Table 4.8: Mechanical System Specifications of Building C

The mechanical system of building C is relatively much more simple 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 obtain cooled and heated air through split heat pumps mounted on the ceiling of the parkade. The heating and cooling setpoint listed in table 2 are the basic settings that are adaptable according to the space function and thermal comfort of the individual occupant. Corridors are ventilated and pressurized by receiving 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 (DF-MUA), which uses the combustion of natural gas to heat the outdoor air being sent to the zone straightly. The utilization of DFMUA grants high combustion efficiency and helps to keep the positive pressure in zones.

4.3.3 Domestic Hot Water System

Building C possesses a solar heating system on the rooftop to preheat the DHW water and stored in four preheat tanks. A gas-fired boiler then reheats the preheated service water which is then stored in four DHW storage tanks to maintain the DHW at 60°C to prevent bacteria. With the installation of low flow fixtures, the building is capable of recovering 42% water consumption compared to the baseline model.

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

Table 4.9: DHW System Specifications of Building C

4.3.4 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

Monthly electricity and natural gas consumption data for building C has been collected and reviewed. Total annual energy consumption given by utility bills for 2016 and 2017 calendar year is 204% and 282% respectively greater than the predicted energy for the proposed design. The results are far beyond the aimed plus or minus 15% range of accuracy level. Additionally, the actual energy used for 2016 and 2017 calendar year is 82.6% and 129% more than the baseline model.

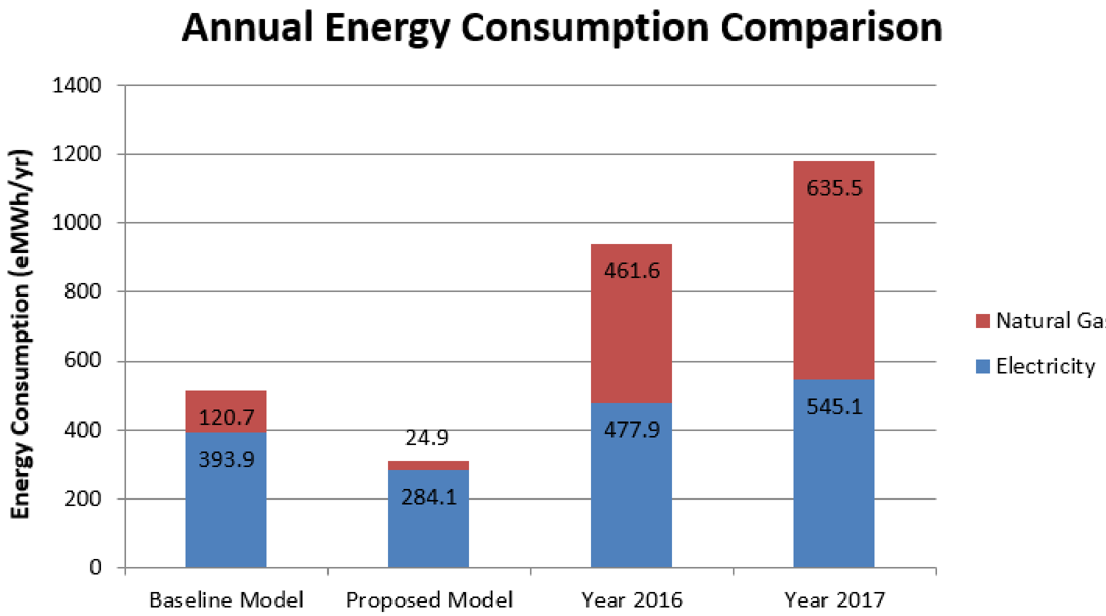


Figure 4.22: Annual Energy Consumption Comparison of Building C

Overall, the actual natural gas burning is 17 and 24 times more than the prediction for the year 2016 and 2017 respectively as shown in table 4. What the tremendous inconsistency between the energy model and the reality happened for building C was predictable considering that the solar system on the rooftop did not work since the first day of turnover. The condensing boiler turned to be the only source for service hot water used by facilities.

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

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

From the snapshot (Figure 4.23) taken from the building management system, it clearly expresses the abnormal operation of the solar panels from the year 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 commanded on during the year 2013 and 2014. This is erroneous since there was no glycol fluid inside the dry cooler system. During the year 2016 and 2017, there was no heating operation with both solar tubes 01 and 02 and the valve was kept closed.

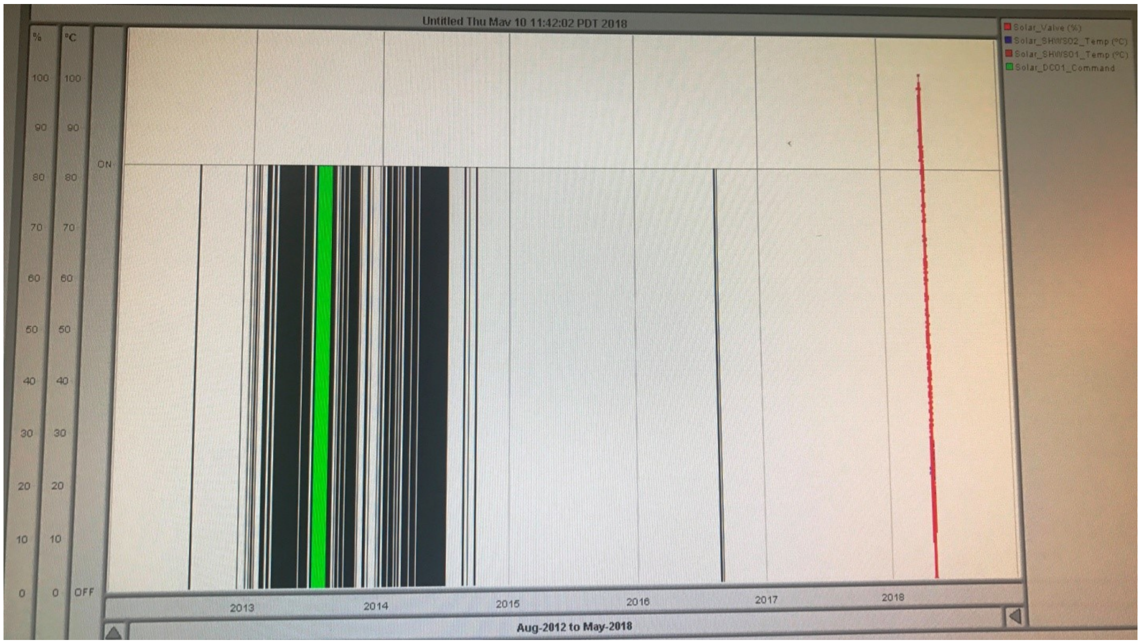


Figure 4.23: Trendlog Graph of Solar Panels of Building C

The discrepancy in electricity occurred with several aspects from unexpected occupancy behaviours mentioned in building B analysis to 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, which did not account for the energy consumption in the energy model. This type of non-regulated plug loads might contribute a lot to the actual electricity use. Another concern would be the electric baseboard heating used in suites. In consideration that most tenants of the building have physical and mental illness, they may have higher heating requirement or usage compared to the data applied to the energy model. Mechanical and operational deviations are listed in section 4.3.4.

Mechanical and Operation Deviations

The following mechanical and operational deviations were obtained from the previous mechanical issues inspection report and discussion with the building maintenance manager.

- **Solar System Failure**

The system was not set in motion since the first day of building operation. The design imperfection of not taking extreme winter weather condition into account led to the freeze damage of some solar vacuum tubes after a short operation. The commissioning would also be responsible for the system breakdown of not recognizing the limitation before occupants moved in. For those panels in good condition, there is no glycol feed tank installed to inject anti-freezing liquid into the tubes for solar energy transfer process. Moreover, the system was switched on with no fluid inside the tubes which caused a pump failure.

- **Air Handling Unit HRV-1**

The system was diagnosed to have short cycling of the compressor and heat wheel exposed to the unfiltered air in the year 2016. The short cycling intended to lead to a significant energy waste since the setpoint was difficult to achieve and the compressor had to operate repeatedly. With unfiltered air entering the heat exchanger core, there was a risk of unhealthy air being supplied to indoor areas. This could be a big issue as a result of people living here with physical and mental illness.

Another critical issue reported in 2016 was that the HRV-1 unit was not capable of providing free cooling to the building and it has not been solved due to the high maintenance fee. The record could not be found because of DDC system used for building C not saving historical data for more than one week. However, from the most recent trend data (Figure 4.24), the control strategy for free cooling/heating might give a foresight. Although May is not typical summer or winter weather, it was not necessary to run the heat wheel to keep the room warm. The heat exchange core cycled on and off during the nighttime from 10 pm to 6 am. The supply air temperature setpoint was set at 18.3°C that was lower than the actual supply air temperatures at most of the nighttime, which indicates the operation of the heat wheel. At the same time, the zone temperature could reach 24°C (shown in the red rectangular in Figure 4.24), from which a waste of energy could be predicted during real summer time.

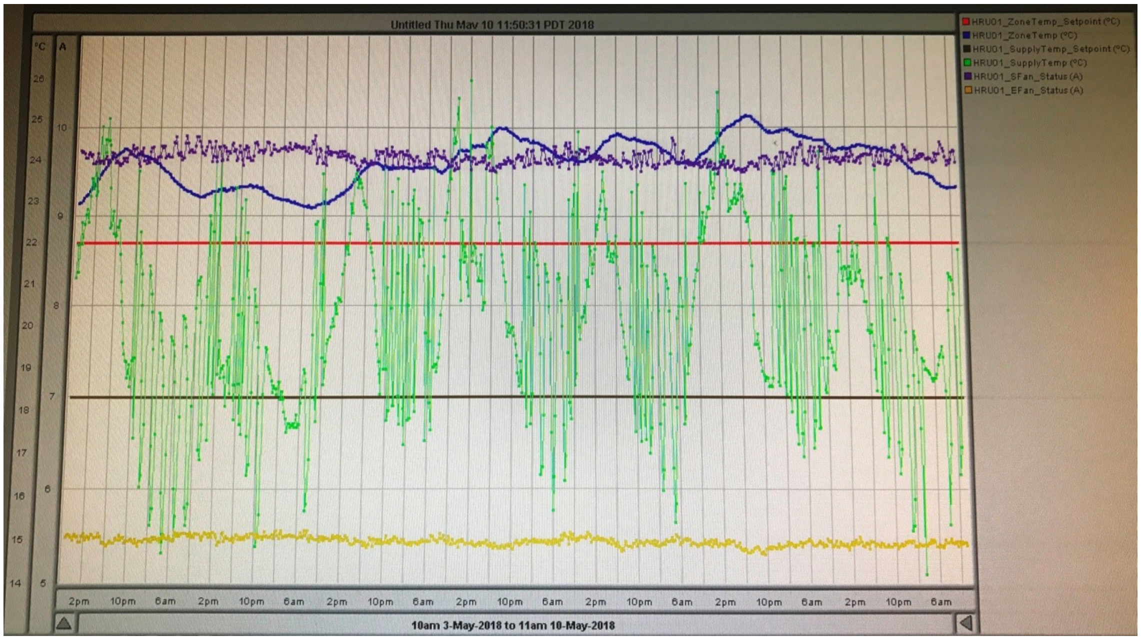


Figure 4.24: Trendlog Graph of Heat Recovery Unit of Building C

- **Gatekeeper DHW System**

Gatekeeper is a high-temperature tank which was prepared for the hot water to be sent to the fixtures. The intention of using the gatekeeper tank was to eliminate legionnaires in tempered water. It was detected not performing for a long time and would be a risk for occupants with physical issues.

- **Split Air Conditioners(heat pumps)**

Installation issues of leaking pipes and design issues of rejecting heat to parkade that made it feel like a sauna were both observed. The heat accumulated in parkade called for more ventilation to mitigate heat to outside. DDC system was not programmed as expected to have common spaces free cooled in summer.

Building Energy Performance Index Comparison

From the annual EUI comparison above, building C performed far away from the anticipation. It is essential to compare the EUI of building C with benchmark buildings. Considering that the solar system of Building C has been abandoned, the natural gas consumption would be within +/-15% range of the baseline model. Nevertheless, for both year 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 around 30% less energy consumption compared to HCSA and AFS. Building C offers hot meal once a day, three breakfast a week and individual support for health recovery which makes it more like health care and food service accommodation. The inputs of the energy model are recommended to be modified according to the characters of different building types.

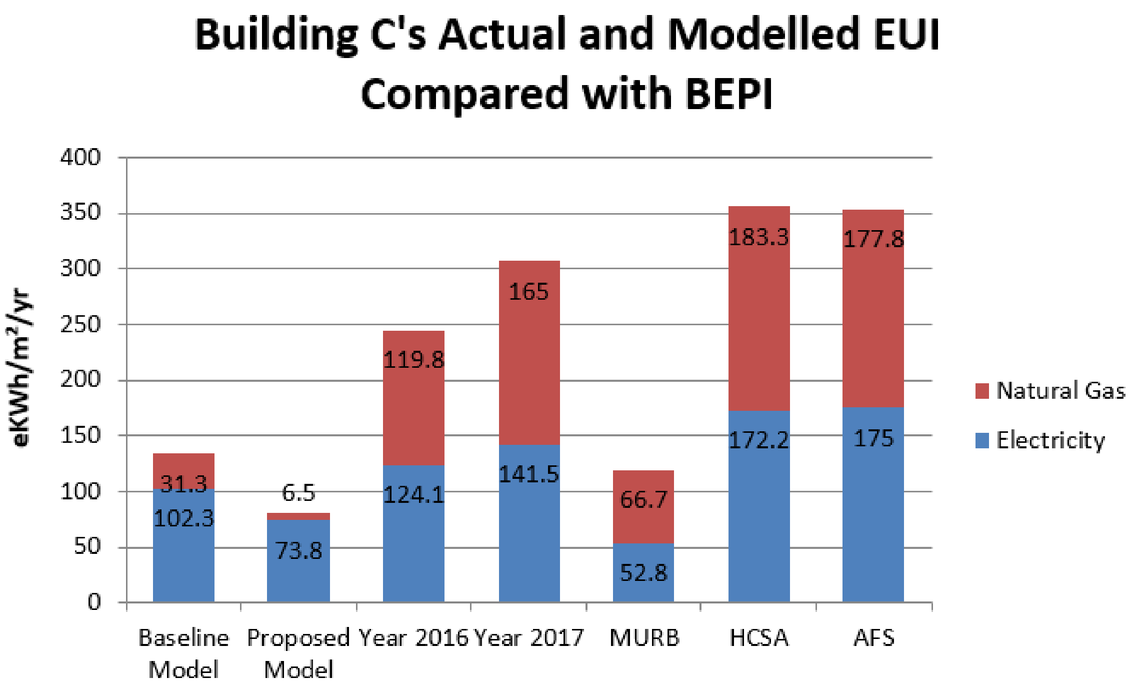


Figure 4.25: BEPI comparison of Building C

Effects of Weather on Results

The heating degree days for the year 2016 and 2017 were compared to the 30-year average weather data used in the energy model. For the year 2016, HDD is 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 should be performed to explore the interrelationship between heating degree days and actual energy usage.

The energy model had an R^2 of 0.9016 signifying the strong relationship between HDD and energy consumption. The R^2 for the year 2016 is 0.6737 which is lower than the reasonable coefficient 0.7. The building uses electric baseboard for in suites heating and tenants have full control of the temperature adjustment. The reason for the weak correlation is that occupants often kept electric baseboard on and left windows open in winter. In this case, extra electricity would be dissipated with the poor heating control procedure. The rough condition of solar systems for preheating DHW had a momentous impact on the total natural gas consumption and could be another explanation for the weak correlation. The baseload energy for the year 2016 is approximately 170eKWh/day more than the energy model, which might partially result from the excluding some non-regulated plug loads.

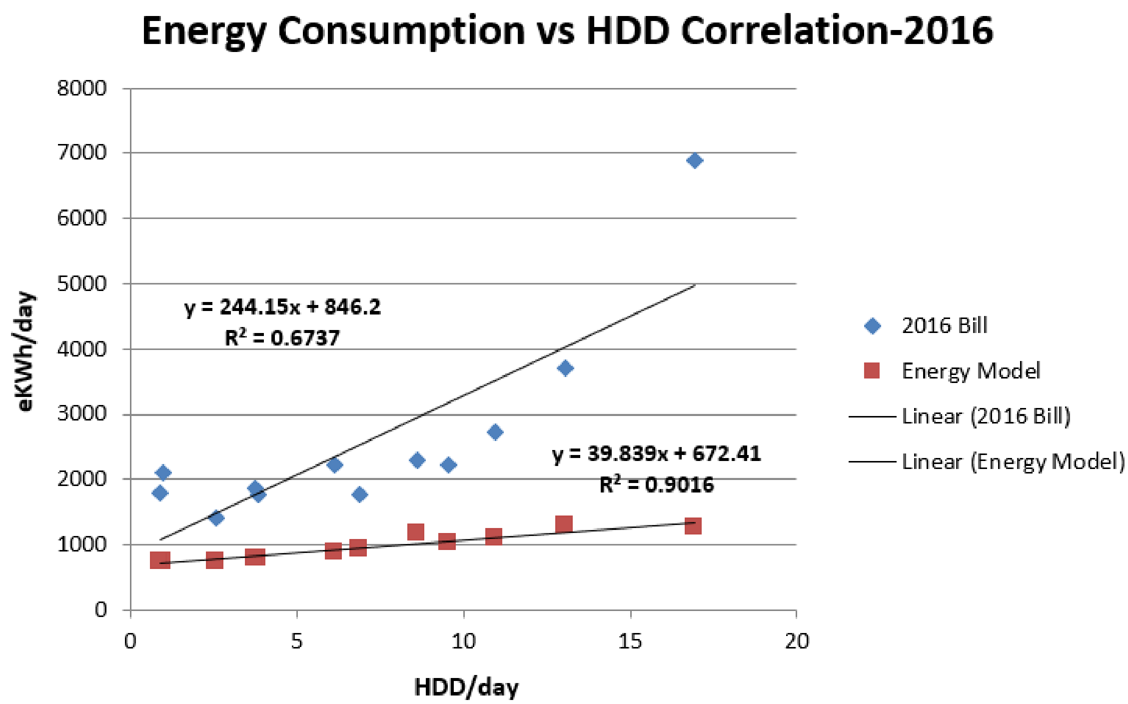


Figure 4.26: Effects of Weather on building C for 2016

For the year 2017, the energy consumption had a much better fit to HDD, with R^2 of 0.8771. Although occupants behaviours on the window opening in winter kept invariable, the colder weather in 2017 gave a compromise of the behaviour conflict against that predicted during energy modelling. Additionaly, the heat wheel's cycling during summer nights resulted in another portion of elerctricity consumption accretion. According to the monthly natural gas consumption trend for a calendar year (Figure 4.28), it is obvious that colder days consumed more gas and expressed higher DHW demand. It corresponds to the good correlation between energy consumption and heating degree days.

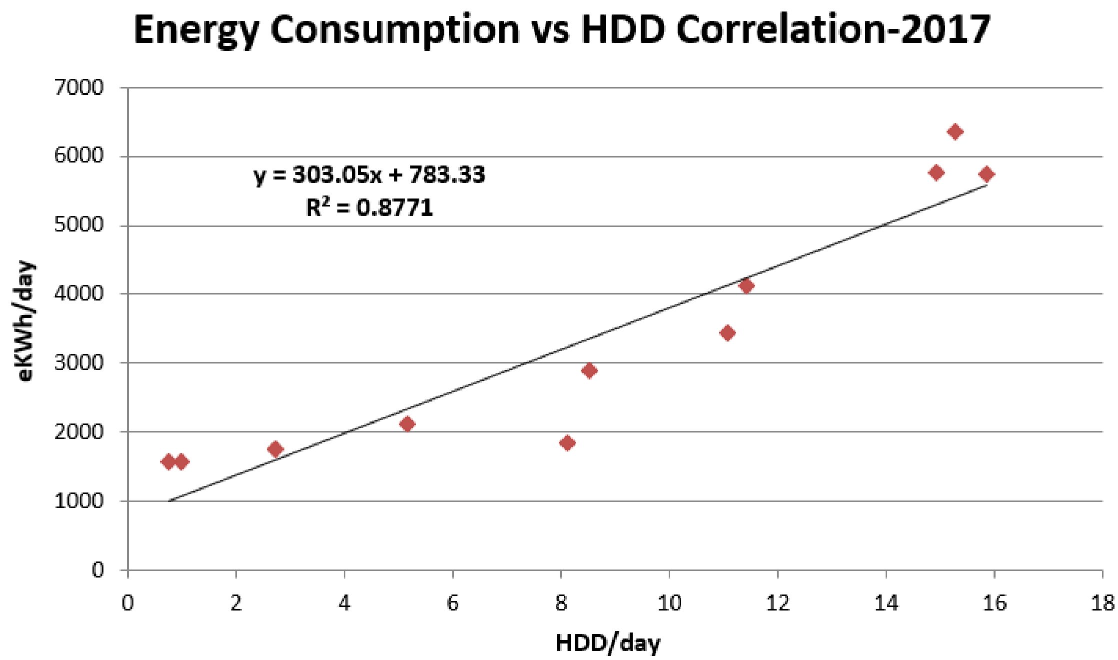


Figure 4.27: Effects of Weather on building C for 2017

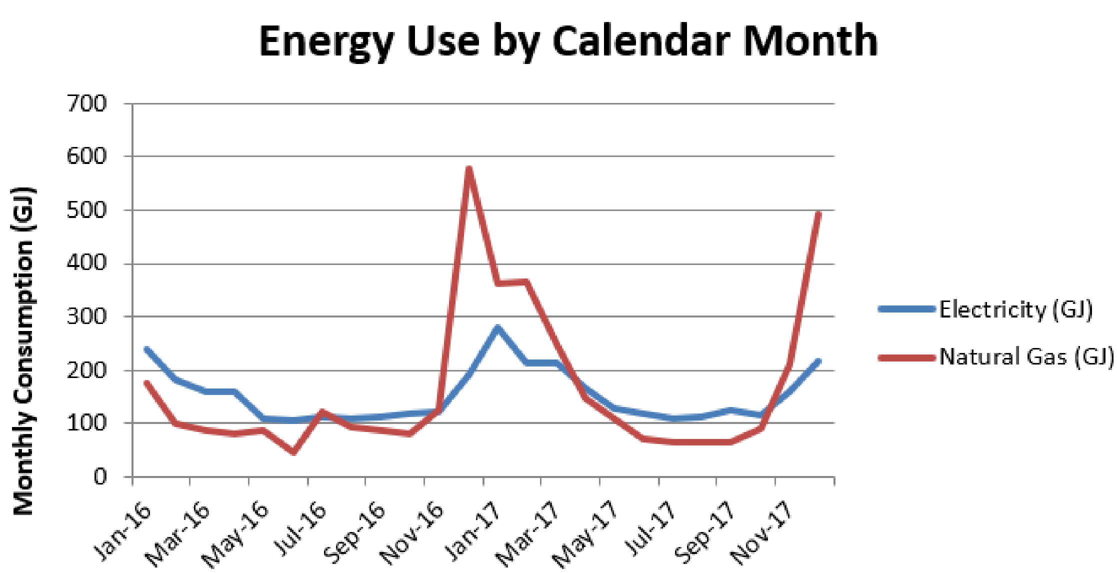


Figure 4.28: Monthly Utility Data by Types of Building C

Monthly Electricity Consumption Comparison

Figure 4.29 and 4.30 present the comparison between monthly modelled results and electricity utility bills for the year 2016 and 2017 respectively. For the year 2016, the three biggest conflicts appeared in January 67.7%, February 60.2% and April 67.5%. For the year 2017, the three biggest conflicts announced much higher than 2016 figuring January 95.1%, February 88.5% and March 83.5%. This is mostly due to the colder weather in 2017 and unexpected occupants behaviour. It is recommended that the future energy modelling takes the supportive housing characteristics into account to generate more accurate predicted consumption data.

