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Post-Occupancy Evaluation of a Passive Multi-Unit Residential Building and a Single-Family Passive House

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Abstract: Passive buildings are increasing in popularity in Canada. This paper examines two passive buildings initially constructed in the past decade: the Peterborough passive multi-unit residential building (MURB) and the Wolfe Island single-family dwelling. A post-occupancy evaluation was performed on the buildings. The buildings were modelled in HOT2000 and the Passive House Planning Package (PHPP) to ensure the validity of the results. The energy bills were collected from the building owners to acquire the real-time consumption of the buildings. The models have shown a good agreement with the collected data. Furthermore, data loggers were installed in both buildings for indoor temperature monitoring to ensure that they adhere to the passive house explicit criteria. Internal gains, shading, and orientation were analyzed to assess their effect on heating and cooling loads. Peterborough MURB has shown more energy-saving potential compared to the Wolfe Island passive house. Heating load reduction has been compared, more than five times, to the cooling load reduction potential. The reduction in GHG emissions can be up to 39% when passive house parameters are applied to the Wolfe Island house. This paper has shown the potential of the passive house in relation to sustainable buildings in Northern climates.

Keywords: sustainability; energy efficiency; passive house; energy conservation; building modelling

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1. Introduction and Review

Buildings have a significant impact on society and on the environment. There are many new technologies to reduce the negative impacts of buildings on the environment. Energy efficiency is very important because it reduces the consumption of fossil fuels, which results in a reduction of greenhouse gas emissions. Furthermore, high-quality and healthy construction improves occupant well-being. It is good for society when a building can help the environment and improve occupant health.

The passive house standard from the PassivHaus Institute in Germany is a rigorous, voluntary standard for energy efficiency in a building. A passive house is an ultra-low energy building that requires little energy for space heating or cooling. A certified PassiveHaus must meet the following requirements [1]:

- The space heating demand is not to exceed 15 kWh/m^2 per year, or must be designed with a peak heat load not to exceed 10 W/m^2;
- The space cooling demand roughly matches the heat demand with an additional climate-dependent allowance for dehumidification;

- The total primary energy consumption is not to exceed 120 kWh/m^2 per year;
- The airtightness at a maximum of 0.6 air changes per hour at 50 Pascals pressure (ACH50) in both pressurized and depressurized states;
- Thermal comfort must be met for all living areas year-round, with not more than 10% of the hours in any given year over 25 °C.

Research has been conducted on the thermal comfort and the energy savings of passive buildings. Research was performed in Sweden by P. Rohdin et al. [1] on the indoor thermal environment and energy use of nine passive homes. They compared on-site measurements with energy simulations. They also conducted a post-occupancy evaluation. They found out that passive houses have shown a significant reduction in loads. However, it is common that indoor temperature variation is higher in a passive house compared to a conventional building. The upper floor of the considered buildings experienced an average indoor temperature of 24 °C.

The CEPHEUS report by Schnieders and Hermelink [2] explores the social, ecological, and economic aspects of passive buildings. They looked at buildings in Germany, Austria, and Switzerland. The analyzed data included 11 houses and 100 dwellings. They reported that the space heating load can be reduced by 80% in a passive building compared to a conventional building. Mlakar and Strancar [3] found that occupants experienced overheating in the summertime in Slovenia. The indoor air temperature has reached as high as 27 °C. This was due to a lack of shading and inadequate nighttime ventilation. Blight and Coley [4] reported a regression analysis to link the passive house load prediction to occupant behaviour. They concluded their data for 100 dwellings in different conditions. The correlations have shown good agreement with real performance data. They found that passive houses' energy performance is not that sensitive to changes in internal loads. If the occupancy load increases seven times, the indoor temperature will only increase 1.8 °C. Wall [5] reported simulation and measurement data for 20 terrace passive houses in Sweden. Variation was found between data reported for space heating and electricity consumption. The energy saving can reach as high as 60% in a passive house.