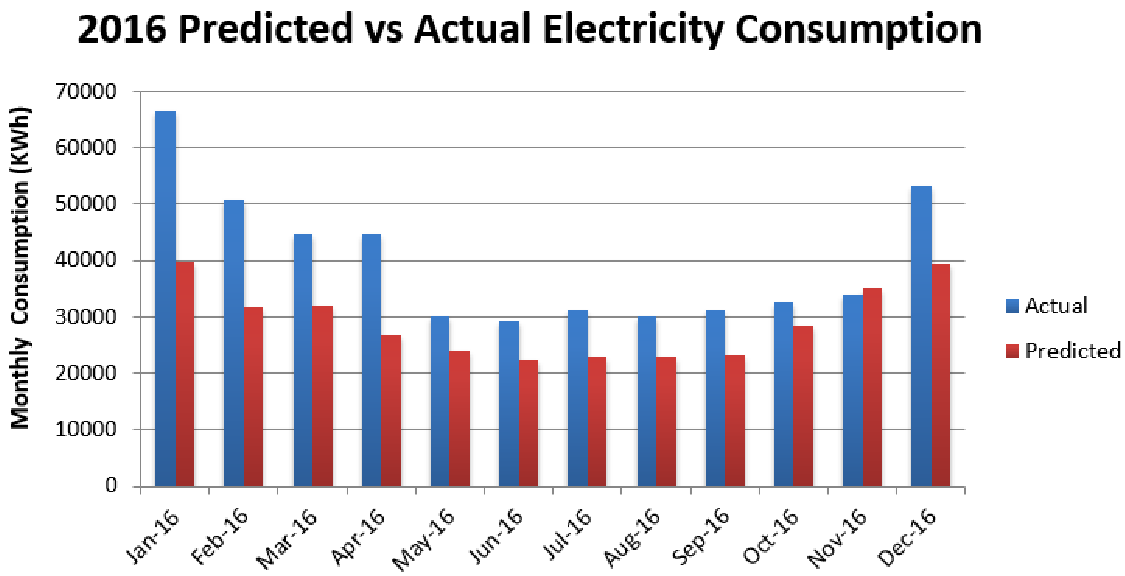


Figure 4.29: Electricity Consumption Comparison for 2016 of Building C

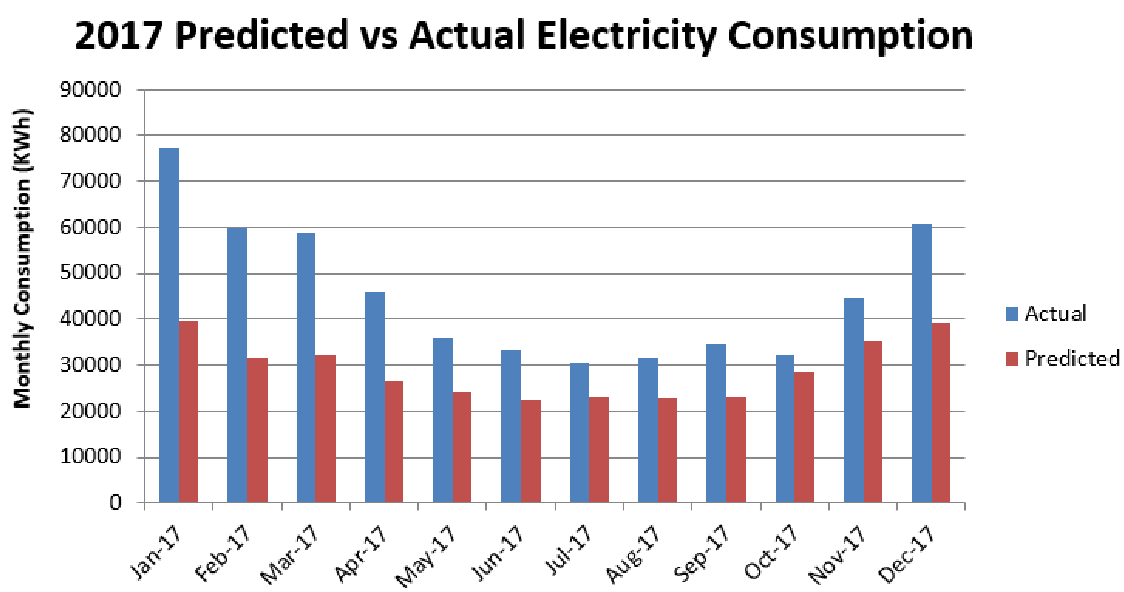


Figure 4.30: Electricity Consumption Comparison for 2017 of Building C

Recommendations

- Careful and correct installation of equipment is one of the most critical sections for the normal operation of mechanical systems. From the solar system failure of building C, it is recommended to cooperate with experienced contractors to ensure problem-free installation process.
- Add sensors to equipment that is more likely to break down or operate abnormally and programme related 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 LEED Gold buildings due to the much more complex mechanical systems.
- Recommissioning is recommended for building C after the abandon of the solar system, the accession of the dry cooler and various issues due to the negligence of the previous commissioning process.

4.4 Case Study: Building D

4.4.1 General Description

Building D is an eleven – storey sustainable high-rise residential supportive housing located in Vancouver, BC. The building was designed as two parts combined with eleven and six floors respectively to shape an “L” structure. It accommodates 147 units and an administrative office on the first level with a total floor area of $9476m^2$. A sub-basement with only 18 parking spots and 123 covered bicycle storage slots was designed for greener building target. A broad courtyard wrapped around the backside of building D provides a superb activity area for tenants. Various amenity spaces including gardens, lounges, libraries and dining areas are spreaded on different floors. Common spaces on the main floor furnished with large floor-to-ceiling windows enables abundant sunlight shining into the inside, which can lower the lighting consumption during daytime and heating demand in freezing days. High window placement in units maximizes sunlight penetration as well as contributes to the overall livability. All non-emergency interior lighting can be automatically controlled to turn them on and off according to the business hour schedule. With well designed irrigation system and correctly selected plants, the use of potable water for irrigation has decreased over 50%. Building D was occupied since 2013 and has received the LEED Gold building under LEED Canada-NC 1.0 in 2014.

4.4.2 Envelope and Construction

The framing and materials were designed and selected towards a long-lasting aim with at least 50 years service life. All the rebars in the building were made from 100% recycled materials and manufactured regionally. 54% of the roof area is covered with vegetation, which can diminish urban heat island effect to a certain extent. Environment conservation and energy dissipation minimization is achieved via absorbing solar heat in summer and limiting heat loss in winter. The vegetated roof also protects waterproofing membranes from being damaged by extreme weather conditions and extends the roof lifespan.

4.4.3 Mechanical System

Building D participated in a Neighbourhood Energy Utility (NEU) program to reduce reliance on electricity and fossil fuels. It is a district heating system with renewable heating energy restored from raw urban wastewater and solar energy collected from the neighbourhood building roofs. The NEU contributes a lot to the GHG reduction featuring 50% less emission compared with conventional peer buildings. A total of 70% energy can be rescued annually from the NEU[88].

HVAC System Specifications	
Temperature Setpoint	Heating setpoint: 21°C Cooling setpoint: 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 supplys conditioned air to suites and corridors *Radiant in-floor heating in residential suites *Radiant heating panels in stairways and laudry 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

Table 4.11: Mechanical System Specifications of Building D

The NEU works similarly to a geothermal heating loop, which moves heat from wastewater to surrounding buildings. The heat transfer process is achieved by using a heat pump system complimented with 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 pressurized to high pressure and temperature gas. The heat is delivered to distributed underground pipes connected to neighbourhood buildings via the condenser. After transferring heat to divided 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 radiant heating system. The DDC system is to modulate NEU control valve to maintain heating plant supply temperature at setpoint.

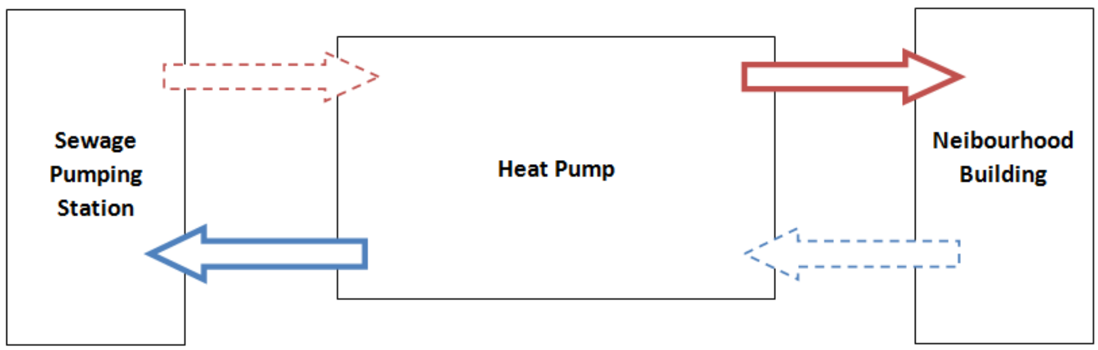


Figure 4.31: Schematic of NEU Working Principle

The heat recovery unit runs continuously 24/7/365 to provide fresh and warm air preheated by a heat pipe. During heating mode, DDC system modulates the control valve to maintain the supply air temperature at 23.5°C. Free cooling is not functional since the unit cannot control the tilt angle of the heat pipe to disable heat recovery action. MUA-1, ecology unit and exhaust fan are activated simultaneously when switching the grease hood on. During heating mode, the MUA-1 heating control valve adjusts to discharge supply air temperature at 23.5°C. FCU-5 will operate when MUA-1 is running for additional space heating. During cooling mode, the control valve modulates to keep supply air temperature at reset setpoint according to the FCU-5 schedule. MUA-2 provides 100% outdoor heated air to the first-floor amenities during the occupied period. The supply air temperature setpoint is primarily attained by a hydronic heating water control valve, supplemented with a heating coil pump if the heating demand cannot be satisfied. Solar panels supplemented with the NEU system prepares heating to air-handling units (HRU-1, MUA-1 and MUA-2). When solar panels loop temperature is not capable of complying with the demand, DDC system will command to mix the NEU loop water with the solar loop water to provide higher water temperature to air handling units.

The fan coil units are independently switched on upon a call from DDC commands for heating or cooling. The FCUs have a gateway interface to the DDC system for control of various functions including occupied/unoccupied mode, space temperature, space temperature setpoint, fan status monitoring and air conditioning mode operation. The outdoor air damper for FCUs remains closed during the unoccupied mode.

4.4.4 Domestic Hot Water System

Both solar panels and the NEU system are DHW heating source 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 will flow into PHT-1 to 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 will forward a command to heat storage tanks via natural gas.

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

Table 4.12: DHW System Specifications of Building D

4.4.5 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

The utility data shows a total of 59.9% and 69.5% more electricity and natural gas consumption than the proposed model for the year 2016 and 2017 respectively. The wide gap partially resulted from the energy modelling inaccuracy since it did not take the electricity consumption of residential units into account. The separated meter for units was not installed making it inaccessible to the electricity consumption of suites. In this research, the discrepancy between the first year's operational data and the proposed model – 255MWh is assumed as the proposed residential electricity usage. After calibrating the model, the performance gap reduces to 22.1% and 29.4% respectively, slightly beyond the accuracy level of +/- 15%.

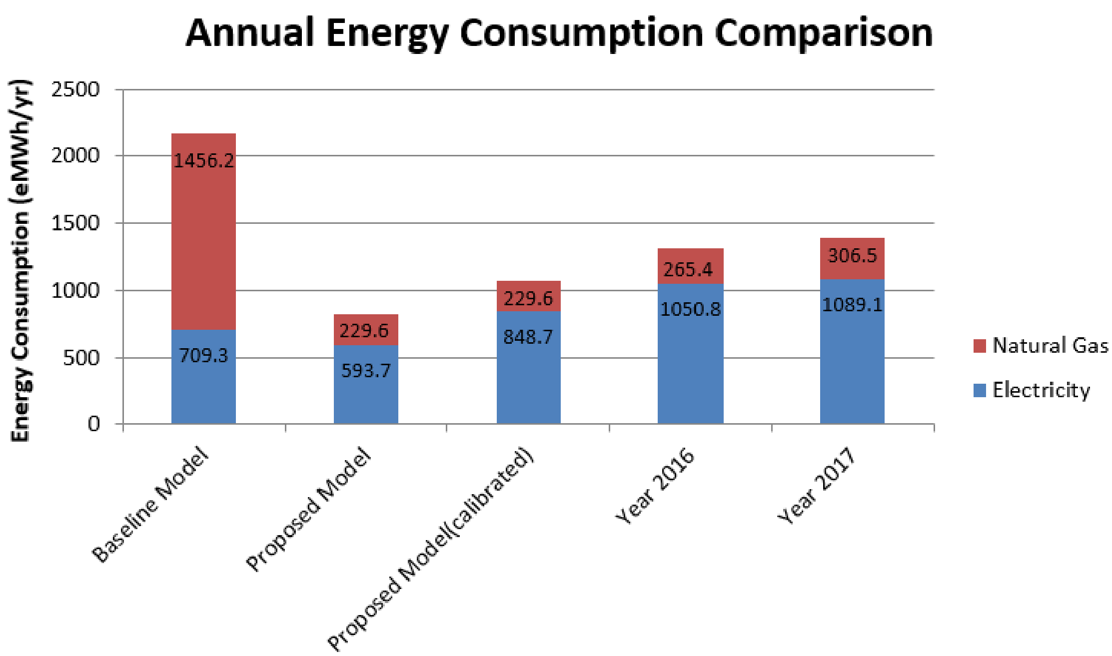


Figure 4.32: Annual Energy Consumption Comparison of Building D

On comparison of the year 2016 and 2017 building D consumption data with the anticipation, 23.8% and 28.3% more electricity consumed and 15.6% and 33.5% natural gas fired in operation. There is no substantial equipment failure and operational issues reported by the maintenance manager. The main concern is the unpredictable occupancy behaviours which can be deduced from the discussion with building staff. Occupants broke the temperature sensors, opened windows in winter, blocked smoke detectors, smashed lights in corridors and so on. Another consideration is the energy modelling excluding the non-regulated loads such as commercial kitchen, elevators and the parkade operation in the simulation process. Moreover, the modelling standard for social housing is not adequate, which caused the imprecise inputs for some parameters such as DHW use intensity.

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

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

Building Energy Performance Index Comparison

On analysis of the comparison between building D's utilization data with the benchmark building, magnificent fossil fuels saving was realized. Although both years displayed a higher natural gas usage than proposed, building D utilized only around 20% of the gas with participation in the NEU system compared against the baseline building. Furthermore, it saved more than half of the gas energy compared to BEPI for the building type MURBs. Although the actual electricity consumption appears over one time greater than the benchmark conventional MURBs and even slightly greater than the baseline model, building D is still within the reasonable range with around 35% less electricity consumed than HCSAs and AFSs.

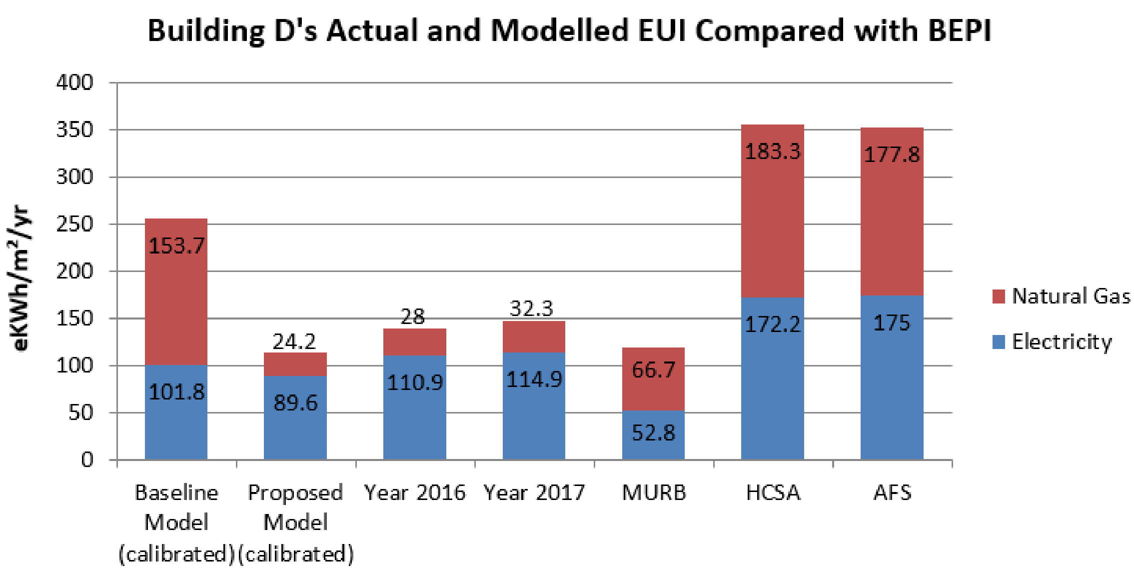


Figure 4.33: BEPI Comparison of Building D

Effects of Weather on Results

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

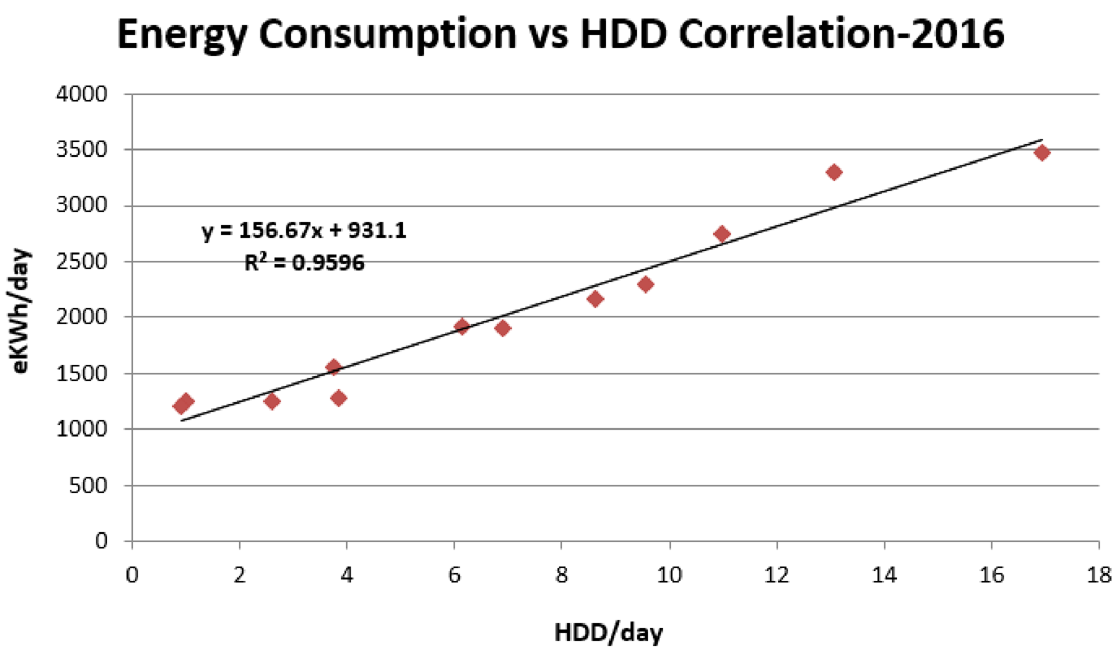


Figure 4.34: Effects of Weather on building D for 2016

Both 2016 and 2017 possess a high value of R^2 featuring 0.9596 and 0.9565 respectively. It indicates a strong interconnection between HDD and energy consumption. From the trendline for both years, the daily energy consumption perfectly follows the growth of HDD/day. With the further investigation via energy use by calendar month, the electricity utilization does not fluctuate with the weather but natural gas presents a close track to season changes. This is mainly dependant on the heating system of building D, which uses renewable energy and the NEU system as the space heating and DHW heating source, and for the NEU system only natural gas consumption was included in the research. The flawless match proved the design intention has been met with the stable operation and control of equipment and accountable maintainence by building staffs.

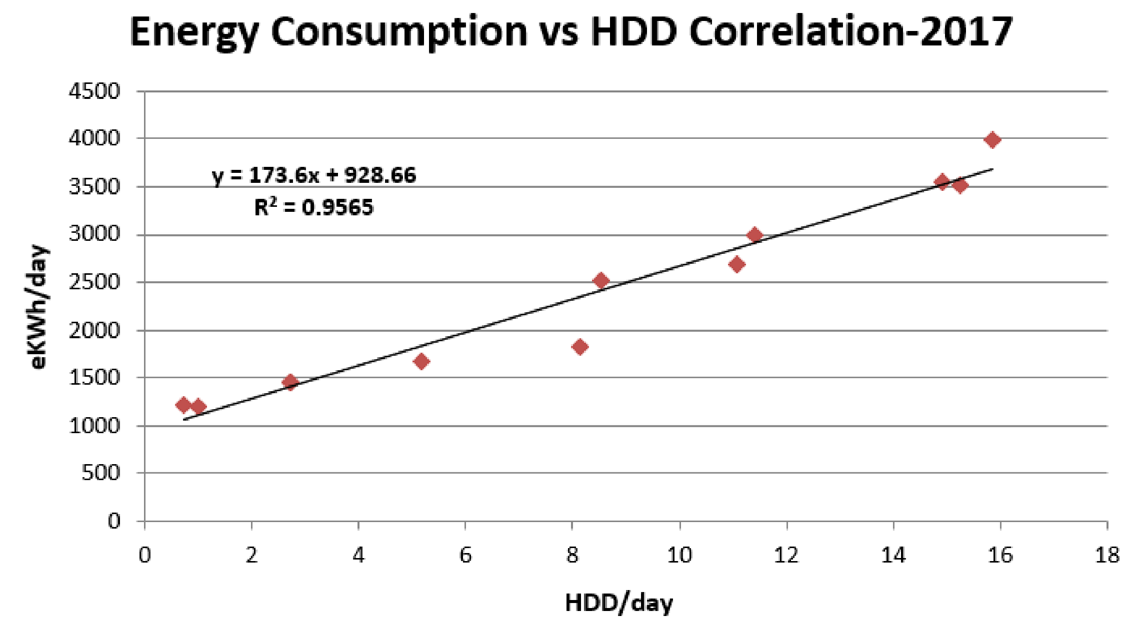


Figure 4.35: Effects of Weather on building D for 2017

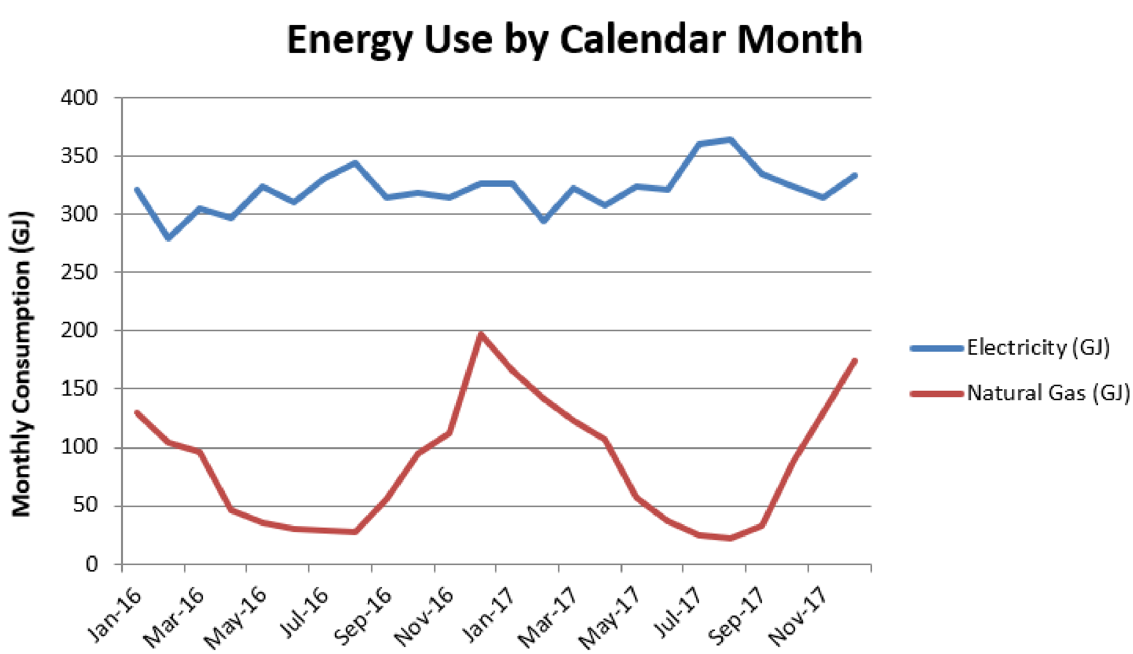


Figure 4.36: Monthly Utility Data by Types of Building D

Monthly Electricity Consumption Comparison

The electricity comparison between the year 2016 and 2017 was performed to justify the normal operation of building facilities. From Figure 4.37 below, the greatest discrepancy occurred in July, August and September. This is primarily due to the weather condition changes during these two years with a total of 57% more CDD in 2017[90].

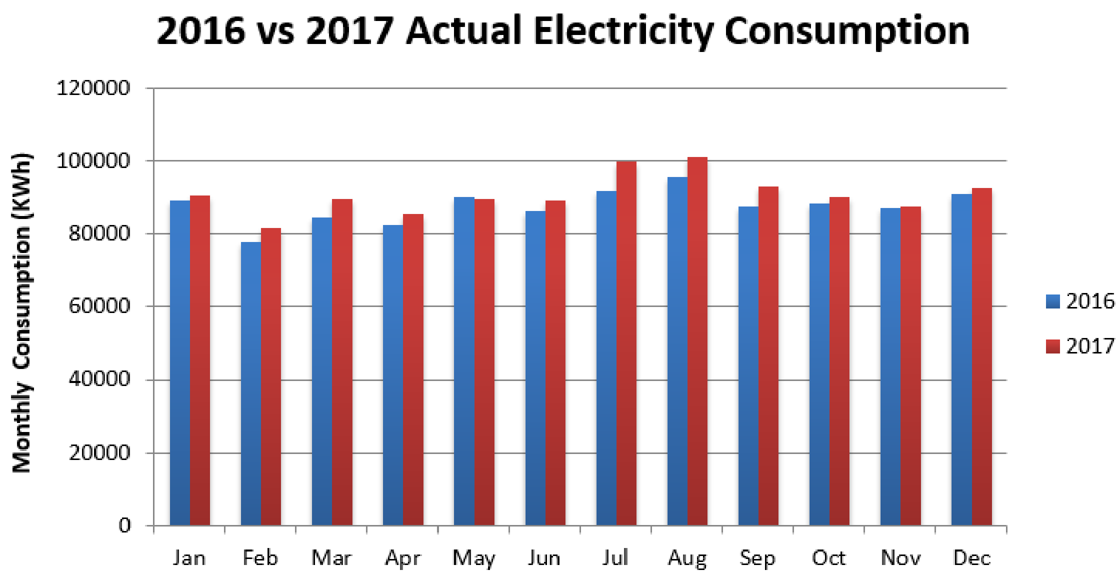


Figure 4.37: Electricity Consumption Comparison between 2016 and 2017 of Building D

Recommendations

- The energy model did not take electricity use of residential suites into the calculation. It is recommended that all the energy modelling process include as much information as possible to avoid inaccurate evaluation for any research.
- Use specific modelling packages (for example, schedules, window opening tendency and shower time), to model 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 located in Vancouver, BC. The building has a total floor area of $4208m^2$ with a patio, four retail stores and amenity spaces with computers and a piano on the ground floor. 80 studio lodges are available and 10 of them are fully wheelchair friendly. A commercial kitchen provides a hot meal once a day. Large windows in common spaces were mounted on the walls to economize lighting consumption during the daytime. Building E was occupied since 2010 and has received the LEED Gold building under LEED Canada-NC 1.0 in 2013.