Energy retrofits for more efficient buildings have been proposed in different climates. Coggins et al. [6] reported the factors that cause energy inefficiency in different buildings in Ireland. The factors were envelope-related or mechanical systems-related. Ventilation was shown to be very important to ensure better indoor air quality. An upgrade in the ventilation system increased the percentage of occupant satisfaction by 16%. Rouleau et al. [7] studied the factors affecting high-performance social housing in Canada. They reported that occupant activities impact up to 75% of building consumption in winter. Opening windows and turning on electrical equipment have an adverse effect on occupant comfort. Koksal et al. [8] presented a two-year detailed analysis of the energy performance of 25 homes in Milton, Ontario. They reported the share of different end uses in energy consumption and GHG emissions. Their paper is valuable guidance for building owners to reduce peak energy consumption. Zhu and Feng [9] performed life cycle analysis on buildings according to the British Columbia energy code. They found that energy saving can be fulfilled, but GHG emission reduction targets remain highly ambitious. The energy saving potential can be as high as 80%, while the emission reduction potential is less than 40%. Edalatnia and Das [10] performed an analysis on social and affordable housing in British Columbia. They considered the data of 23 houses in the period from 2019 to 2022. They reported that there are a lot of energy inefficiencies in such units. There needs to be massive retrofits to comply with standards due to a lack of amenities.

Review papers on potential energy retrofits in residential buildings were reported in the Canadian climate. Karunathilake et al. [11] presented a comprehensive overview that analyzed research outcomes. Although there are plenty of studies, the information is

scattered. There needs to be more focus on presenting research results to decision makers to guide informed decisions. Prabatha et al. [12] discussed the retrofits implemented in Canadian residences and their feasibility. They considered life cycle analysis in their discussions. They found that energy savings and emissions reduction do not always go hand in hand. They reported that the energy-saving potential can be up to 80% with suitable retrofits. However, an emission reduction of up to 50% can be optimistic. Some retrofits can reduce energy consumption but increase emissions, and vice versa. Policy makers need to consider trade-offs in their decisions.

Winkler et al. [13] discussed the shading technologies to overcome overheating in passive houses. They listed the benefits and the hindrances. They found out that a more detailed analysis is needed for assessing the shading benefit on reducing energy consumption. Georges et al. [14] reported the effectiveness of wood stoves in the space heating of passive houses. They found that the wood stoves reduced overheating in moderately cold climates. An 8 kW wood stove with power modulation of 50% eliminated the possibility of overheating. However, in extremely cold climates, they need to be considered as one method of space heating in addition to others.

Borrallo-Jiménez et al. [15] compared the building code regulations in Spain and the passive house standards. They found that the Spanish building code can be stricter in some areas. However, they emphasized that this is not the case in different climates. From a financial perspective, they found an increase of only 4% in project running costs when the photovoltaic system was integrated. Qu et al. [16] presented the retrofits of a historic building in the UK to the passive house standard. They found the most influential factors to be advanced glazing, a tighter envelope, and more insulation. This can result in up to a 52% reduction in energy consumption. Figueiredo et al. [17] assessed the feasibility of a passive house in the Portuguese climate. They performed an analysis of overheating possibilities. They found out that a passive house is feasible in the Portuguese climate under optimized design conditions. If not carefully considered, overheating can happen between 13% and 43% of the time. Colclough and Salaris [18] quantified overheating in 50 Irish residences, 37 of which meet the passive house standards. They found that 26% of the nonpassive houses experienced overheating. However, only 5% of the passive houses had overheating problems.

Occupant comfort has been a critical topic in recent research on passive house. Review articles have considered their assessment under different conditions. Rojas et al. [19] have reported that comfort conditions can be maintained in different passive houses. However, they reported that it is a dependence on internal gains control. They found that kitchen exhausts, in particular, need to be considered accurately in the analysis of energy losses. Wang et al. [20] reported a critical review on the relation between energy performance and comfort conditions in passive houses. They found that some of the research that reported energy efficiency has compromised air quality. Some others were able to maintain comfort conditions. CO_2 level monitoring has been shown to be of great importance to consider.