4.5.2 Envelope and Construction

Building E utilizes mainly Masonry products as the exterior wall material with a small portion of metal siding walls for the first level of the building. The long durability of at least 50 years and costless maintenance of clay masonry and metal siding products contribute to the energy efficient design. The materials used for construction consist of 13% recycled content. The whole construction process was carried out environmentally friendly with 75% of waste materials diverted from landfills.

Exterior Wall ($hr \cdot ft^2 \cdot^\circ F/Btu$)	*Clay, with steel stud inside, R=23 *Clay, with concrete inside, R=23 *Metal panels, with steel stud inside, R=12 *Metal sideing, with steel stud inside, R=12 *On average, R=19.31
Roof ($hr \cdot ft^2 \cdot^\circ F/Btu$)	*Flat roof with concrete inside, R=30 *Sloped metal roof with concrete inside R=30
Overall Glazing U-value ($Btu/hr \cdot ft^2 \cdot^\circ F$)	*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 space function

Table 4.14: Envelope and Construction Specifications of Building E

4.5.3 Mechanical System

HVAC System Specifications	
Temperature Setpoint	Heating setpoint: 18 Cooling setpoint: 25
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 supplys 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

Table 4.15: Mechanical System Specifications of Building E

The air-handling unit MAU-1 on rooftop runs highly efficiently with VSDs controlling the air flow of supply and exhaust fans. The ventilation for the main floor spaces is disabled by closing the corresponding dampers according to the control schedule. The air flow 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 at the minimum setpoint 13°C. During heating seasons, the DDC system commands to discharge the supply air temperature at 25°C when the average building temperature falls below 18°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 almost the same as an air source heat pump except for its extracting heat from the soil instead of the ambient air. The vertical loop frees from the soil temperature change compared with the horizontal loop due to the equipment deeply buried under the ground.

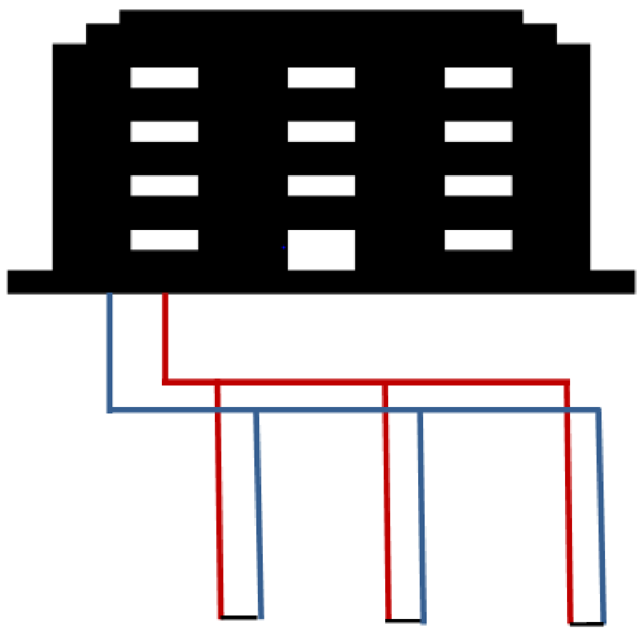


Figure 4.38: Schematic of Vertical Geothermal Loop

The geothermal source side 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 being supplied to specific zones.

4.5.4 Mechanical and Operation Deviations

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

- **Thermal Wheel Operation in Cooling Mode**

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

Figure 4.39: Trendlog Graph of Thermal Wheel Amps during August 2016

Figure 4.40: Trendlog Graph of Outdoor Air Temperature during August 2016

4.5.5 Domestic Hot Water System

Building E reached the goal of saving almost half of the water consumption 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, an overall of 59% energy is saved regarding the DHW heating.

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 kithen sink faucets *Low flow shower heads

Table 4.16: DHW System Specifications of Building E

4.5.6 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

Building E overperformed than the predicted model at a rate of 29.3% and 19.2% for the year 2016 and 2017 respectively. Total energy consumption decreased by 58.5% and 52.6% for both years compared against the baseline building created based on MNECB standards. During the year 2016, both the electricity and natural gas consumption were less than the proposed building. The 29.3% discrepancy beyond the accuracy range +/-15% might result from the specific weather condition for the year 2016, this will be discussed later. For the year 2017, 24.2% less of electricity yet with almost the same gas use is identified, which is slightly beyond the preferable accuracy scope. The consumption of laundry, commercial kitchen and elevator were added to both the proposed and baseline model for calibration according to the M&V analysis. The unexpected occupancy behaviours existed but not a crucial factor for extra energy usage.

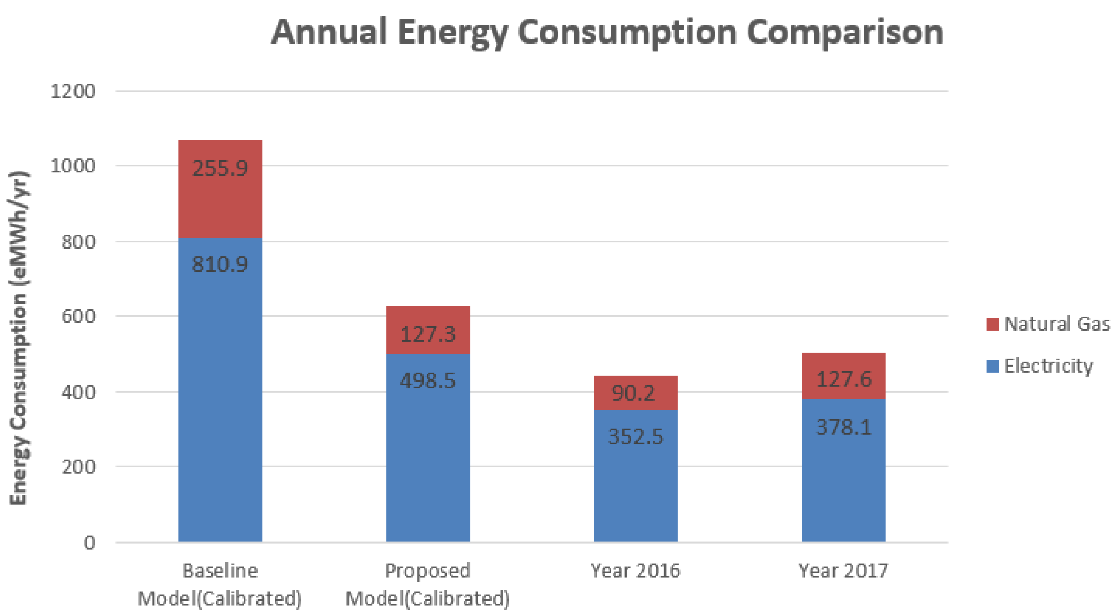


Figure 4.41: Annual Energy Consumption Comparison of Building E

Building Energy Performance Index Comparison

On comparison of the energy performance of building E with BEPI, the natural gas consumption appears much less than the conventional peer buildings. For both years, the gas utilization is below half of the BEPI buildings for the type of MURBs.

Considering that building E is more than a residential building with administrative offices, common spaces and commercial kitchen, the electricity use of more than 50% greater than BEPI MURBs is acceptable. Moreover, the total EUI for the year 2016 and 2017 is 12% less and 0.6% more respectively than BEPI residential buildings. The utilization of vertical geothermal loop for mid-rise apartments is proved to be an effective method for better energy performance.

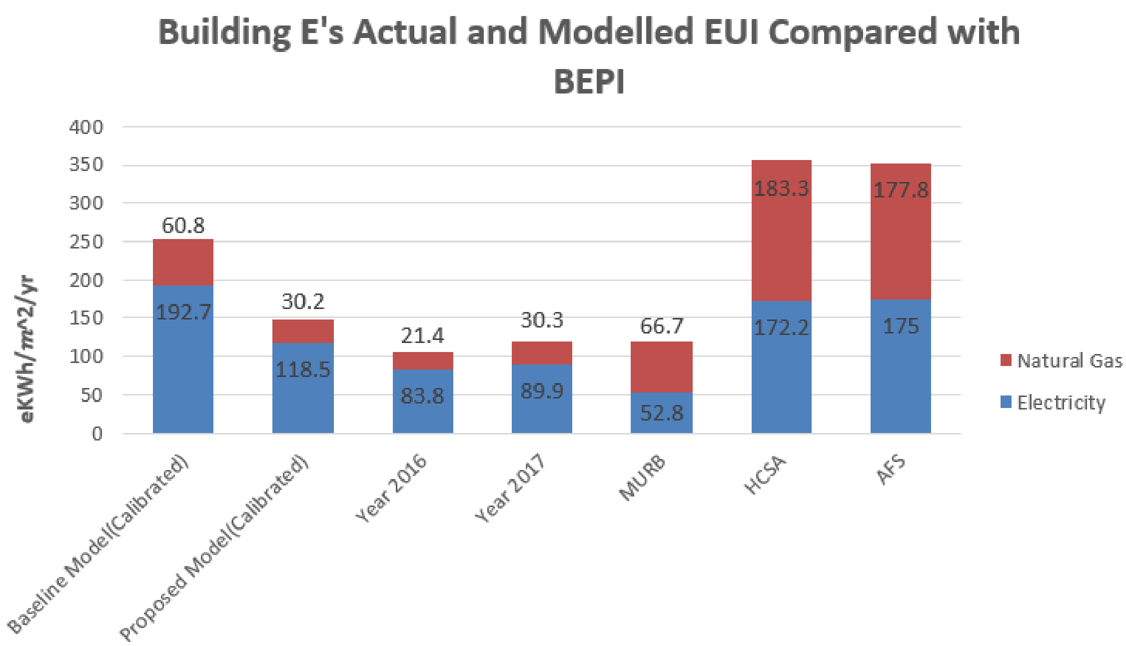


Figure 4.42: BEPI Comparison of Building E

Effects of Weather on Results

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

The building is located in a heating-dominated region, the difference in CDD is negligible in this research. The primary space heating system for building E is electricity motorized. The normalization of natural gas consumption is not included due to its independent of HDD. Accordingly, the space heating energy utilization 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 reduced to 25.5% for 2016 and 23.6% for 2017 which are still far better than the prediction.

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 environment-friendly high-rise residential supportive housing located in Vancouver, BC. The building consists of various types of suites including 105 studios (20 30m^2 each unit), 5 mobility accessible units and 30 units for addiction recovery. It has a modelled floor area of 4667m^2 with assorted common areas on the ground floor. South and West facing walls of building F was 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 for the reduction of lighting energy consumption, and also grants sunlight shining into the units in winter for taking advantage of solar energy. The curtain wall system is inserted partially for the main floor facades to maximize daylight. Natural ventilation is enabled with operable windows being installed at the end of each level's corridor. Building F was occupied since 2011 and has received the LEED Gold building under LEED Canada-NC 1.0 in 2013.

4.6.2 Envelope and Construction

The thick and well-insulated walls and roofs are one of the most straightforward methods to attain high performance of a building. Building F utilizes cost-effective brick walls with concrete and steel stud back up to provide a stable structure. The mixed-use of Composite and Mansory cladding enabled exceptional weather resistance and additional recycled materials utilization which can reach a ratio of 16%.

Exterior Wall ($hr \cdot ft^2 \cdot ^\circ F/Btu$)	*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 ($hr \cdot ft^2 \cdot ^\circ F/Btu$)	*Roof assembly, R=30 *Roof deck, R=30 *Patio deck, R=30
Overall Glazing U-value ($Btu/hr \cdot ft^2 \cdot ^\circ F$)	*U assembly=0.45 *SHGC=0.36
Glazing to Wall Ratio	37%
Lighting Controls	Occupancy sensors
Plug Loads (W/ft^2)	Based on space function

Table 4.17: Envelope and Construction Specifications of Building F

4.6.3 Mechanical System

The energy recovery unit MAU-1 of building F runs continuously 24/7/365 to provide fresh, conditioned air to 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 daytime (7 am to 23 pm), and at a reduced speed during the night time (23 pm to 7 am). The specific control dampers for the ventilation of the ground floor remains closed at night. The supply air temperature setpoint can swing from minimum 13°C for cooling and maximum 22°C for heating. Energy recovery wheel will be activated under following conditions: 1) In heating mode, RT is higher than OAT but lower than the RT setpoint; 2) In cooling mode, RT is lower than OAT but higher than the RT setpoint.

The distributed water-to-air heat pumps HP-2 to HP-9 are not monitored by DDC system but by electronic programmable thermostats. When the zone is occupied during the daytime, fans in the heat pumps will cycle on/off to maintain the room temperature. During the nighttime, cooling is disabled while the ceiling mounted heat pumps will operate to maintain minimum set-back room temperature.

The vertical geothermal loop not only provides heating/cooling fluid to hydronic coils built in the MAU-1 and HP-2 to HP-9 but serves radiant floor heating system and DHW preheating as well. Two secondary circulating pumps P1&2 work following the lead/lag order on the geothermal source side. P1&2 are variable speed driven pumps which can provide the various flow of fluid based on the pressure difference between the supply and return pipes.

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 amenities
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

Table 4.18: Mechanical System Specifications of Building F

The water-to-water heat pump HP-1 connected to a buffer tank serves MAU-1 and radiant floor system. During heating mode, the water temperature in the buffer tank is reset between 40°C and 49°C by the OAT. During cooling mode, the water temperature in the buffer tank is reset 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&2. HP-10 works to maintain the water temperature of both preheat storage tanks at setpoint 52°C. It will be activated when the return water temperature is below 46°C and the preheat storage tanks average temperature below 52°C. DHWT tanks work as the second stage of DHW heating resource. Low flow fixtures including low flow single flush water closet, lavatory faucets, kitchen faucets and shower heads were introduced for 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 lower zone *Low flow fixtures

Table 4.19: DHW System Specifications of Building F

4.6.5 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

The performance gap between the proposed model and utility data is 45.4% and 50% for the year 2016 and 2017 respectively. The offset partially results from the exclusion of unregulated loads including the lighting and plug-loads from residential suites, commercial kitchen, laundry rooms, elevators and parkades. The proposed model was then calibrated according to sub-metering data of the first operational year. The electricity consumption for both years is lower than the prediction at a rate of 5.9% and 3.1%. Extra natural gas usage during the real operation is issued from 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 circumstance.

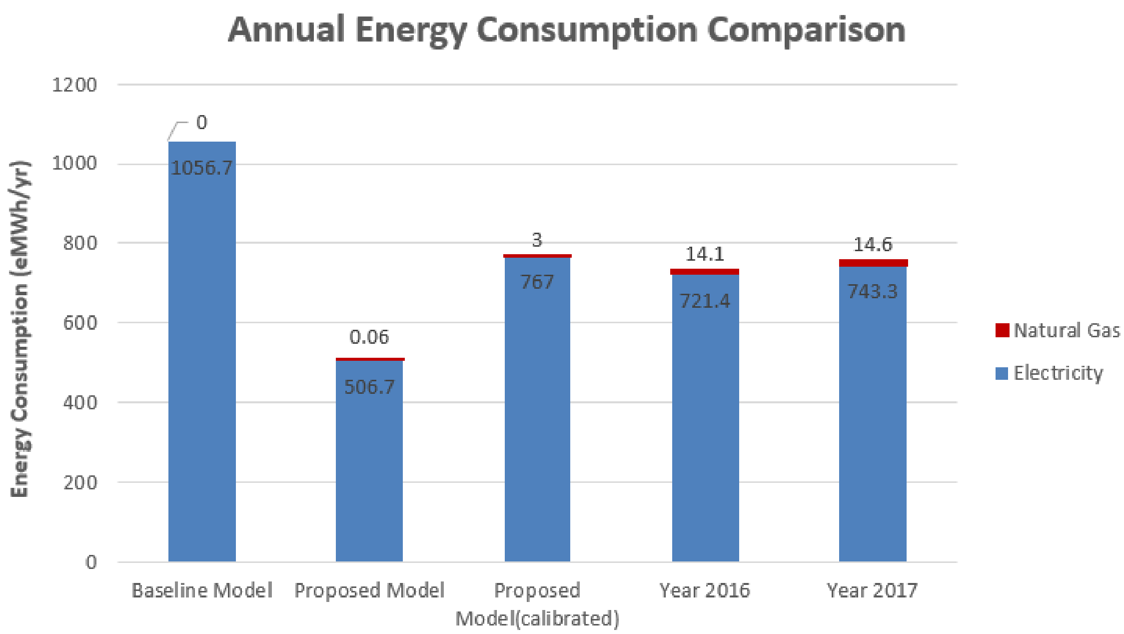


Figure 4.43: Annual Energy Consumption Comparison of Building F

Building Energy Performance Index Comparison

For both years, building F consumed around five times natural gas than the proposed model. However, in comparison to the BEPI MURBs, 95.5% of fossil fuel consumption is saved by introducing the geothermal heat pump plant for heating and cooling. The hydro utilization increased with the reduction in gas usage, which is two times more than the typical residential apartments. Considering that the commercial kitchen provides five meals a week and the resource center service for all the tenants, building F is more like accommodation and food service place rather than conventional apartments. The electricity consumption is within the proper range of 10% compared to HCSAs and AFSs.

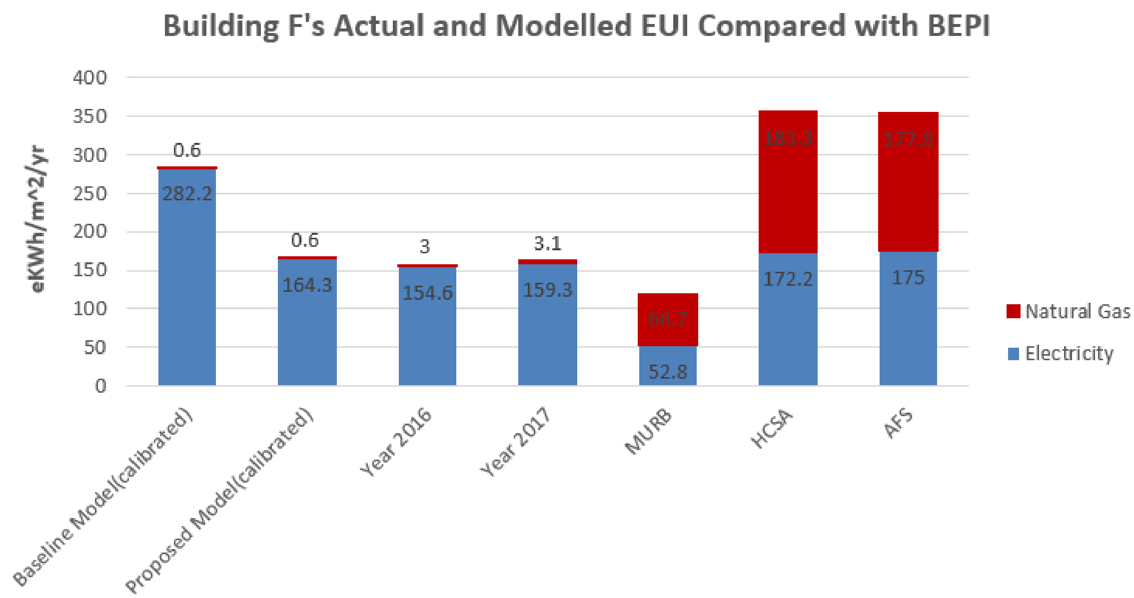


Figure 4.44: BEPI Comparison of Building F

Effects of Weather on Results

The annual energy consumption for the year 2016 and 2017 for building F state lower than the predicted model. However, HDD for both years is 14.9% and 2.2% less than the 30-year average weather data used in the modelling process. A calibration of the space heating energy regarding the weather aberration for the energy model was carried out to verify the equipment functioning level. The building energy utilization for both years is still 2.6% and 1.3% lower than the regulated proposed model, which is within the expected accuracy level of +/-15%.

The regression analysis for both years with R^2 of 0.76 and 0.87 was displayed in Figure 4.45 and 4.46. The highest energy use in 2016 is in February with the third most HDD, which used 9.6% more electricity and 47.3% less gas than January with the second most HDD and 5.2% less electricity and 50% more gas than December with the most HDD as shown in figure 5. In consideration that the performance of the geothermal loop was within the anticipation, the more frequent occupant behaviour of opening windows could be the most possible reason since February was warmer than December and January. The year 2017 shows a closer relationship between the energy consumption and HDD with an R^2 of 0.87. The electricity usage strictly follows the heating demand change with regard to the season change as shown in Figure 4.47.

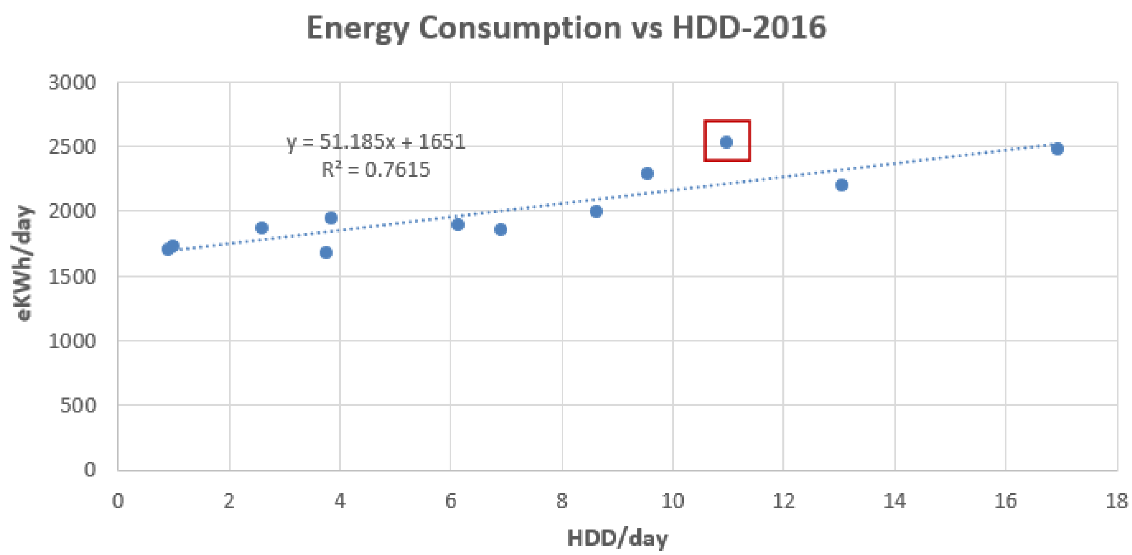


Figure 4.45: Effects of Weather on building F for 2016

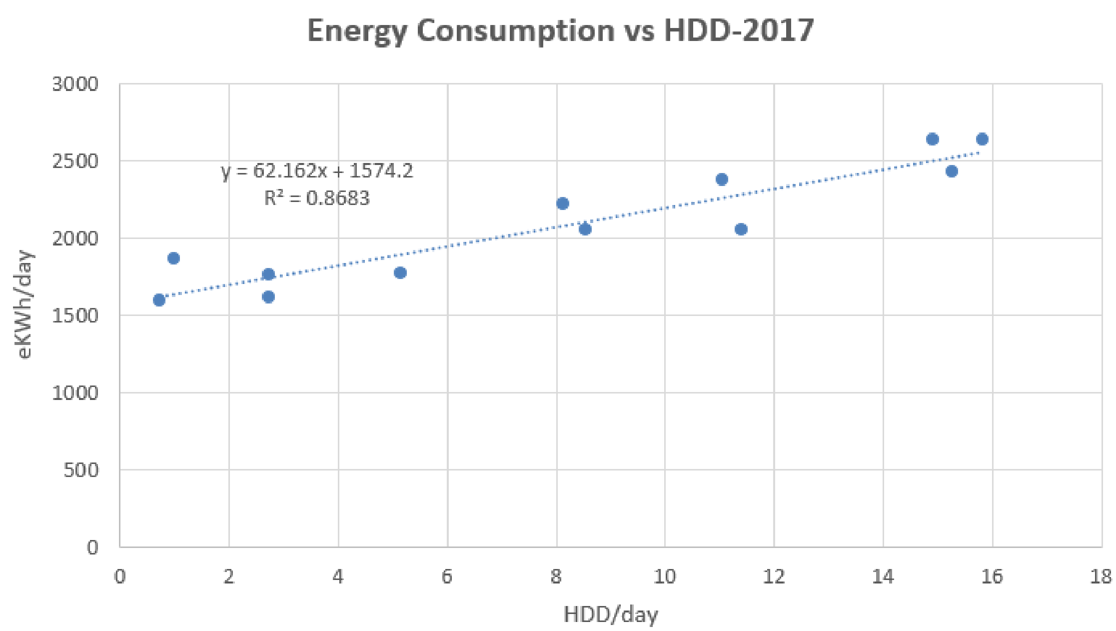


Figure 4.46: Effects of Weather on building F for 2017

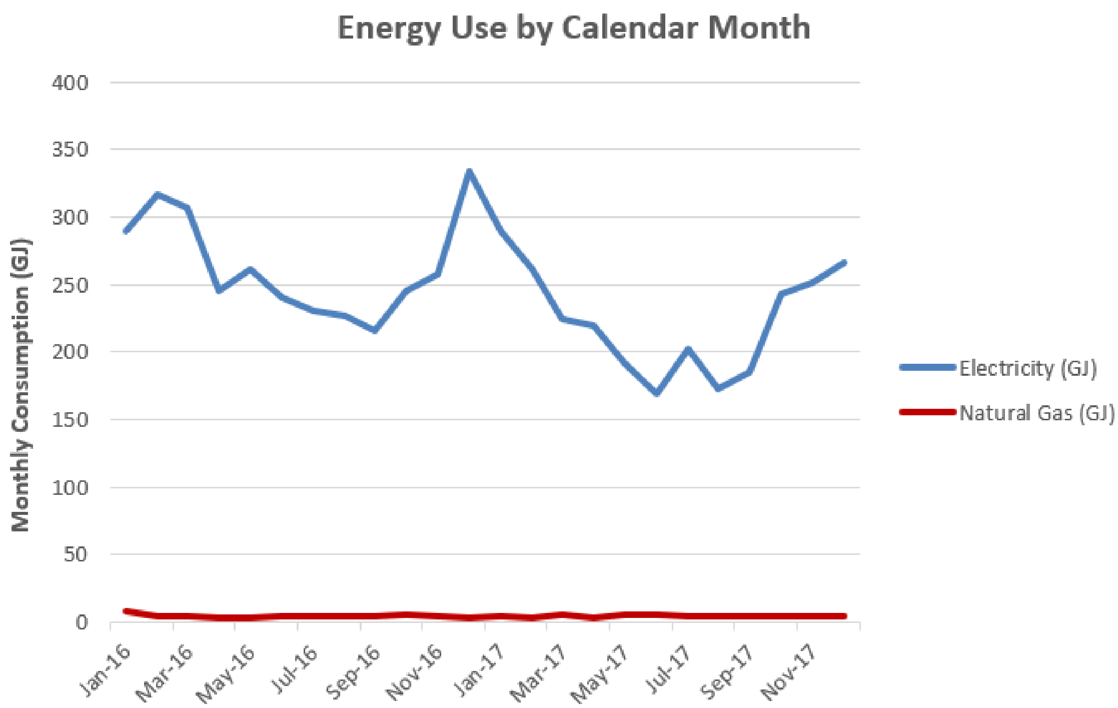


Figure 4.47: Monthly Utility Data by Types of Building F

Monthly Electricity Consumption Comparison

Considering that the computer got hacked a few months before the case study and all historical data is lost, a comparison of the monthly hydro bill between 2016 and 2017 was implemented to confirm the normal operation of building F as presented in figure 6. The most significant discrepancy occurred in January, October and November with 22%, 20.9% and 19.1% more electricity used in 2017 than in 2016, which is mostly caused by 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 in 2017 also indicated more HDD, the electricity consumption trend does not follow the HDD pattern. Unpredictable conditions such as occupancy behaviour variance and equipment maintenance and repair could be the explanations.

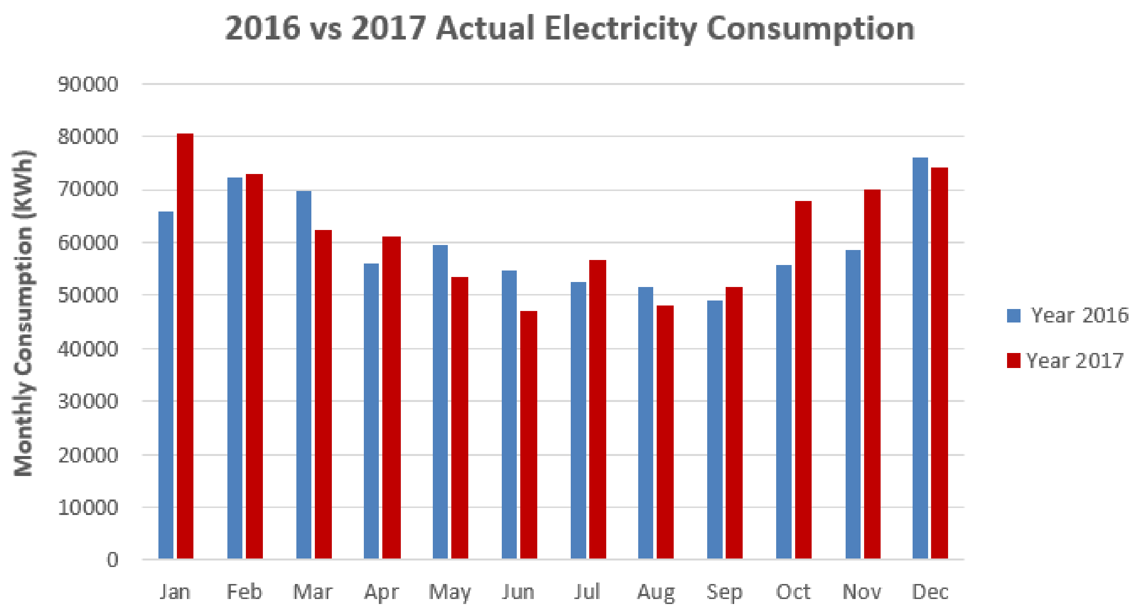


Figure 4.48: Electricity Consumption Comparison between 2016 and 2017 of Building F

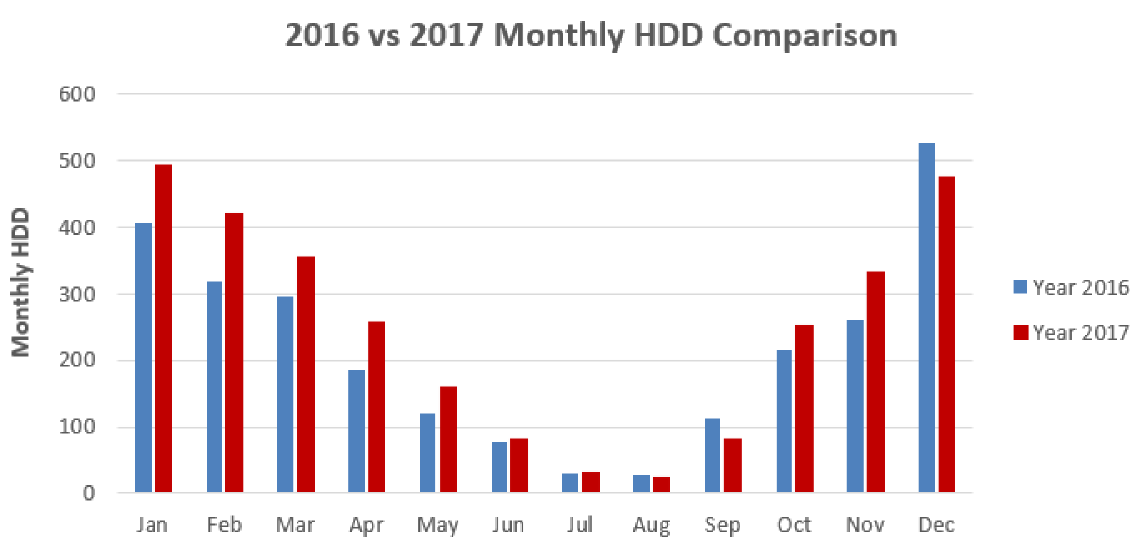


Figure 4.49: Monthly HDD Comparison between 2016 and 2017 of Building F

4.7 Case Study: Building G

4.7.1 General Description

Building G is a nine-storey environmentally-safe high-rise residential supportive housing located in Vancouver, BC. The building with a floor area of $4366m^2$ accommodates 62 studio units, amenity spaces, administrative offices and a social resource centre serving tenants and people in need. Building G possesses two levels of underground parking with limited vehicle parking spots and electric vehicles charging points. The building is located within the walkable distance to bus lines and skytrain station as well as shopping areas. Building G was occupied since 2012 and has received the LEED Gold building under LEED Canada-NC 1.0 in 2013.

4.7.2 Envelope and Construction

Materials containing 20% recycled content used in building G are easy-to-maintain and long-lasting to achieve a targeted building life of at least 50 years. The use of fibre cement panels and metal siding panels grants the exterior walls resistance to fire, thermal, water, insects and rotting. The well-insulated building and the low glazing-to-wall ratio contribute to the energy reduction as one of the most effective and straightforward approaches. More than 96% of construction waste was diverted from landfills.

Exterior Wall ($hr \cdot ft^2 \cdot^\circ F/Btu$)	*Concrete with steel stud walls *On average, R=16.6
Roof ($hr \cdot ft^2 \cdot^\circ F/Btu$)	R=29
Overall Glazing U-value ($Btu/hr \cdot ft^2 \cdot^\circ F$)	*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 space function

Table 4.20: Envelope and Construction Specifications of Building G

4.7.3 Mechanical System

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 amenities and offices on the first, second and third level
Space Cooling System	Ceiling mounted heat pumps serving amenities and offices 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

Table 4.21: Mechanical System Specifications of Building G

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

Water-to-water heat pump HP-1 supplies heated/cooled fluid to the central heat recovery ventilation unit MAU-1 and heated fluid to the radiant floor system. Two VSD pumps working in the lead/lag order extract water from the geothermal loop and discharge 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. A buffer tank was installed to reduce the time of heating/cooling water to setpoints and minimize the energy consumption at the same time. Two natural gas boilers as the backup heating source provide auxiliary heat to the HP-1 loop during the heating demand peak time.

HP-3 to HP-19 are the 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 will mix the return air with the preconditioned air from MAU-1 to flow through the filter. The clean air is then heated/cooled by the operation of compressors and discharged to spaces through the air diffusers. Each heat pump is equipped with a DDC controller and will operate to serve specific zones upon a call for heating/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 3 to maintain the water at its preheated setpoint. Before serving to the tenants, the preheated DHW will be heated by gas-fired water tanks DHWT-1 to 3 which work as the second stage heating source.

DHW System	*Vertical geothermal loop *Water-to-water heat pump HP-2 *Preheat 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 shower heads

Table 4.22: DHW System Specifications of Building G

4.7.5 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

The annual energy consumption for both reference and proposed model 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 is 50.9% and 64.4% more than the proposed model yet 21.9% and 14.9% less than the reference building. Extra natural gas consumption from either space heating or DHW heating or both contributed for the most part to the performance gap. For DHW loop, preheat tanks provide service water at the setpoint of 40°C to gas-fired water heating tanks, which then serve the building with domestic hot water at the setpoint of 50°C. For ground loop, boilers provide supplemental heat when the heating demand is high, or HP-1 is not operating efficiently. From the precedent verification report, HP-1 was not functioning during March to May in 2013 and January to April in 2014. With continuous issues of HP-1 from past years, the additional boiler firing during 2016 and 2017 could be predicted. From the discussion with building staff, the unexpected hydro consumption resulted from the different operating schedule of the resource center, the unpredictable tenant habits, the wear and tear of equipment and control conflicts with the energy model.

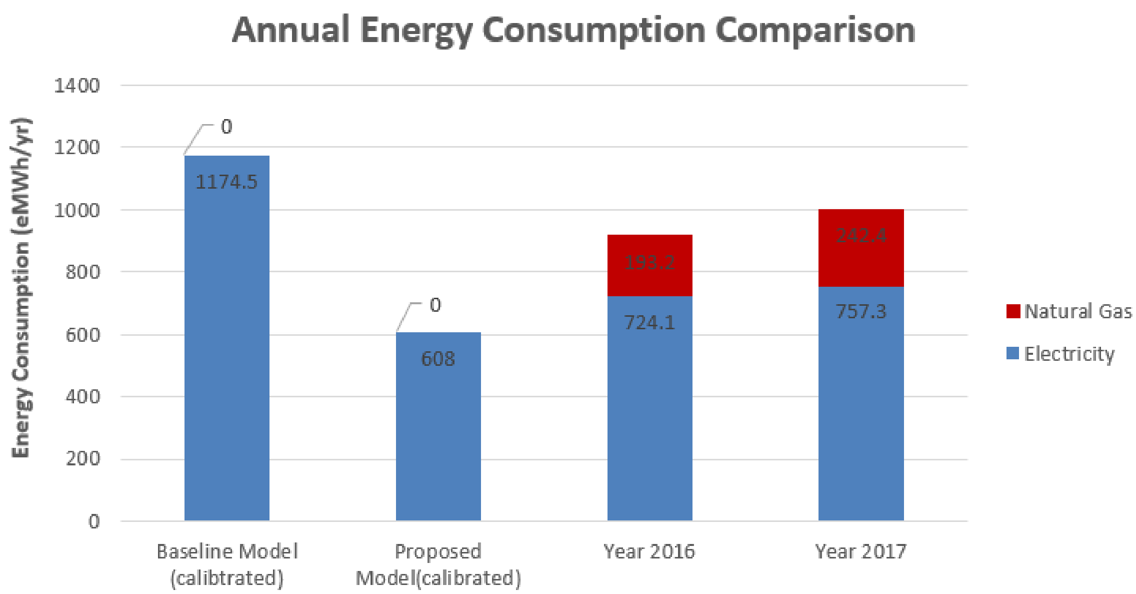


Figure 4.50: Annual Energy Consumption Comparison of Building G

Building Energy Performance Index Comparison

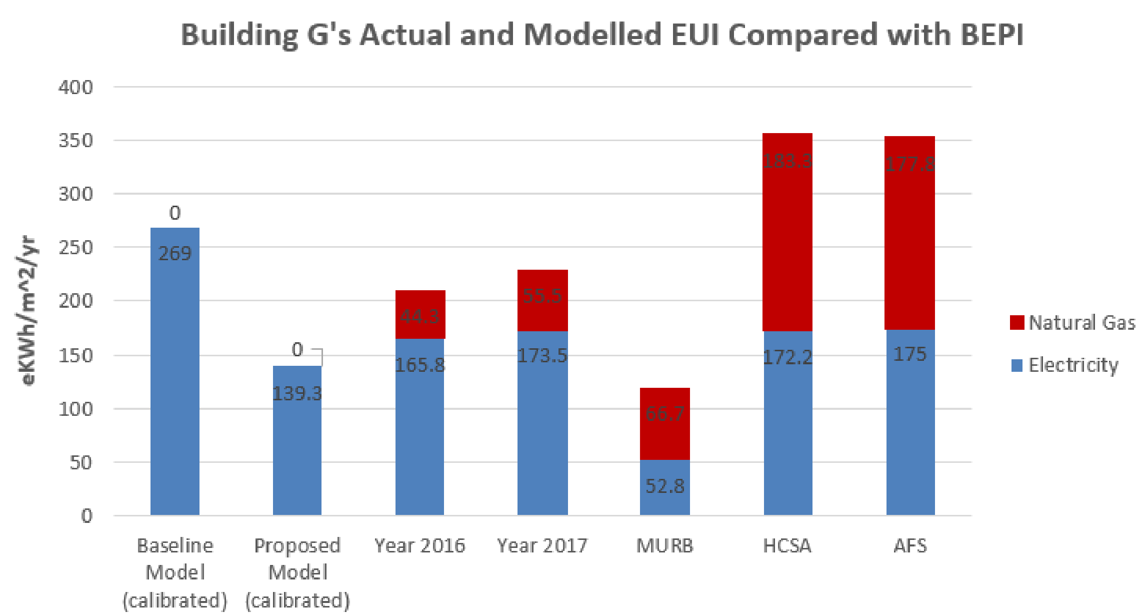


Figure 4.51: BEPI Comparison of Building G

From the comparison of the actual performance of building G with BEPI for the type of MURBs, natural gas consumption was avoided at the expense of hydro usage. However, the building is rather than a residential apartment with a resource center serving 80 100 visitors per day, a commercial kitchen supplying meals once a day and various amenities, which can be justified by comparing the proposed model to peer MURBs. The actual electricity consumption for both years is on the trace of BEPI for the type of HCSAs and AFSs. The total energy consumption is about 80% greater than MURBs and 40% less than HCSAs and AFSs, which fairly describes the real function of building G.

Effects of Weather on Results

Based on the performance gap as described above, the analysis on the effects of weather was implemented. The regression analysis between energy consumption and HDD was performed and the correlation factors for the year 2016 and 2017 are 0.73 and 0.83 respectively. It proves a reasonable relationship between the building energy consumption and HDD variation.

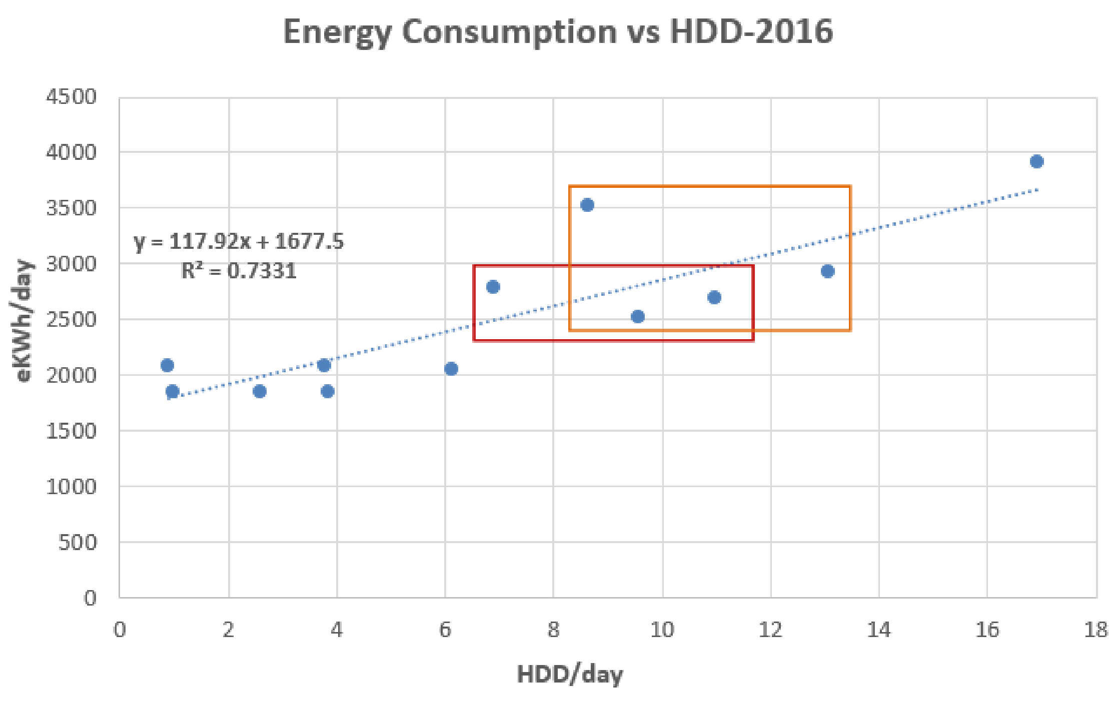


Figure 4.52: Effects of Weather on building G for 2016

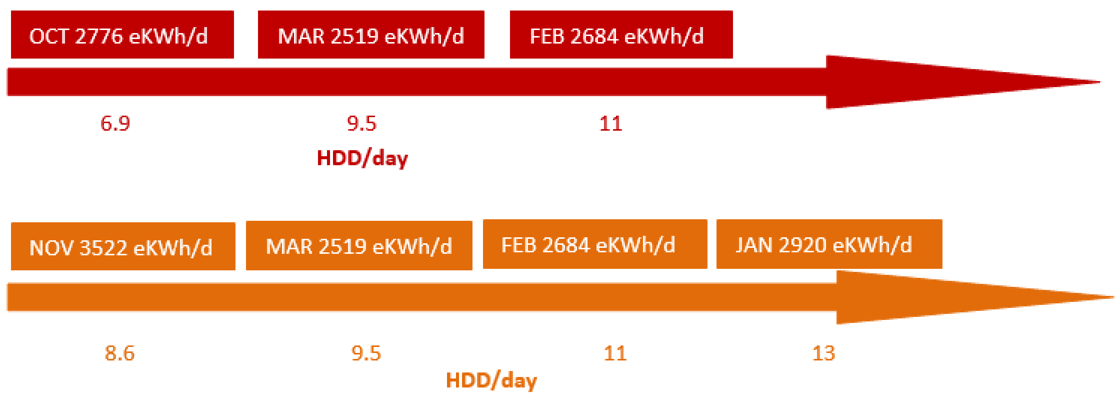


Figure 4.53: Abnormal Energy Consumption against Weather of 2016

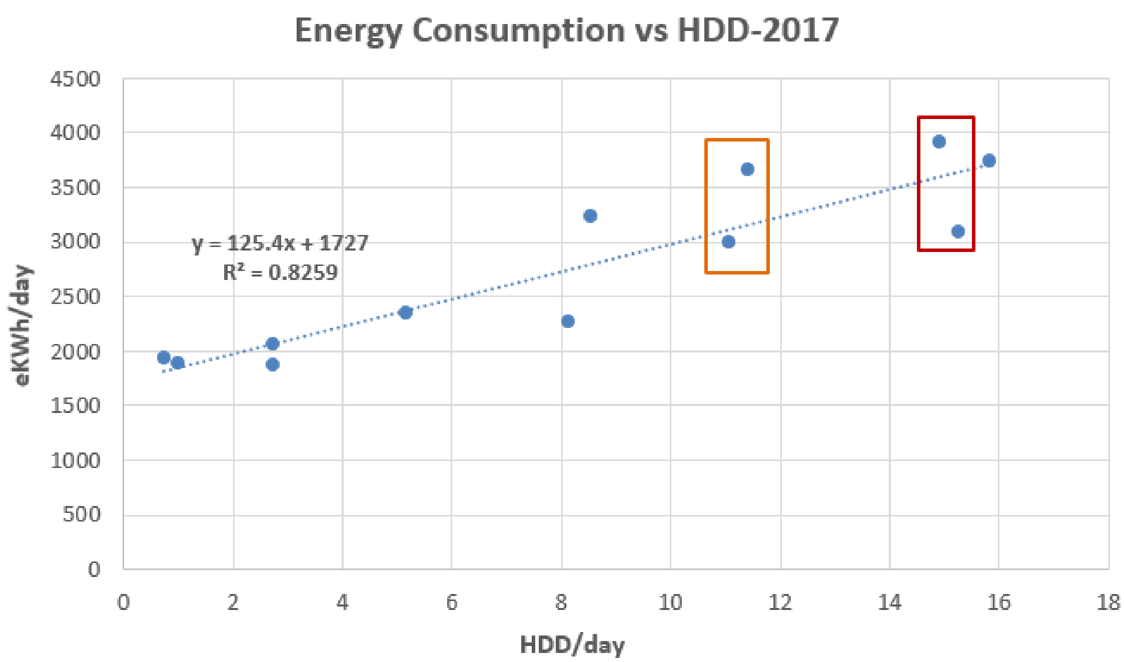


Figure 4.54: Effects of Weather on building G for 2017

For both years, two groups of plots which are within the red and orange rectangle reveal anomalous energy usage. For rectangles of the year 2016, months with fewer HDD/day consumed more energy/day as shown in figure 4.52 and figure 4.53. For rectangles of the year 2017, months with the approximately same HDD/day presented a noticeable difference in energy consumption emphasizing March against November and February against December as shown in figure 4.54. From the investigation of electricity and gas usage by calendar month, there exists a considerable increment in gas firing from 2016 October to 2017 March as shown in Figure 4.55. One of the reasons for the jump could be the extremely cold days in 2016 December and 2017 January, which also signifies the unforeseen inefficiency of the geothermal loop under extreme weather. Besides, the poor performance of ground source heat pump during cold days between 2016 October and 2017 March might result from some related mechanical issues.

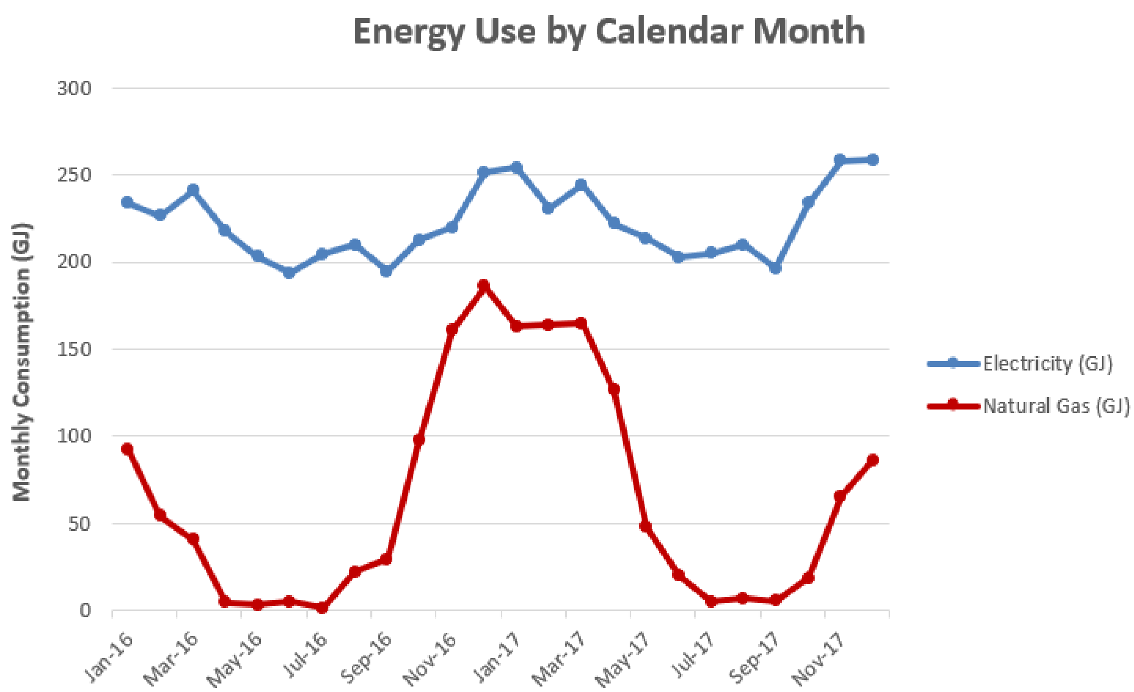


Figure 4.55: Monthly Utility Data by Types of Building G

Monthly Electricity Consumption Comparison

On comparison of the hydro data between 2016 and 2017, most of the months preserve approximately the same electricity consumption for each year. The biggest variation takes place in heating seasons featuring November, October and January. The explanation cannot be attributed merely to the more freezing weather in 2017 since the most sizable difference in HDD is in February. Dissimilar occupant behaviours, minor control issues and ineffectual equipment maintenance/repair could be other contributed elements.

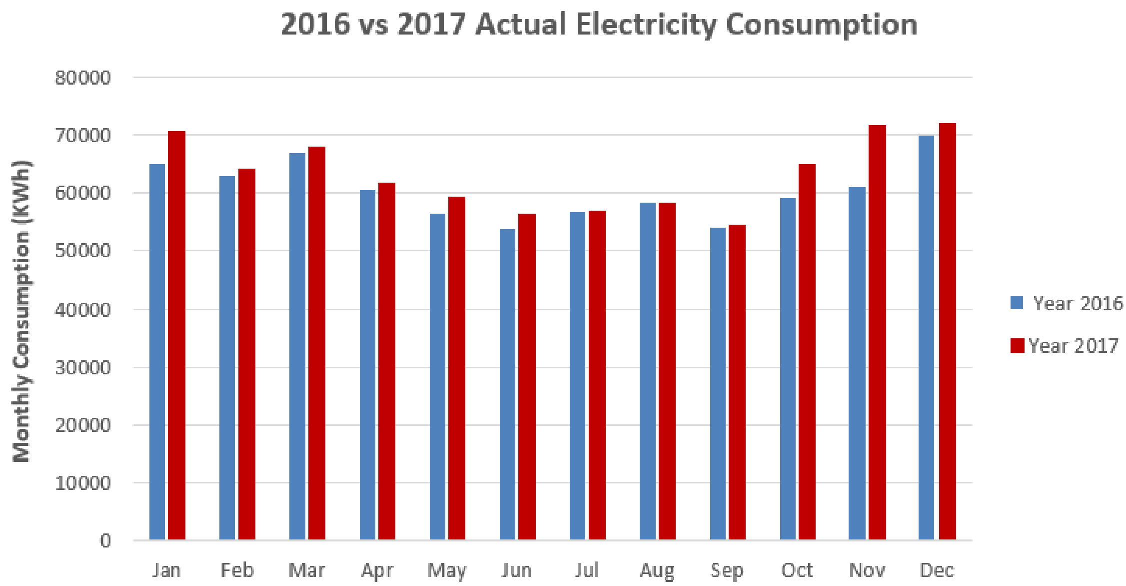


Figure 4.56: Electricity Consumption Comparison between 2016 and 2017 of Building G

Recommendations

- Fix sub-meters on boilers for DHW and boilers for space heating to ensure a close match to the actual natural gas bill.
- Identify where the extra high natural gas consumption came from, 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 backup boilers firing.
- Review the control sequences of HP-1 to minimize backup boilers operation.
- Monitor VSD pumps and fans to identify that their motors are running following the heating/cooling demand.
- Review the control sequences of HRV and radiant floor system to confirm free cooling and no unnecessary heating during summer time.
- Continuous commissioning is recommended to monitor the geothermal loop and verify its ability to provide 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 residential supportive housing located in downtown Vancouver, BC. The place has advantageous access to public transit systems, grocery stores and clinics. With a floor area of 9600m^2 building H provides 111 units for adults and 30 units for youth as well as amenity rooms, parking and bicycle storage spots. It has a youth supported center on the first and second floor offering meals once a day, inclusive of medical and support services operating 24 hours a day, 365 days a year. There's a garden for tenants growing vegetables, fruits and herbs by themselves. With large floor to ceiling windows installed in the shared spaces, amenity rooms receive abundant natural light in the day and thus, lower the heating season energy consumption to a certain degree. It was occupied since 2014 and has been received the LEED Gold building certification under LEED Canada-NC 1.0.

4.8.2 Envelope and Construction

Exterior Wall ($hr \cdot ft^2 \cdot^\circ F/Btu$)	Metal cladding and brick walls with framed mineral fibre insulation R=16.1 (8% higher than the baseline)
Roof ($hr \cdot ft^2 \cdot^\circ F/Btu$)	R=25.32 (62% higher than the baseline)
Overall Glazing U-value ($Btu/hr \cdot ft^2 \cdot^\circ F$)	U assembly=0.413 (36% lower than the baseline)
Lighting Controls	*Daylight sensors *Occupancy sensors in common spaces
Light Power Density (W/ft^2)	Overall 0.95, 19% less than the baseline model
Plug Loads (W/ft^2)	Based on space function

Table 4.23: Envelope and Construction Specifications of Building H

Building H was designed to target a life cycle of at least 60 years. Materials used for the building are not only durable but costless maintained as well. The building featured a total of 19% of construction materials containing recycled content, and 21% of the materials were manufactured and extracted in the locality. The proposed

R-value for walls and roofs are 8% and 62% higher than the baseline model respectively, which can easily decrease the thermal bridge of the building envelope largely. Operable windows in suites can provide occupants with extra thermal comfort and sufficient air flow during summer time.

4.8.3 Mechanical System

The air handling unit with heat recovery pipes HRU-1 operates continuously to supply conditioned air to suites and corridors. The heating coil valve modulates to maintain supply air temperature at the setpoint of 18°C. Heat recovery bypass damper opens when OAT is between 18 and 25°C, which is capable of saving energy on preconditioning of outdoor air. Another heat recovery unit HRU-2 runs on an occupancy schedule, which enables excellent energy saving with the system shut down during unoccupied periods. The supply air temperature setpoint can be reset based on the outdoor air temperature. The heating coil valve will modulate to keep the supply air temperature at setpoint. The return fan always follows the supply fan speed at minus 5% to preserve a positive building pressure compared to the outside. Residential suites also gain heat from radiant slab system. Residents have control over how much heat being supplied to their units via the adjustment of thermostats installed in suits. The request is then sent to the building management system, and the valve position will be adjusted according to the computing results through DDC system. The pumps are disabled when OAT exceeds 18°C.

The heating loop handles the various hydronic heating coils built-in 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 performs as the primary heating source and a natural gas boiler that functions as backup heating. The heating plant loop contains a buffer tank that helps to reduce the amount of time for HP-1 heating up the water to its setpoint and saves energy consumption for the reason that HP-1 cycles less. The boiler is enabled when there is a call for heating and HP-1 cannot sustain the buffer tank temperature for 30 minutes after HP-1 has been operated for at least one hour. The boiler is disabled when the tank temperature is at setpoint for at least 15 minutes. The heating plant return pipes interchange heat with DHW heat exchanger HX-1 to preheat service water in preheat tanks. An energy meter was installed to keep track of the energy use by the heating system via monitoring the main heating system's supply water temperature, return temperature and supply flow rate.

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 make-up air unit serving the fan coils in the sub-basement *Kitchen Ventilation System: -MUA-1: 100% outdoor air, hydronic heating make-up air unit serving kitchen on level 1 -MUA-2: 100% outdoor air, hydronic heating make-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	*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 souce heat pump (HP-1) serving 2-pipe fan coils

Table 4.24: Mechanical System Specifications of Building H

4.8.4 Domestic Hot Water System

The heat exchanger HX-1 enables when the temperature of the warmest preheat tank is 5°C lower than the heating plant's return water temperature, and meanwhile, there is no call for heating. The two DHW boilers work in a lead/lag sequence. If the lead boiler had enabled for 15 minutes and the temperature of the warmest DHW storage tank is still 5°C lower than the setpoint, then the lag boiler starts to operate. Upon attaining the DHW storage tank's setpoint, both lead and lag boilers shut down.

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

Table 4.25: DHW System Specifications of Building H

4.8.5 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

The total energy consumption for both the year 2016 and 2017 was 1.3 times more than the proposed model, and even 39.5% more than the baseline building. The performance gap is far beyond the expected accuracy level of +/-15%. The reason for the high discrepancy would be the real operation of building H in conflict with the energy model. The supportive youth centre operates 24 hours a day, 365 days a year which might not be modelled according to this schedule at the design stage. The building utilized around 15 times more natural gas than predicted and even higher than the reference building for both years. At the same time, about 85% more electricity is consumed compared with the proposed model and still higher than the reference building.

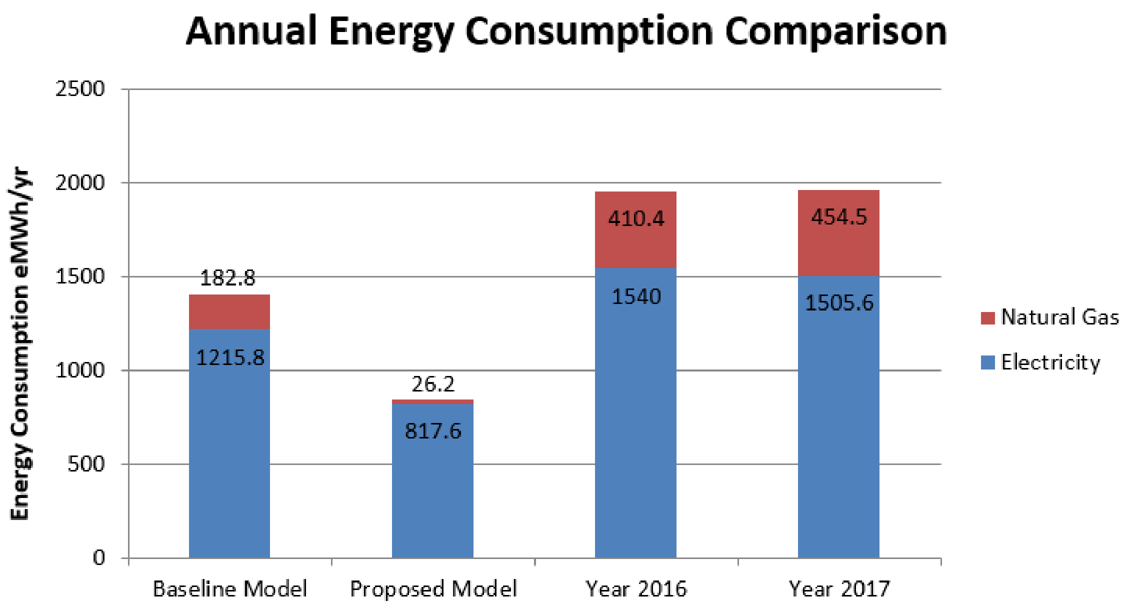


Figure 4.57: Annual Energy Consumption Comparison of Building H

Mechanical and Operation Variations

The following mechanical and operational deviations were obtained from the discussion 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 HP-1 failure was not coherent due to the absence of detailed overhaul record. Besides, HP-1 was not working as efficiently as assumed when the OAT dropped below 5°C, while other related equipment including pumps and fans keep cycling.

- **Excessive Radiant Floor Heating at Summer Nights**

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

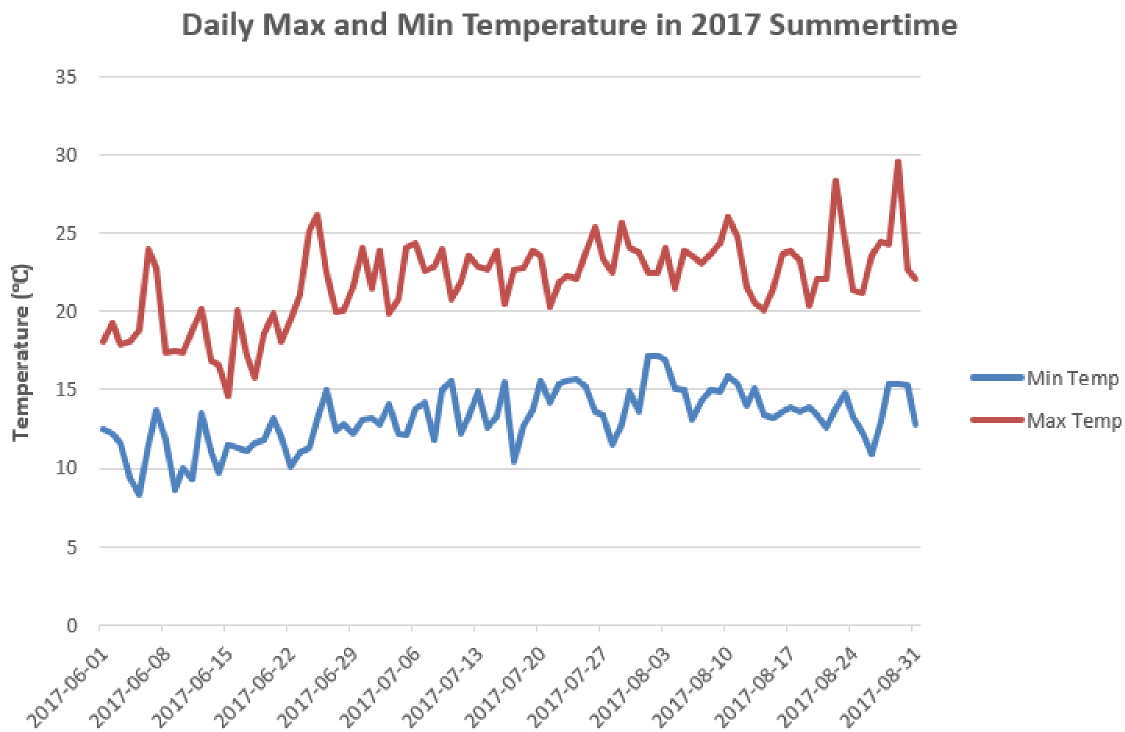


Figure 4.58: Daily Max and Min Temperature in 2017 Summertime

- **Radiant Floor Heating Time Delay**

There are some complaints from tenants about the slow heating process of units. The radiant floor system in building H requires a long response time to the occupant demands, especially in extreme weathers. Tenants tend to adjust the thermostats to a much higher value than needed to expect faster warm ambience, which can lead to unanticipated energy waste.

- **HP-1 Control Setting**

The control settings for HP-1 operation does not involve a deadband. In consideration that the enormous performance gap exists for building H, it is recommended to add a deadband of 5°C to minimize the heat pump cycling. The generally accepted setting is to operate 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 model identify higher electricity consumption than MURBs indicating that the design focuses on the electricity as the primary source for space heating and service water heating. Although compared to MURBs the total actual energy consumption for both years is approximately 70% higher, more than 30% of gas is saved with the sustainable design. The actual EUI of building H is between MURBs and HCSAs (or AFSs), which is reasonable since it has a two-floor resource center operating 24 hours a day.

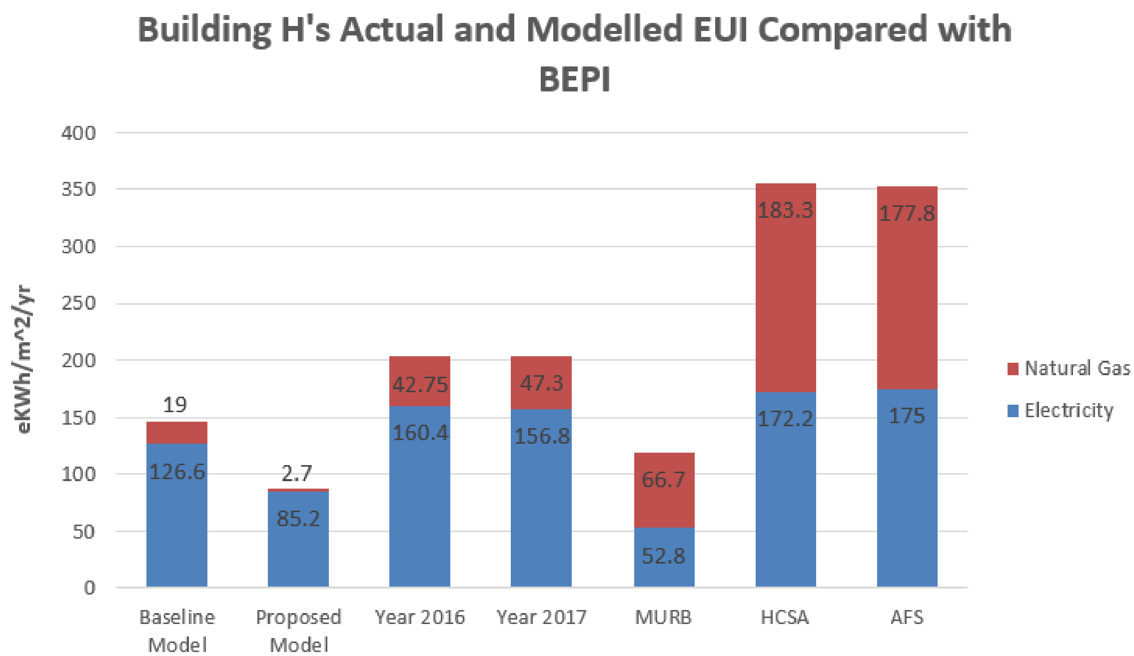


Figure 4.59: BEPI comparison of Building H

Effects of Weather on Results

The analysis on the effects of weather on the performance gap for building H is necessary. The correlation coefficients between energy consumption and HDD are 0.68 and 0.88 respectively for both years as shown in Figure 4.60 and 4.61. Although for both years the building consumed much more electricity and natural gas than the prediction, the higher energy use for 2017 is closely tied to the weather condition. The correlation factor for 2016 is a bit lower than the minimum advised value of 0.7, which mostly results from the two points within the red rectangular. It indicates the unregular more energy use during June and July, higher than shoulder seasons April and October. The possible reason would be the frequent cooling module operation for general spaces.

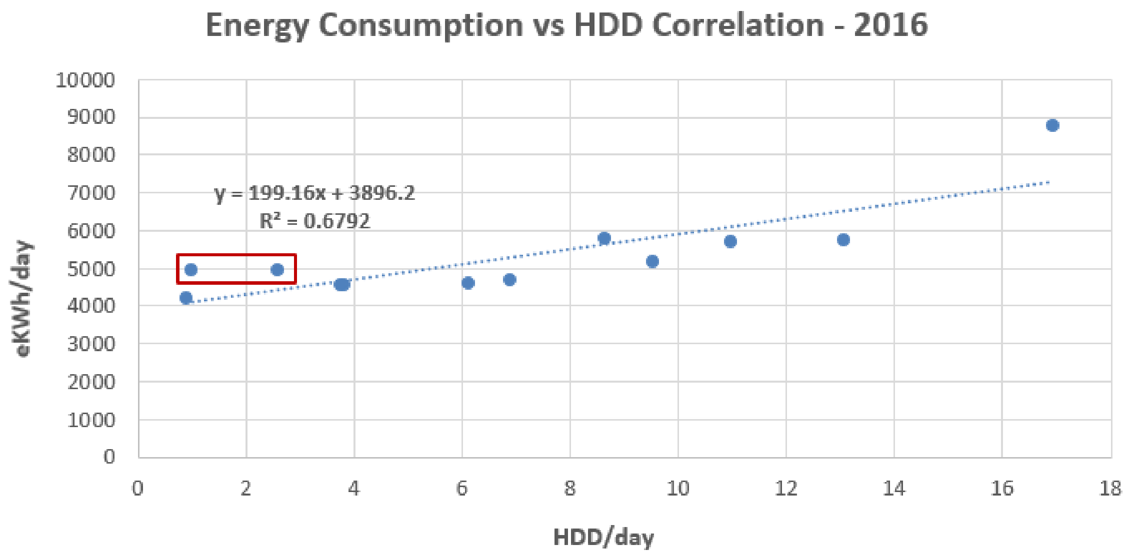


Figure 4.60: Effects of Weather on building H for 2016

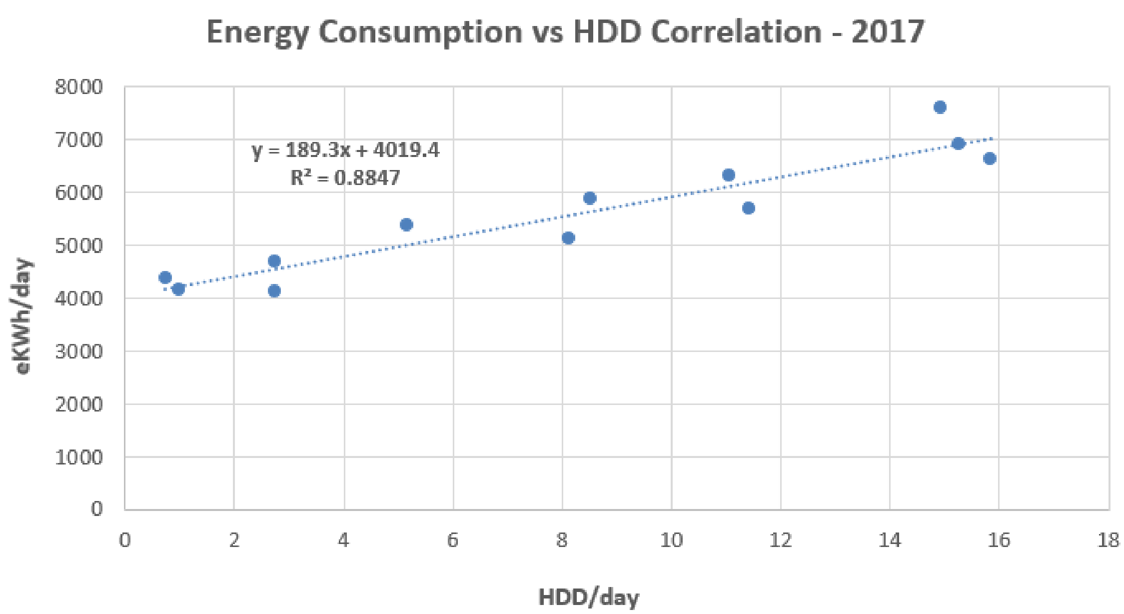


Figure 4.61: Effects of Weather on building H for 2017

Monthly Energy Consumption Comparison

From the monthly electricity usage comparison, the most prominent conflicts for 2016 occur 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, the concerned months are February and October with a difference quotient of 108% and 86.5%. It is recommended that the energy modelling of air source heat pumps consider reinterpreting performance curves according to the practical operation and employing empirical curves instead.

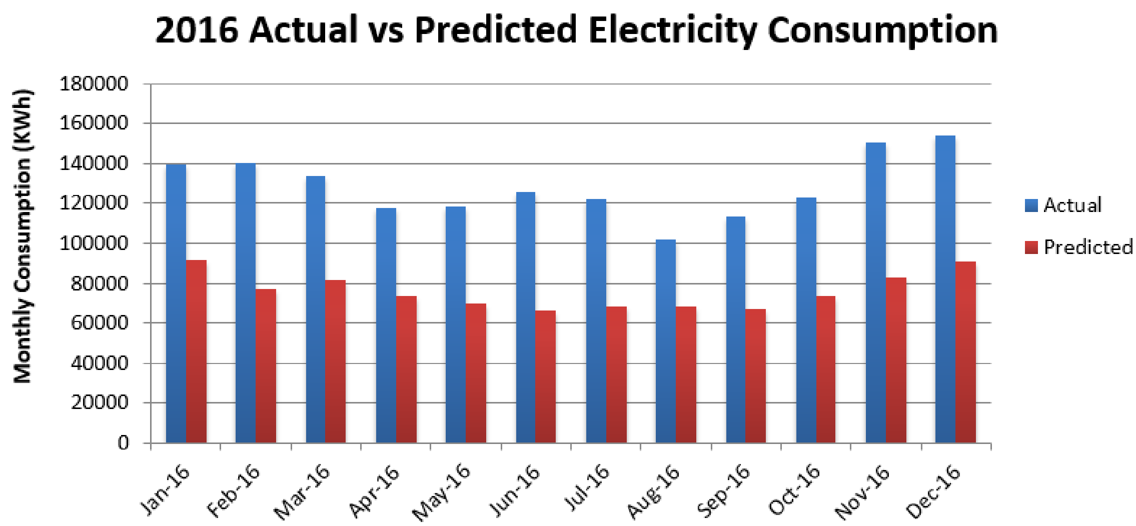


Figure 4.62: Electricity Consumption Comparison for 2016 of Building H

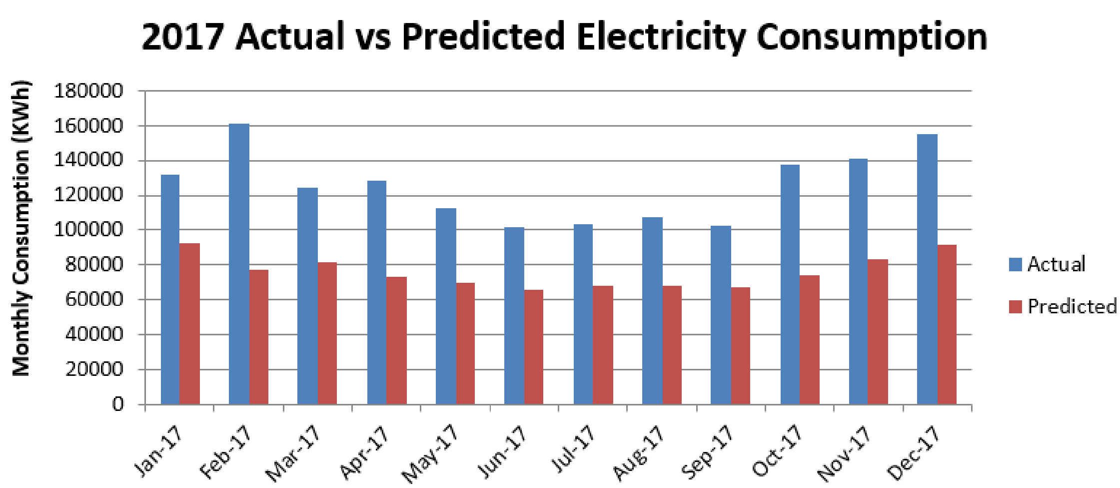


Figure 4.63: Electricity Consumption Comparison for 2017 of Building H

Figure 4.64 demonstrates a natural gas consumption jump for 2016 December and 2017 January occurring with the increment of heating degree days and incapability of ASHPs. It is essential to calculate the gas and electricity cost related to space heating in cold months to verify when it is more economical to switch to gas-fired boilers rather than heat pumps. Without the expected COP of the heat pump system, the running of relevant fans, pumps and compressors under specific temperatures cause massive electricity waste every year.

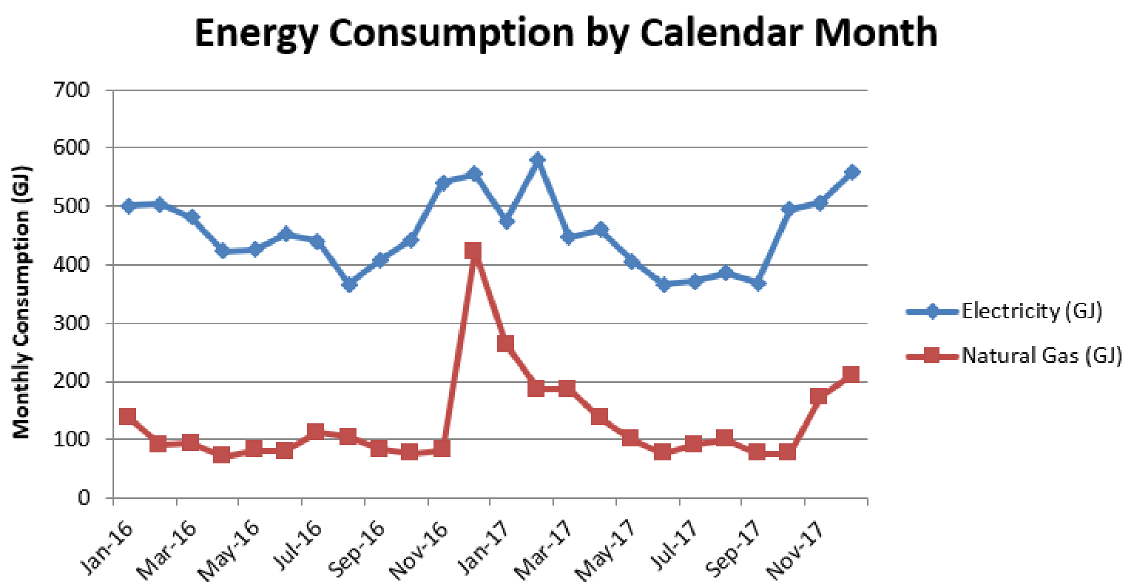


Figure 4.64: Monthly Utility Data by Types of Building H

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 boilers instead.

- Keep the overhaul record of HP-1 for the reference of 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 concentrate on developing energy conservation methods for those having large discrepancy compared to the designed model.

- Continuous commissioning for HP-1 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 located in Vancouver, BC. The building was designated to provide housing for homeless and homeless at-risk residents with mental issues. The building has a total floor area of $5509m^2$ excluding the unheated parking garage. It houses 96 suites including 12 handicapped specialized units with a commercial kitchen serving one meal to tenants daily. The curtain wall system on the main floor allows the positive use of sunlight to reduce not only the lighting energy consumption but the heating energy in winters and shoulder seasons as well. Large windows installed in the units also contribute to the energy saving and furthermore increase the livability level considering that the unit size is small with an average of $20m^2$. It was occupied since 2011 and has received the LEED Gold building 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 SBS roof to resist the extreme weather and extend the roof service life. On average, the R value of the roof is 225% higher than the reference building. Occupancy sensors were equipped to save 39% lighting energy compared to the reference building model.

4.9.3 Mechanical System

The two energy recovery units HRV-1 and 2 operate continuously to deliver fresh conditioned air to building I. The DDC system monitors the supply fan, exhaust fan and pump status to confirm the normal performance. Upon receiving a call for heating, the DDC system will control hydronic heating coils, the energy recovery core and bypass dampers to maintain the supplied air temperature at the setpoint of 17°C. The DDC system will modify the supply and exhaust fan speed when the room CO_2 level increases. The make-up air unit MUA-1 operates to maintain the discharge air heated by gas at 21°C to commercial kitchens.

Upon a call for heating, HP-1 to 3 will operate to heat the hydronic loop with two boilers working on a lead/lag rotating basis to supply hot water to the radiant in-floor heating system and various hydronic coils. The excessive heated water will be stored in the water tank ST-1.

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

Table 4.26: Mechanical System Specifications of Building I

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 for maintaining the water in DHWT-2 at setpoint. If the call for heat from the DHW storage tank temperature sensors sustains, the DDC system controls HX-1 to exchange heat with B-1 and B-2 for heating the DHWT-3 and 3A to supply water setpoint. The booster tank DHWT-1 operates to mitigate legionnaires before the hot water being supplied to the fixtures. If the supply water temperature exceeds the high limit thermostat setpoint, HX-1 will be disabled, and a high limit alarm will be generated in the DDC system.

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

Table 4.27: DHW System Specifications of Building I

4.9.5 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

Total actual annual energy consumption for 2016 and 2017 calendar year is 61.6% and 61.4% respectively more than the proposed building model. The results exceed the demanded 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 around 46% and 48%, which results from various mechanical system issues of building I.

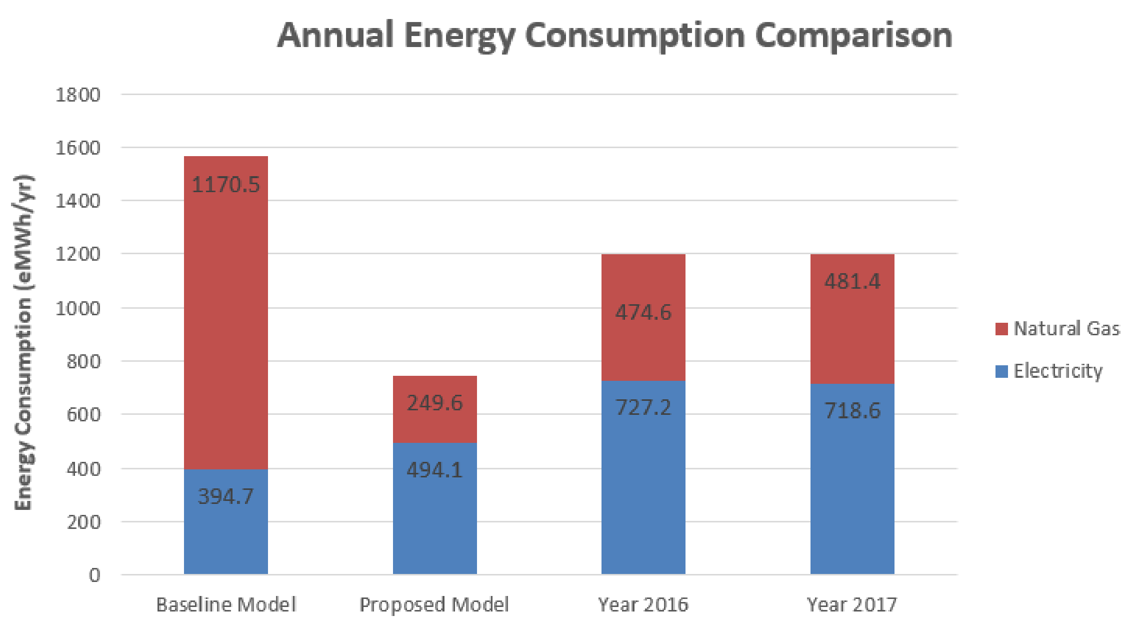


Figure 4.65: Annual Energy Consumption Comparison of Building I

Mechanical and Operation Deviations

The following mechanical and operational deviations were obtained from the previous mechanical issues inspection report and discussion with the building maintenance manager.

- **Failure of HP-1,2 and 3**

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

The predominant reason for the heat pump failure is that the design intent mismatches the equipment working principle. The heat pumps are not able to function to maintain the aimed loop temperature when the inlet air temperature is above 26.7°C in cooling mode. The manufacturer did not break through the product limitation as expected which causes a conflict in the physical operation. A three-way valve was installed and programmed to overcome the 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**

The gatekeeper tank issue was discovered the same as described in the building C case study.

- **Pump VSD Failure**

Some variable-speed-drive pumps are observed not performing as designed. From the previous inspection report, the pressure differential sensor is not placed correctly and requires relocation.

- **Radiant Floor Heating Respond Time Delay**

The in-floor heating system has a long response time up to several hours for the heating demand from occupants. Since the occupants have the permission to adjust the thermostats, they may tune the temperature to a very high level. After the room receives heating through the radiant floor system, tenants may open windows to lower the room temperature and get fresh air passingly.

- **DDC System**

There is no historical data saved in the DDC system which makes it impossible to identify the possible issues for the performance discrepancy. The alarm/alerts function was not working. No trend log data can be plotted, and thus, no graph is generated for the operators to review the system performance or identify existed/potential operational issues.

Building Energy Performance Index Comparison

In consideration that some dominant energy-saving design strategies such as air source heat pumps were not realized, it is necessary to perform an EUI comparison between building I and the peer benchmark buildings. Two gas-fired boilers provide both space heating and DHW heating for the entire building, and a dry cooler is used to reject heat to cool the building down. Both natural gas and electricity consumption is expected to be higher than the proposed case since boilers and dry coolers are not as efficient as heat pumps. The building utilized about 148% more electricity and 30.4% more gas for the year 2016 and 2017 compared against BEPI for the building type MURBs, while over half of the gas and 25% of electricity is saved against HCSA and AFS. The result is reasonable since building I is a social housing offering supportive services other than conventional residential buildings.

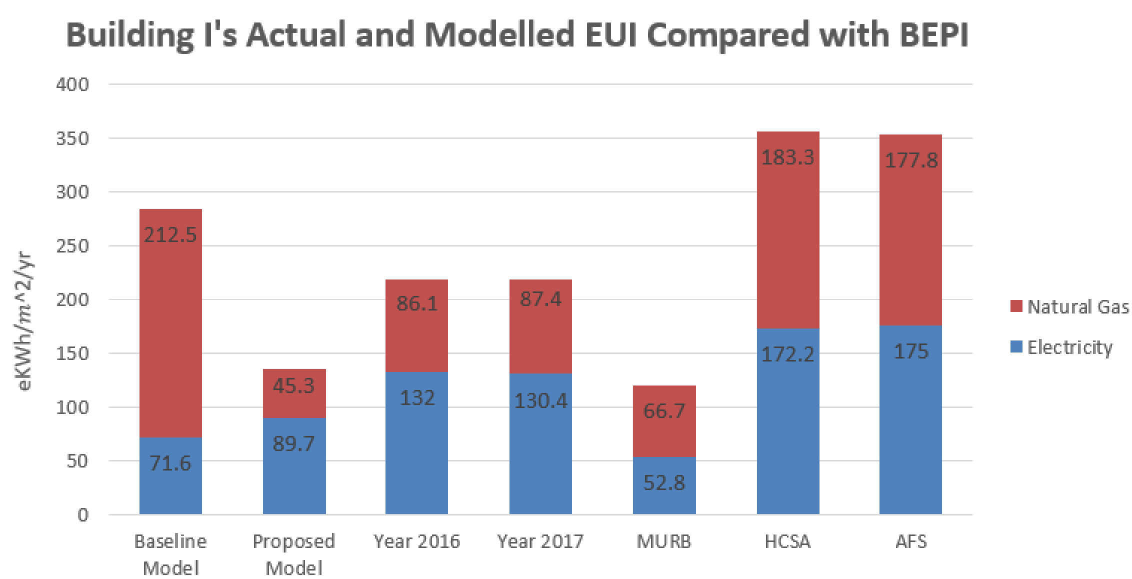


Figure 4.66: BEPI Comparison of Building I

Effects of Weather on Results

Regression analysis for the year 2016 and 2017 has been performed to investigate the correlation between the energy consumption and HDD. For both years, the energy consumption is poorly correlated to HDD with coefficients of 0.6 and 0.4 which is atypical since Vancouver is a heating-dominated place. In this case, another regression analysis for the proposed building model was plotted. For both years, it shows a strong interconnection to HDD with coefficients of over 0.9. The weak correlation indicates that the building was not operated as designed.

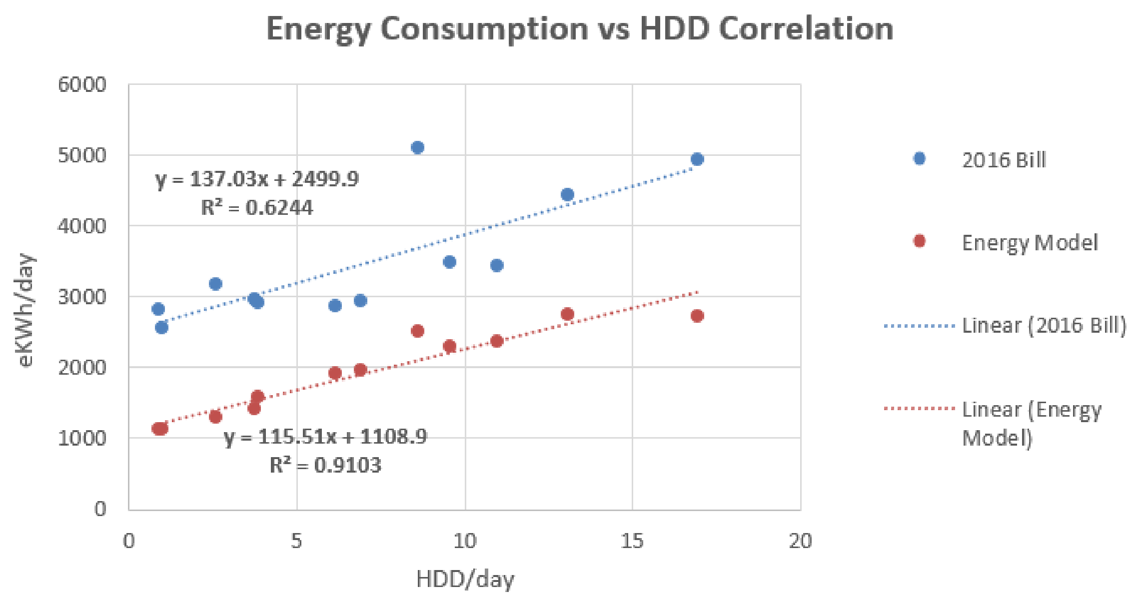


Figure 4.67: Effects of Weather on building I for 2016

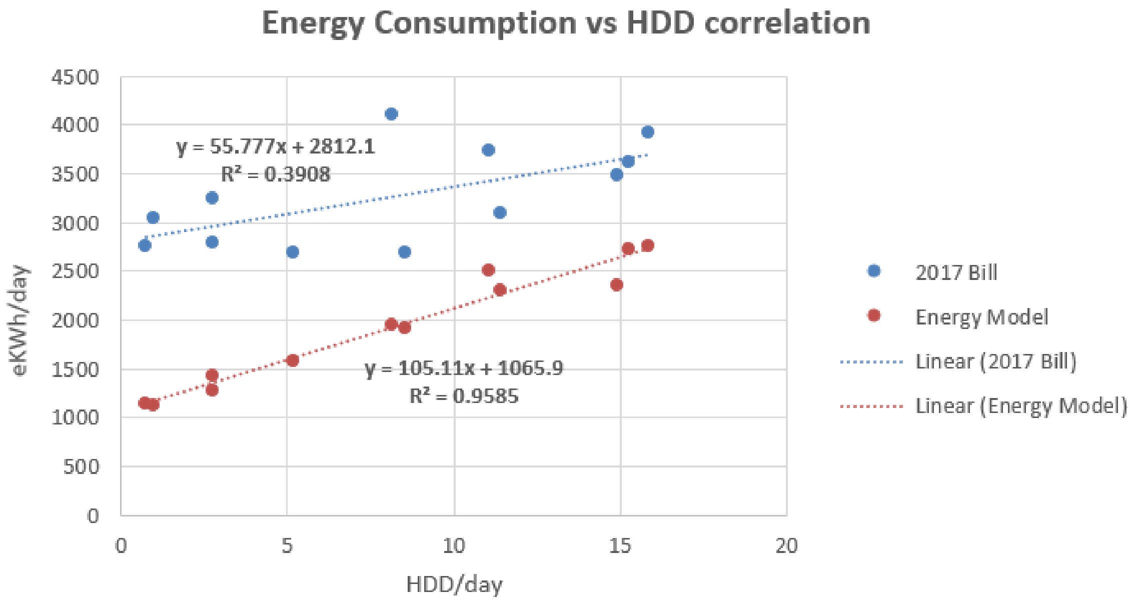


Figure 4.68: Effects of Weather on building I for 2017

In order to explore the reason for such colossal conflict, the monthly electricity and natural gas utilization were sketched as shown in Figure 4.69. Considering that gas is the only source for space heating and service water heating, higher gas consumption during winter months is within the expectation. However, the electricity consumption should theoretically be lower than other months during summertime based on the proposed design as shown in Figure 4.70. From utility bills, 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 is not as efficient as ASHPs. Another principal argument would be the deviation from unpredictable occupant behaviours. Not only the cooling energy but also excessive plug loads and lighting consumption contributed to the high electricity use in summer.

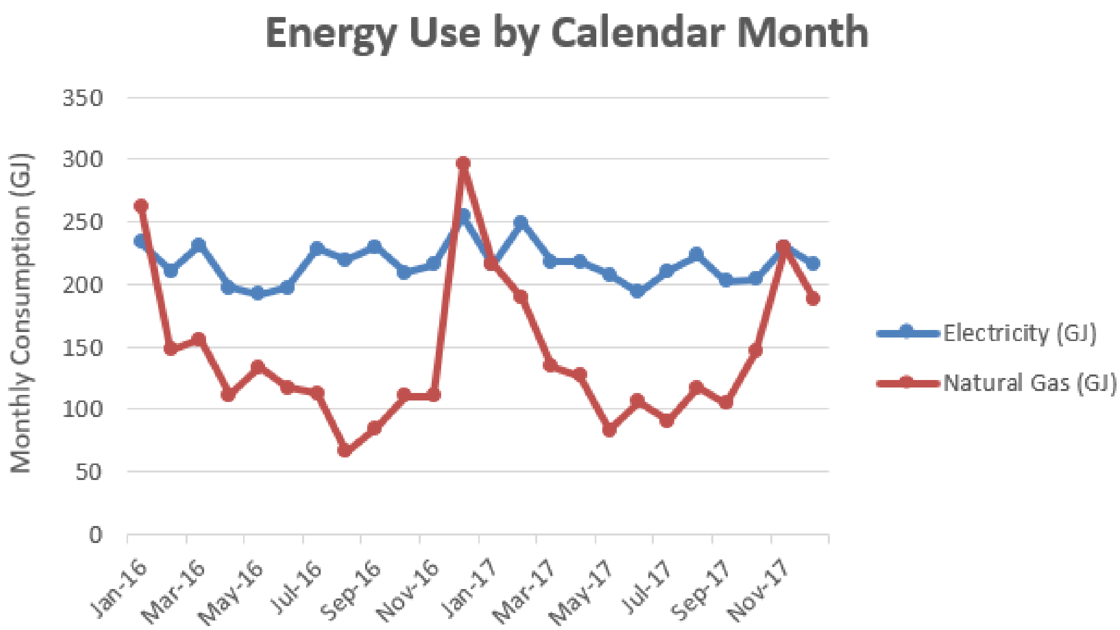


Figure 4.69: Monthly Utility Data by Types of Building I

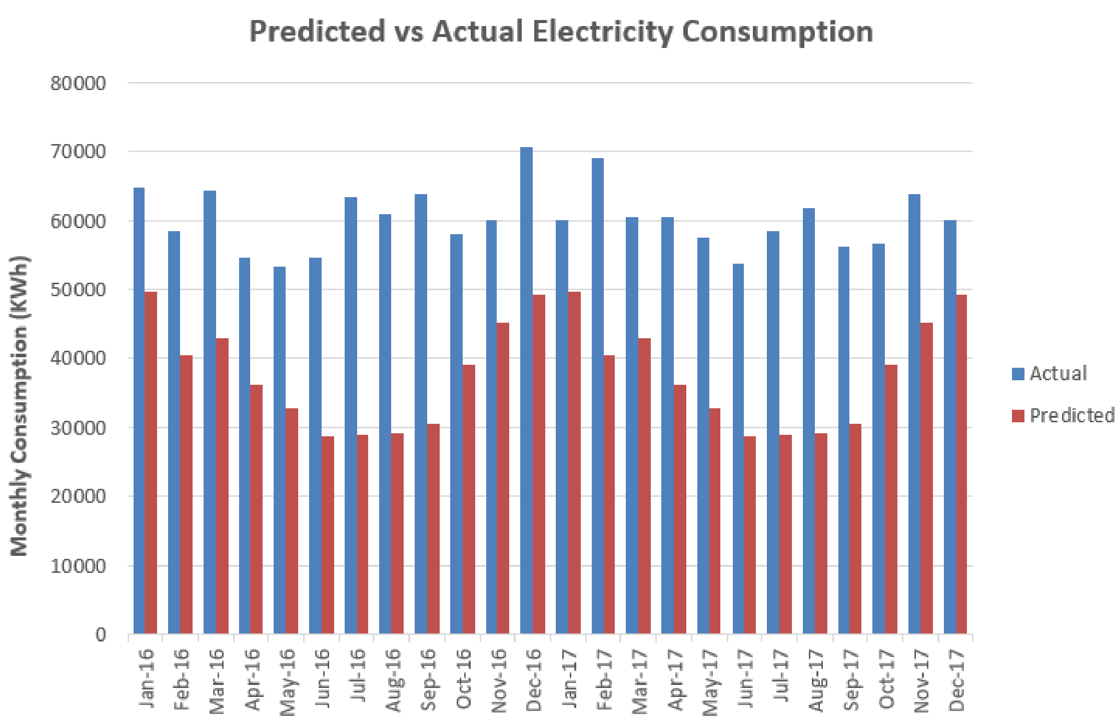


Figure 4.70: Electricity Consumption Comparison between 2016 and 2017 of Building I

Recommendations

- The design of the ASHP system is recommended to be developed by experienced engineers exceptionally knowledgeable in sustainable buildings design.
- The selection of an appropriate appliance is one of the most influential parts to achieve the predicted energy target and the normal operation of the building.The HP 1-3 and various pumps have limitations to realize the predicted design.
- Install sub-meters to track detailed end-uses for implementing energy saving measures.
- 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 existed/potential issues of the building performance.
- The boiler room on the top floor is extremely tight which makes it impossible to change the large equipment on the rooftop. The design of access to the rooftop needs to be attentively considered for future alteration of sizeable appliances.

4.10 Case Study: Building J

4.10.1 General Description

Building J is a four-storey mid-rise low-carbon residential supportive housing located in New Westminster, BC. The wood-frame building has a total floor area of $1591m^2$ sheltering 24 units including 11 transitional housing units and 13 permanent independent suites. The public transit with a sky train 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 society kitchen for tenants entertainment and communication. Large operable windows with blinds were installed in the lobby which allows sufficient daylight and natural air change to save energy during the daytime. It was occupied since 2011 and has been received the LEED Gold building certification under LEED Canada-NC 1.0 in 2012.

4.10.2 Mechanical System and DHW System

The heating and cooling for the building were designed to be supplied by the central air source heat pump HP-1 at the planning stage. HP-1 will be disabled instead of firing the boiler B-1 when the OAT falls below 0°C. The OAT heating/cooling changeover setpoint 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 outdoor air temperature is lower than -5°C and 13°C when the OAT is higher than 12°C. The radiant loop is programmed to serve supply water at the temperature of 40°C when the OAT is lower than -5°C and 25°C when the OAT is higher than 13°C.

HVAC System Specifications	
Ventilation Air Handling Unit	*AHU-1: Rooftop air handler with hydronic heating and cooling serving corridors on 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	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

Table 4.28: Mechanical and DHW System Specifications of Building I

4.10.3 Results, Discussions and Recommendations

Annual Energy Consumption Comparison

There is a lack of natural gas utility bill for January and February 2016; all the analysis was based on the 10-month data for the year 2016. On the comparison of annual energy consumption between actual performance and predicted model, both years used around 90% more energy than the proposed model and even over 10%

greater than the baseline model. The vast difference in natural gas utilization is foreseeable since the ASHP system has failed 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 leaking issues from the previous inspection report which reduced the heating efficiency and led to extra gas waste. A dry cooler has been applied to the cooling system to provide cooled water for AHU-1. Another contributing factor would be the occupant behaviour offset including leaving windows open in winter and lights on all the time.

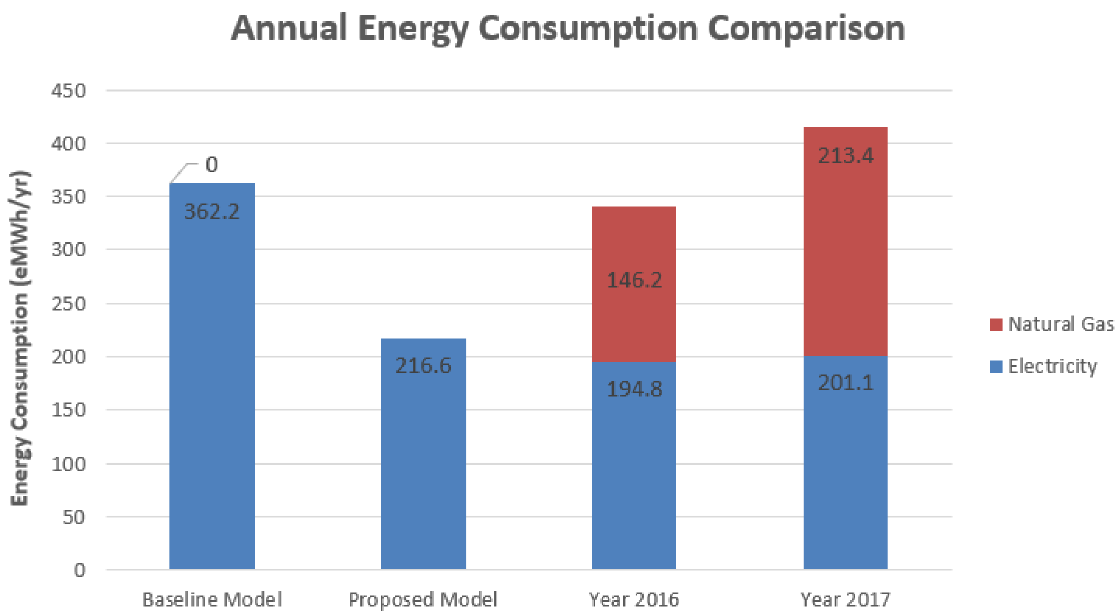


Figure 4.71: Annual Energy Consumption Comparison of Building J

Building Energy Performance Index Comparison

Both reference and proposed building model demonstrate higher EUI compared with BEPI MURBs, which confirms the unusual housing type of building J. Although the post-occupancy energy consumption exceeds the prediction, it still maintains around 25% less than the peer HCSA and AFS buildings.

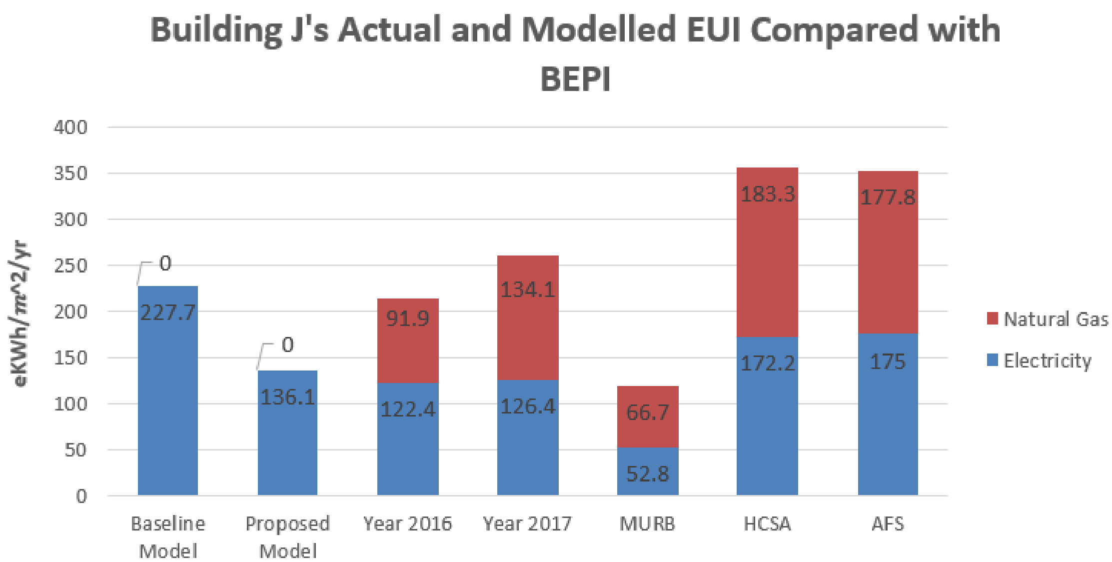


Figure 4.72: BEPI Comparison of Building J

Effects of Weather on Results

The regression analysis for both years presented weak correlations between energy consumption and HDD with R^2 of 0.56 and 0.27. For 2016, the correlation was plotted from March to December. For the two points circled in a blue rectangle, it indicates that November with about only half of the HDDs compared to December consumed almost the same energy as December. Furthermore, the yellow rectangle reveals that months of November and March with approximately the same HDDs had a huge difference in the energy consumption. It can be concluded that there might be some equipment issues during November 2016. For 2017, three groups of noticeably unusual consumption data were circled in red, orange and green rectangles. The two points in red rectangle represents June and September which have the same HDD yet with highly different energy consumption. The orange rectangle indicated that September with much fewer HDDs consumed almost the same energy as January. Even though the month of December within the green rectangle has the second most HDDs, the total monthly energy consumption appears much less than most of the months. Mechanical issues of the heating/cooling system and occupant behaviours have more significant effect on the energy consumption than the weather for building J.

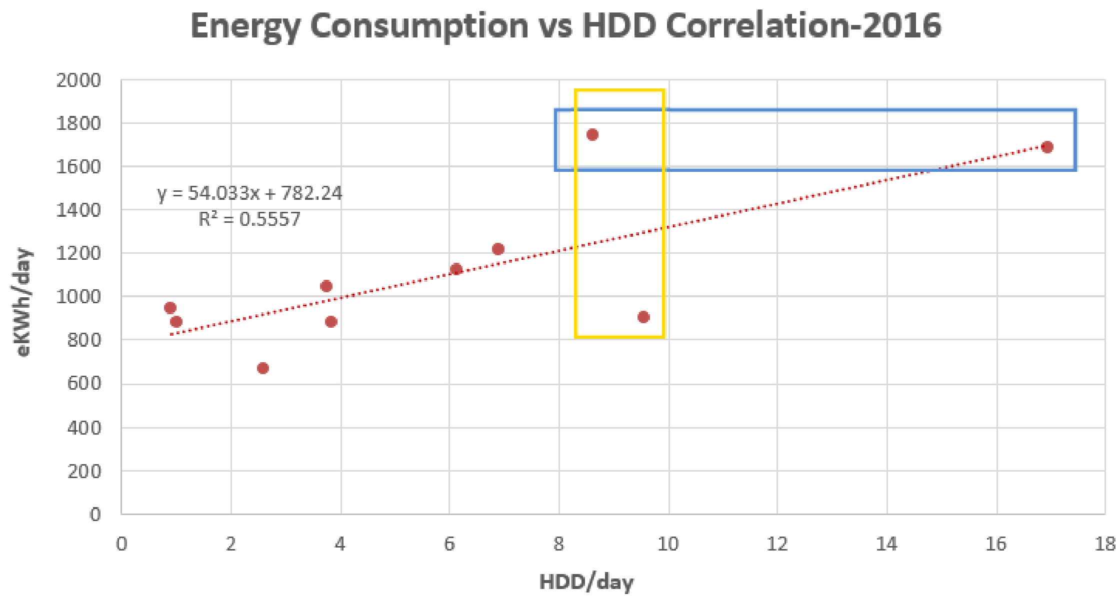


Figure 4.73: Effects of Weather on building J for 2016

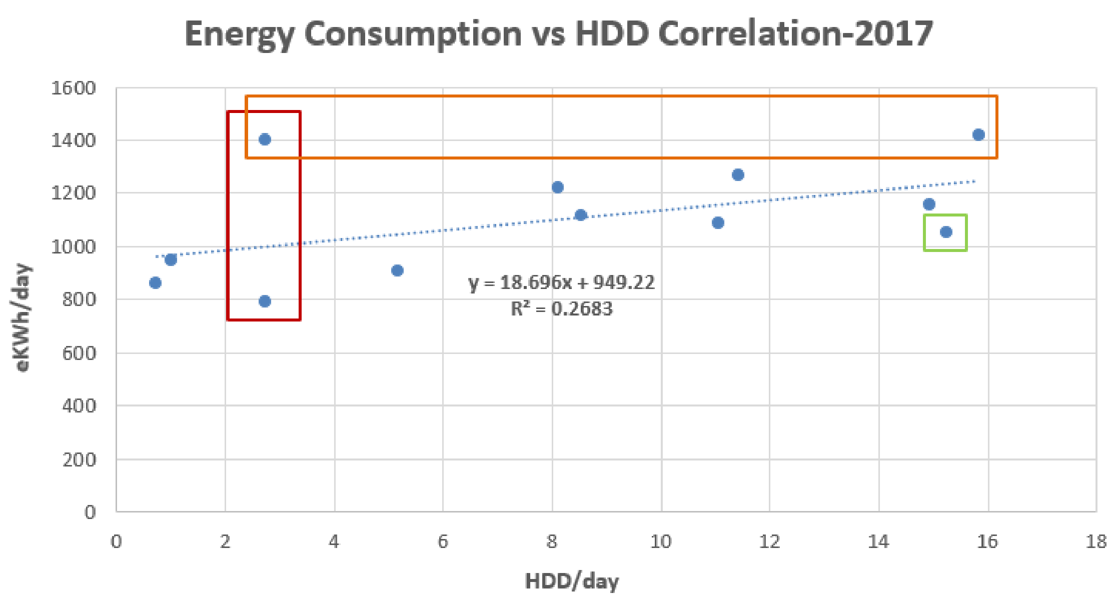


Figure 4.74: Effects of Weather on building J for 2017

Monthly Electricity Consumption Comparison

From plotting the electricity consumption for the year 2016 and 2017, August tends to consume the most electricity due to the additional fans being used in residential units and more frequent air conditioner operation for common spaces. The biggest discrepancy appears in May, July, October and November with an average consumption variation of 3760KWh. There seems like no law to follow on the hydro consumption for building J which most possibly result from mechanical issues of equipment and occupant behaviour offset.

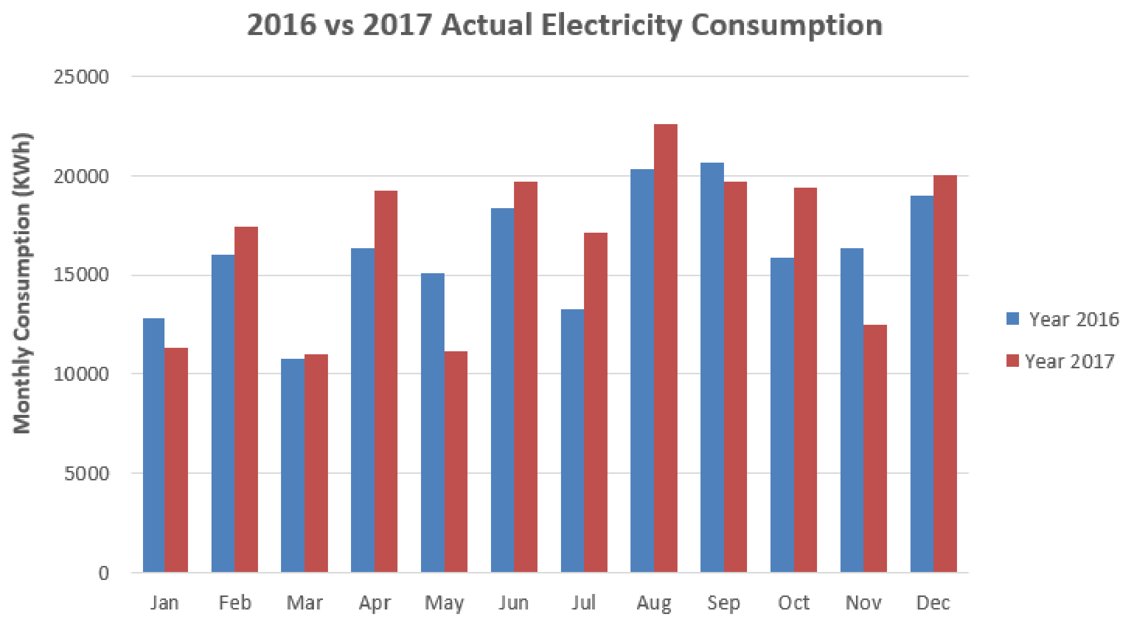


Figure 4.75: Electricity Consumption Comparison between 2016 and 2017 of Building J

Recommendations

- Maintenance managers are strongly recommended for thermally-efficient buildings due to their advanced and complex design of mechanical systems.
- Add sensors on the boiler and alarms in the DDC system to detect leaking issues immediately and thus, save natural gas energy.

4.11 Summaries and Discussions of Case studies

4.11.1 Summary of 10 Buildings

Upon the case studies above, buildings performed dissimilarly from each other due to diverse architectural and engineering designs along with different building issues in design, construction, commissioning and operation. A summary of findings from individual case studies can be found in this section emphasizing the interrelationship between performance gaps and designed EUI, floor area, type of central plant and M&V credit categorically.

The designed EUI for each building varies widely from 80.3 to 164.9 eKWh/m^2/yr. figure 4.76 shows the summary of identifying if these buildings achieved the designed target. Each building contains four bars that demonstrate the reference baseline model, the proposed model, 2016 and 2017 energy consumption results from left to right respectively. Two of the buildings – building E and F – overperformed compared to their proposed models while other remaining buildings did not reach the high-performance goal. All buildings except for building C, H and J, realized significant energy savings especially in the reduction of fossil fuels compared with the baseline building models. The minimization of natural gas use follows the BC Housing's High Performance GHG Strategy goals of a maximum of 10% fossil fuel use from the total energy. For building C, H and J, possible non-regulated loads excluded in the energy model cannot explain the huge discrepancy.

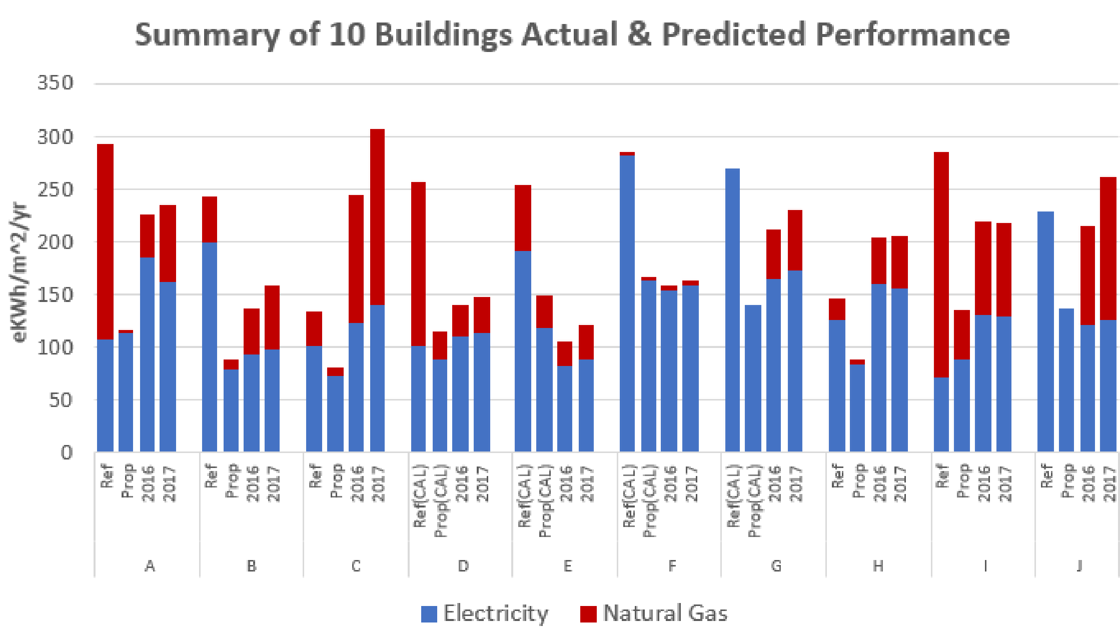


Figure 4.76: Summary of Annual Energy Consumption Comparison

Figure 4.77 is a graph used to explore if energy consumption discrepancy is influenced by the size of buildings. Upon getting rid of the two exceptional points of building C with over 200% gap, the performance gap percentage fluctuates among various sizes which indicates a weak interrelation to building floor areas.

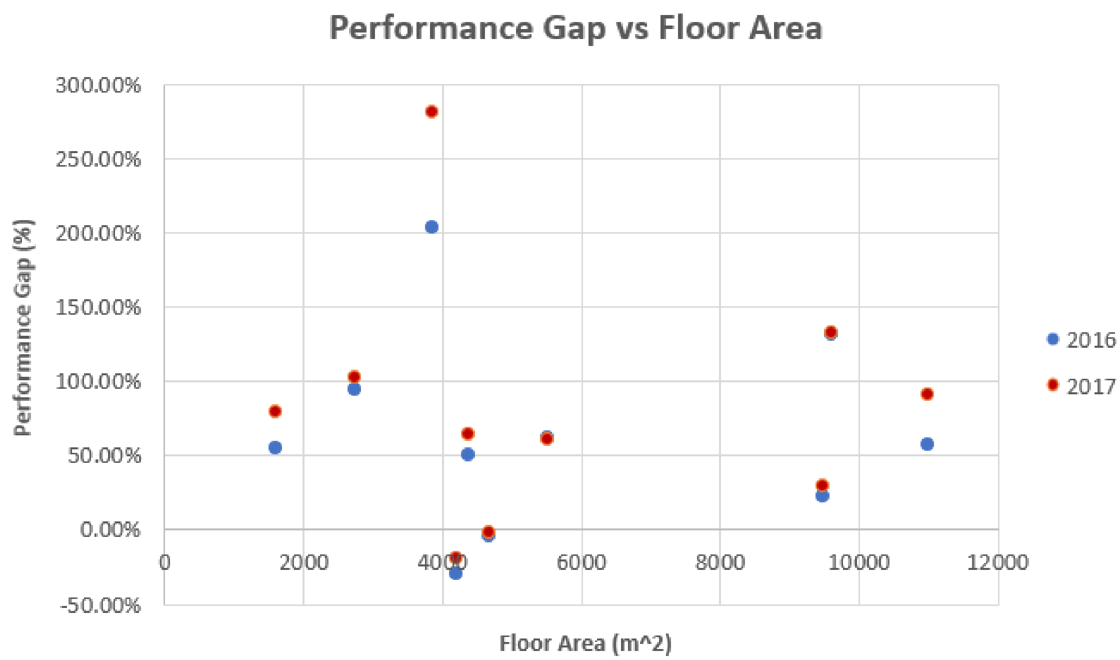


Figure 4.77: Summary of Performance Gap vs Floor Area

Table 4.29 summarizes the core equipment of the central plant, the total performance gap for both years and the M&V credit application. From figure 4, the building without applying an efficient central plant for the mechanical system performed the furthest away from the prediction. Buildings adopting ASHP systems were likely to face more challenges in achieving the designed targets. Building D to G employed M&V method to evaluate the post-occupancy building performance, among which 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 method is effective for energy conservation. Furthermore, from the previous case studies, the GSHP system had much fewer issues compared to the ASHP system.

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%

Table 4.29: Summary of the building system, performance gap and M&V

4.11.2 Lessons Learned on These 10 Buildings

- **Establish the Design Strategy**

The first obstacle that is likely to appear in the design of sustainable buildings is the collaboration among stakeholders. The conflict between aesthetics suggested by architects and high performance targeted by mechanical engineers remains as the potential risk in post-occupancy building performance. The design probably moves to the next step even with this kind of issues unsettled, which can lead to overly complex mechanical system design. The complicated building system leaves a highly challenging design of the control system for control engineers. The contradictory process brings either higher budget at the planning stage or higher cost of maintenance after turnover.

Lifecycle assessment in both energy and cost is necessary to be consulted at the design stage. From the above discussion, the lifecycle assessment can probably play an essential role in integrating divided opinions between architects and contractors since low energy consumption and cost is their conjunct aim.

The mechanical design principle of these buildings was generally the same that was using highly efficient core equipment – heat recovery ventilation unit, ASHP, GSHP, and solar panels – generating heating/cooling energy. However, each design was different when it comes down to details, for example, sizing of each equipment, water flow calculation, pump pressure and so on. From the review of evaluation reports, designers had a tendency to create a brand new design each time rather than using previous successful design as the reference and modifying to improve the whole performance. Each new design had a risk to bring new issues during the operation and might be difficult to fix. The failure of solar panels and the unreasonable physical size of the mechanical room from the above case studies are both representative examples. Furthermore, designers rarely consider the rationality of their conceptions at the post-turnover stage which can lead to a quite high maintenance fee.

From the above case studies, buildings addressing M&V methods were more likely to achieve the energy performance goals. It is recommended to include M&V into the whole building design at the beginning of the planning stage, and introduce M&V specialist to the design team meeting. Otherwise, it would be costly to build sub-metering points after the complete design of the building's mechanical and electrical systems.

- **Improve the Accuracy of Modelling**

The recommendation of the improvement in energy modelling process does not signify that there were errors in the energy model. In fact, each model was validated and reviewed by experienced energy consultants to ensure the correctness. However, most of the modelling results included in this research cannot present the actual energy performance of these buildings. The most common reason is that the energy model did not consider every non-regulated load. It is necessary to include all spaces and all metered energy in the simulation for the precise post-occupancy evaluation. Other causes for the discrepancy can be classified into two aspects which are occupant-related and weather-related.

The most typical representation of weather-related inaccuracies is the performance curves applied in the ASHP modelling. For some cases, the performance data provided by manufacturers are apparently unreliable. The unforeseen low energy efficiency of ASHPs during freezing days led to incredibly 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 submit experienced performance curves for energy modellers.

Occupant-related factors involve specific schedules for social housings and parameters influenced by occupant behaviours. The calibration process can be very troublesome and burdensome due to its uncertainty. One feasible approach is to recalibrate existed LEED social housing buildings based on their real monitoring data. Through quantitive recalibrations of this particular type of residential buildings, a set of standard inputs especially for social housings can be created to reduce the negative impact from occupants.

- **Extend the Commissioning Engagement**

The commissioning of buildings confirms the normal operation of various mechanical systems including correct installation of equipment, active control sequences and appropriate system performance as designed. An experienced commissioning agent is a key factor to complete a thorough examination. From the case studies above, large numbers of issues popped up, for example, the failure of solar energy systems, wrong locations of VSD pump pressure sensors, erroneous control of 3-way valves and so on. The commissioning engineer is responsible for the prevention of these undesired problems but not always successful. Installing a sub-metering system to monitor various real-time end uses can assist the commissioning agent to locate and analyze the issue.

Normal commissioning process usually happens before the building's hand-over which means the verification of the building is conducted under unoccupied circumstances. However, from the case studies and literature reviews, occupants are reported to have a significant influence on the outcome of building performance. Continuous commissioning introduces a repeated test process to probe control sequences of the building system and optimize the building performance as well as satisfy the thermal comfort of tenants. The efficiency loss due to seasonal changes, improper operations and wear and tear of equipment has a chance to be largely reduced or eliminated by continuous commissioning. It is recommended to keep the record of any maintenance, repair and commissioning as the reference for future retrofit and overhaul.

- **Strengthen the facility management's capability**

From site visits to case study buildings, it is striking to recognize that operators usually had very few knowledge in the renewable building systems, and even had no background in facility management. Some maintenance managers are not familiar with the DDC system and have to rely on the remote supervision by their control contractors. Control contractors may not care about the building's operation and maintenance which results in much more waste in energy and service cost. It is obligatory to train operators to appreciate initial design objectives, to understand renewable systems and to familiarize themselves with control strategies. Besides, detailed mechanical drawings and O&M manuals need to be put at places where is visible and accessible.

- **Update the DDC system**

The DDC system is one of the hard cores to warrant the building operated as initially designed through advanced control and monitoring approaches. All the DDC systems need to be available to store hourly data, generate trend graphs and deliver alarms and alerts to verify current and potential operating issues. The monitoring data is recommended to be saved in the system for at least two years and be effortlessly exported which can function as the reference for future retrofit and research. Regular checks on the DDC system to ensure the generated graphs consistent with monitoring data is also necessary.

Chapter 5

Conclusions

This study explored the performance discrepancy between modelling outputs and field energy consumption in 10 LEED Gold social housing buildings located in Victoria and Vancouver, BC and identified causes for the mismatch. A comparative study of different green building rating systems among Passive House, Living Building Challenge, LEED 2009 and LEED v4 was accomplished to comprehend each program's benefits and limitations. A literature review compiled performance gaps from existing researches, summarized possible causes from the 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 buildins(MURBs) were developed to bridge the gap, which is the primary motive of the study.

The comparison was completed by collecting monthly electricity and natural gas bills of the year 2016 and 2017 from either building management organizations or energy suppliers including BC Hydro and Fortis BC and gathered energy models from energy modellers and LEED consultants. These buildings were then compared with NRCan's database benchmarking buildings to verify their superior energy savings to other conventional peer buildings. The effect of weather was also investigated to eliminate potential deficiency in the analysis. The investigation of individual buildings and review of prior inspection reports supported the verification of problematic mechanical systems, control strategies and defective operating techniques.

The evaluation shows only two out of ten buildings outperformed compared to the predicted modelling results and three buildings even consumed more energy than their baseline buildings. The extra natural gas firing is typical for most of the case study buildings. Although the design intent rigorously followed the BC Housing's fossil fuel combustion criteria to minimize natural gas usage, the outcome demonstrates the limitations on planned approaches. However, a large amount of gas use was saved compared to baseline buildings.

It was not surprising to observe that air source heat pumps have been the most common barrier due to its low coefficient of performance(COP) during cold days. Two buildings have abandoned their ASHP systems and the remaining three buildings equipped with the air source heat pump(ASHP) system experienced extremely high natural gas consumption resulting from the inefficiency of heat pumps in winter. Ground source heat pumps performed much better in this case. Almost all buildings served by heat recovery ventilation(HRV) systems have not benefited from free cooling during summer nights which is attributed 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 system was found to be another reason behind the performance gap. Tenants might have no patience to wait several hours for heating supplied to their suites which usually led to a higher than needed temperature adjustment to the thermostat (up to 28 even 30°C). Besides, the careless design of solar panel systems and its connection to other systems led to unexpected discard of this renewable energy. Other small defects such as installation and positioning errors reinforced together contributing to the discrepancy.

It is essential to simplify the design of mechanical systems and control strategies to ensure that the energy target is achievable. Uncertainties existing at the construction and operation stages may increase with the boost of system complexity which is likely to bring the energy penalty. The future maintenance cost and service availability need to be considered during the preliminary design. The service availability refers to whether the equipment is easily accessible and whether the service cost is affordable.Effective communication within the team to finalize designs and budget can be attained by using Integrated Project Delivery Alliance (IPDA) which gathers stakeholders together to establish a stable infrastructure for the project success.[91]

The advanced criterion of data collection is found to be a practical approach to improve the building performance. The data collection contains not only submetered consumption data but service and retrofit costs as well, which are valuable for both troubleshooting and property management. Furthermore, it is surprising to observe that some properties do not have the full set of building system drawings and descriptions on site. Softwares like EnergyStar and PUMA work as a database for the collection of adequate tracking of energy flows. The organizations can share each other's utility data and thus, acquire cost-effective methods for energy saving from successful projects.

The various performance gaps resulted not only from mechanical issues but also from the limitations of energy modelling. The unique parameter inputs for social housing type of buildings based on occupant behaviours need to be published by relevant institutions. Heat pumps need to be tested in real operation to modify performance curves applied in the energy model. The energy model needs to contain as much non-regulated load as possible to provide convenience and preciseness for post-occupancy evaluation.

In general, a successful green building project requires the reliable and simple design, precise energy modelling, careful construction detailing, adequate commissioning, and qualified operation to continuous commissioning. The future research can focus on 1) calibrating energy models based on BC building codes and LEED v4 standard to help improve the modelling guidelines, and 2) further exploration in the building design, construction and commissioning process and get in touch with contractors for more detailed analysis of the performance gap between field performance and predicted results.

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.
   O Below 30 O 31~50 O 51~64 O Above 65

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

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

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

6. How often do you open windows in winter **daytime**?
   O Everyday O 3~5 days a week O Depending on weather O Never

7. How often do you open windows in winter **nighttime**?
   O Everyday O 3~5 days a week O Depending on weather O Never

8. Is your room too hot in summer?
   O Yes O No

   *If yes, please answer the following questions 8.1,8.2, and 8.3

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

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

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

9. Is your room too cold in winter?
O Yes O No

*If yes, please answer the following question 9.1,9.2, and 9.3

9.1 Is your room too cold **every winter**?
O Yes O No

9.2 Are you using other equipment for heating such as electrical heaters?
O Yes O No

9.3 How comfortable do you feel after using additional heaters?
Not Comfortable O 1 O 2 O 3 O 4 O 5 Very Comfortable

10. How satisfied are you with the in-floor heating in winter?
Not Satisfied O 1 O 2 O 3 O 4 O 5 Very Satisfied

11. Is the ventilation sufficient in summer?
O Yes O No

12. Do you feel any air leakage during winter nighttime?
O Yes O No

13. How satisfied are you with the thermal comfort of your room?
Not Satisfied O 1 O 2 O 3 O 4 O 5 Very Satisfied

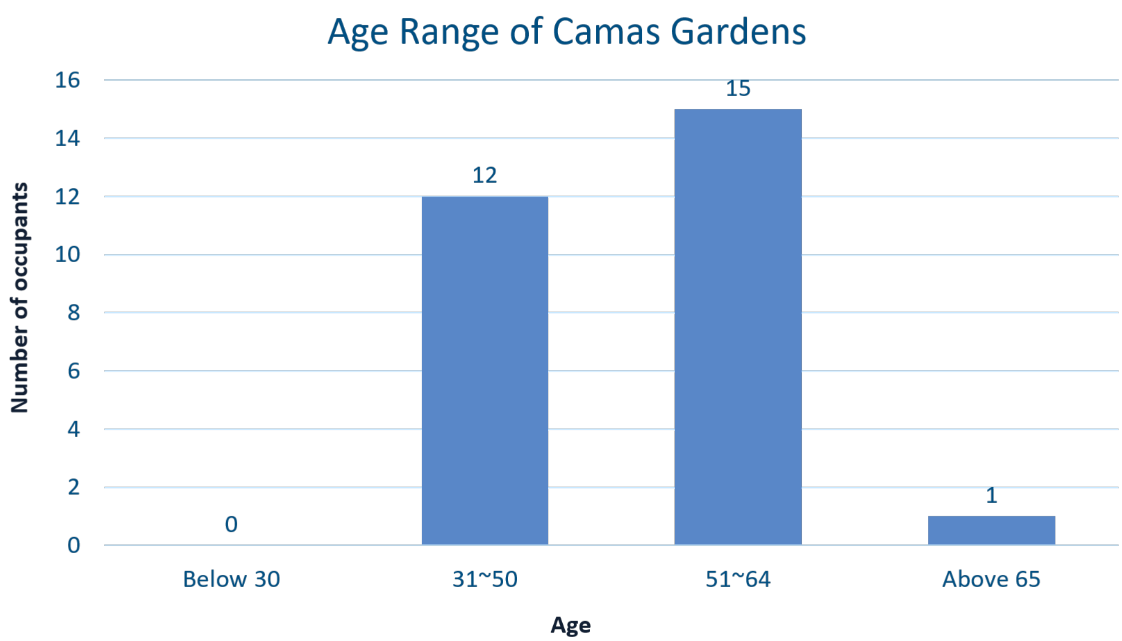
14. How satisfied are you with the acoustic privacy of your place?

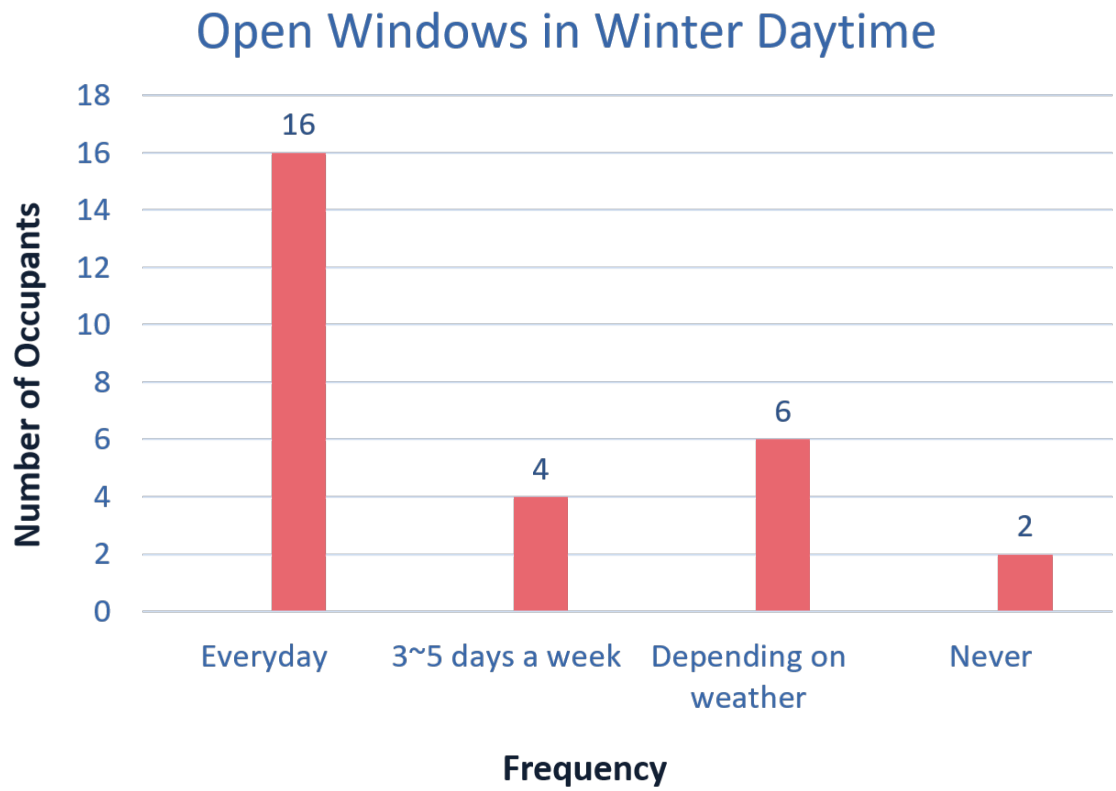
Not Satisfied O 1 O 2 O 3 O 4 O 5 Very Satisfied

*Please comment below if you have any other concerns or suggestions.

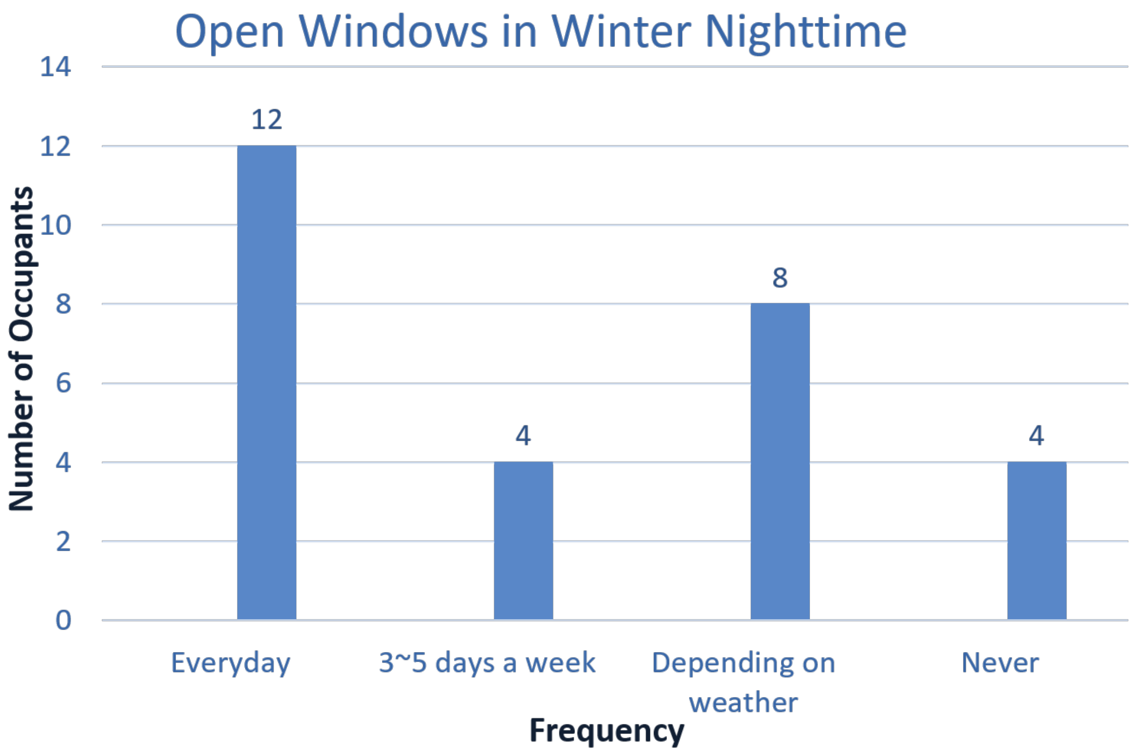
A.2 Occupant Satisfaction Survey Summary

28/49 suites attended the survey.

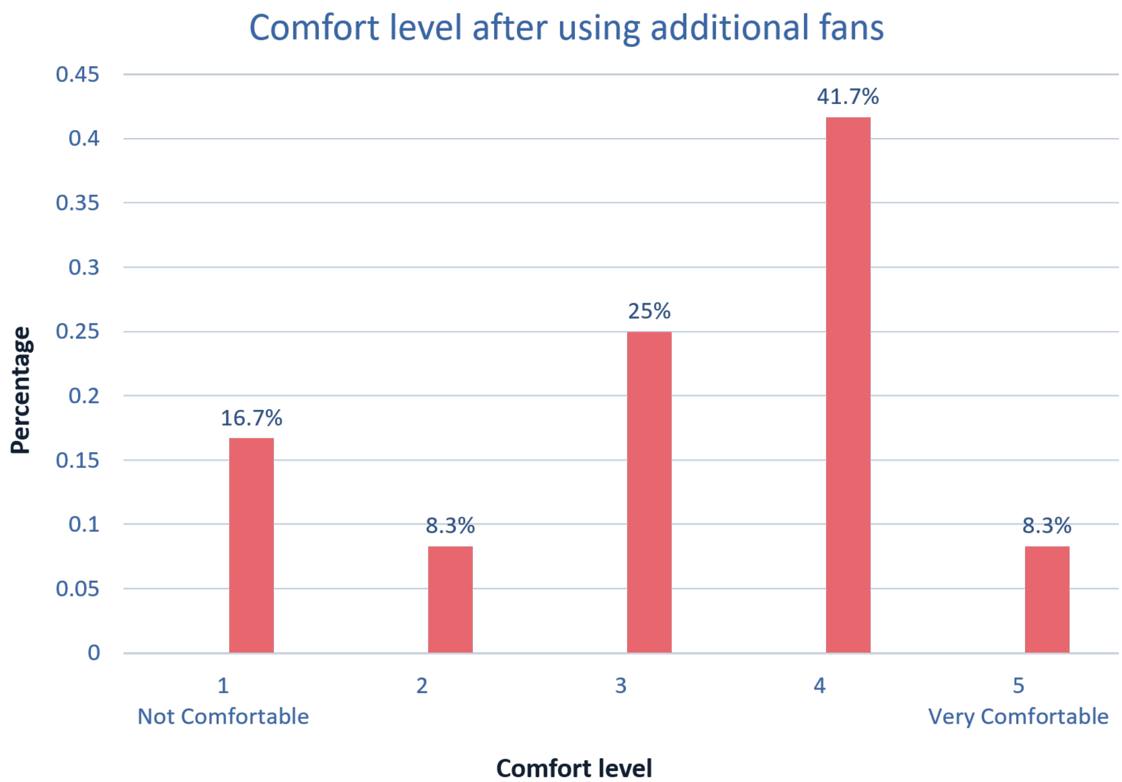




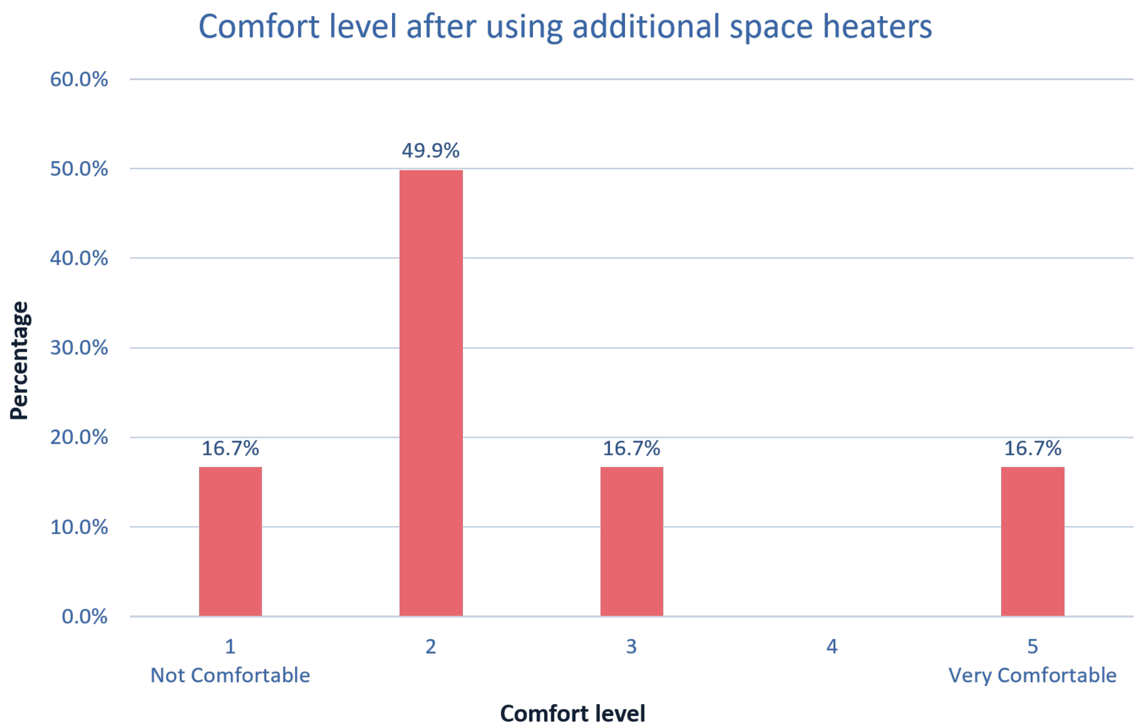
Frequency	Everyday	3~5 days	Weather	Never
Percentage	57.1%	14.3%	21.4%	7.1%



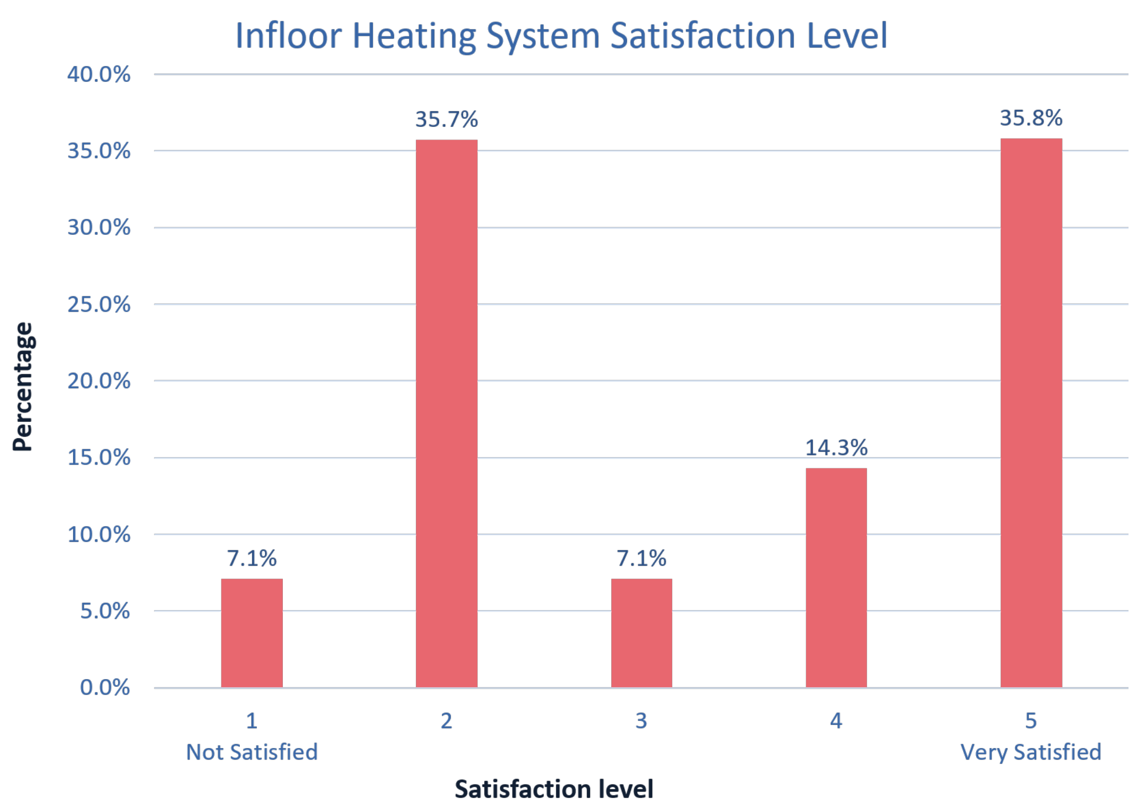
Frequency	Everyday	3~5 days	Weather	Never
Percentage	42.9%	14.3%	28.6%	14.3%

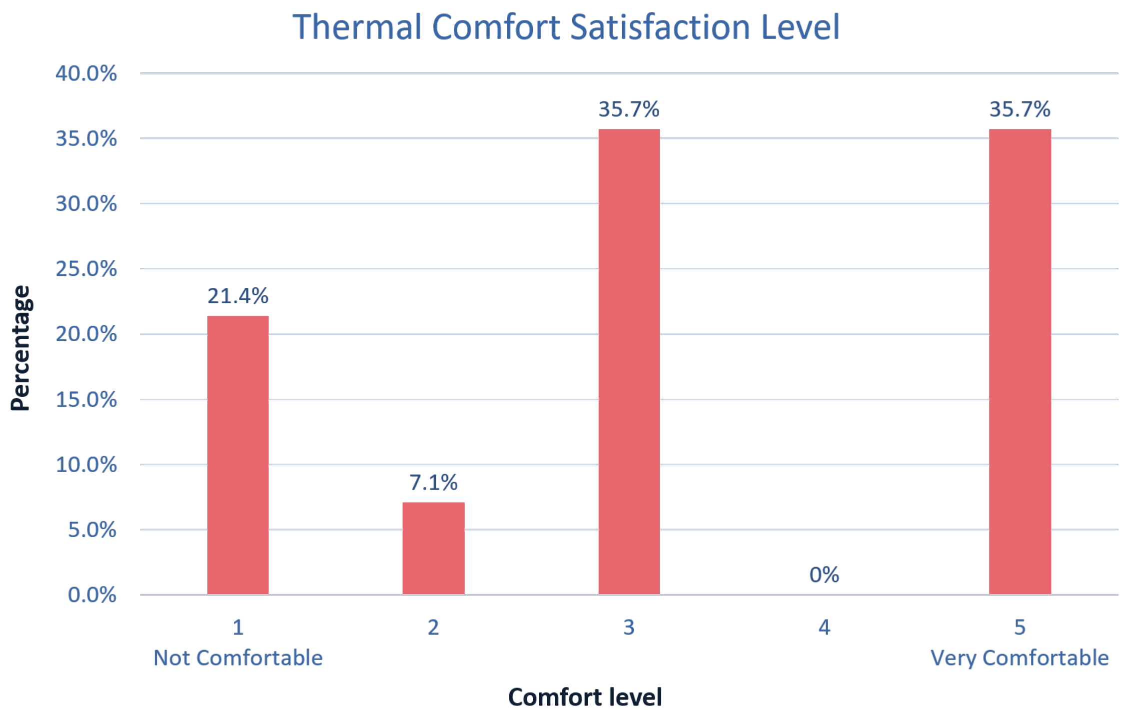


24/28 (85.7%) occupants use additional fans in summer; Some of the occupants use more than one fan.



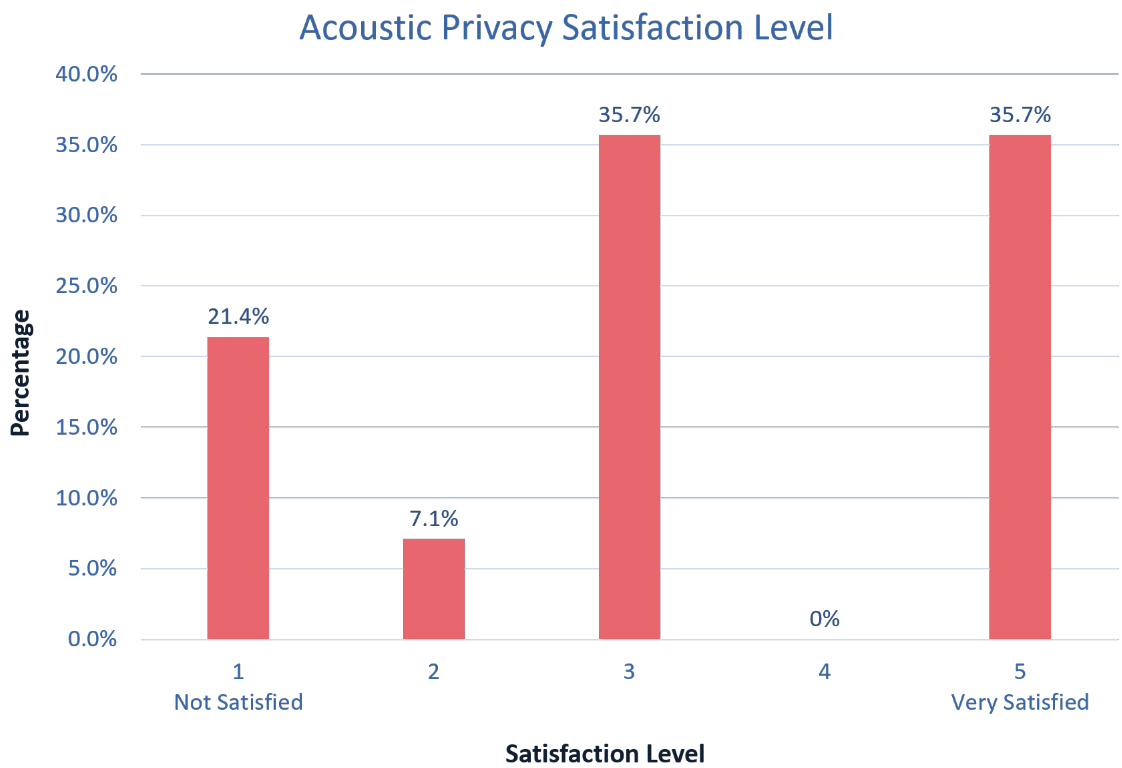
12/28 (42.9%) occupants use additional heaters in winter.





16/28 (57%) occupants complained ventilation not sufficient in summer.

12/28 (43%) occupants have feel of air leakage in winter nighttime


Acoustic Privacy Satisfaction Level
40.0%
35.0%
30.0%
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
Percentage
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

<u>Thank you for participating in the ***Building Performance Survey***</u>

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

2. Please indicate what new technologies 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 of the building? **You are welcome to add your comments to the blank area below**

   A. None
   B. Overheating issues during summer nights
   C. Too warm in summer at certain areas

D. Too cold in winter at certain areas

E. Poor quality of specific equipment

F. Poor installation of specific equipment

G. High maintenance fee

H. Others (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 design

    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 (e.g. 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 to 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. Compressor
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 (e.g. the complexity of controlling the system, poor design leads to barriers in adjusting, repairing and maintaining)? **Please feel free to comment below**

7. Do you have further suggestions or recommendations for the 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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