Sazabados et al. [21] analyzed the indoor air quality parameters in 15 passive houses in the Hungarian climate. They found that the outdoor conditions affect the particle concentration in the passive house. The presence of a high nitrogen oxide concentration outside compromised the indoor comfort. A mean value of 35.1 $\mu g/m^3$ was observed for the nitrogen dioxide concentration. Mihai et al. [22] presented the analysis of the integration of photovoltaic panels to a passive house located in Bucharest. The photovoltaic system was able to supply the majority of the building's electricity needs. In addition, indoor comfort conditions were maintained. The house energy consumption was found to be close to 13 kWh/m^2 year. Udrea et al. [23] assessed the thermal comfort in an office building in the Romanian climate. They analyzed the measured and simulated data during the summer

period. They found out that the overheating effect can be mitigated in the passive house as long as the internal gains are simulated to mimic the real conditions. Wang et al. [24] reported that the building envelope is as crucial as internal gains in attaining comfort in passive houses. They performed a three-stage optimization that showed an improvement in thermal comfort of 37.8%. Through sensitivity analysis, Figueiredo et al. [25] were able to obtain a 62% reduction in heating demand for a house in Portugal. This was in addition to ensuring a comfortable temperature and humidity within the building.

Most passive buildings are built in Central Europe, where the standard was developed. There are almost 4000 buildings listed on the Passive House Database [26]. However, there are only less than a hundred passive house buildings in Canada listed on the Passive House Database [27]. The first certified passive house in Canada was the "Austria Haus", built in 2009 in Whistler, British Columbia. The design fundamentals of a passive house are pre-planning, efficient building shape, solar exposure, superinsulation, advanced windows and doors, airtightness, ventilation with heat recovery, ventilation air pre-heating, and thermal bridge-free construction.

The aim of this paper is to analyze two newly constructed passive buildings in Ontario, Canada. The first project building is the Peterborough passive house apartment building, located in Peterborough, Ontario. It is a three-storey multi-unit residential building (MURB) with a gross floor area of 1213 m^2 that faces south. The building is shown in Figure 1. The average daily solar radiation on a horizontal surface in Peterborough is 3.53 $kWh/m^2/day$. It contains twelve apartment units. The building owner was also the general contractor on the project. The second project building is the Wolfe Island passive house. Wolfe Island is located at the entrance of the St. Lawrence River near Kingston, Ontario. It is a single-family dwelling for a family of three. The gross floor area is 172 square meters. It has two storeys with a storage loft. It is built on a super-insulated slab-on-grade foundation. The walls and roof of the Wolfe Island house are made from cross-laminated timber (CLT) panels, which is a new method of construction in Canada. The house is facing southeast and is shown in Figure 2. The average daily solar radiation on a horizontal surface at Wolfe Island is 3.56 $kWh/m^2/day$. Table 1 shows the monthly average climate conditions in both buildings. A cold, humid climate is experienced in both locations. The average air temperature throughout the year is about 7 °C. The average annual humidity is 76.2%, and the average wind speed is 4.7 m/s.



Figure 1. Front view of Peterborough MURB.



Figure 2. Front view of Wolfe Island house.

Table 1. Climate conditions at the buildings' locations.

Month	Air Temperature (°C)	Relative Humidity (%)	Daily Solar Radiation on Horizontal (kWh/m^2/day)	Wind Speed (m/s)
January	−6.3	76.4	1.48	5.7
February	−6.7	74.4	2.39	4.9
March	−1.6	73.6	3.33	5
April	4.9	71.9	4.47	4.7
May	11.8	76	5.16	4.1
June	16.8	78.3	5.78	3.8
July	20.6	76.5	5.83	4
August	20.2	77.9	4.96	3.9
September	15.3	77.6	3.9	4.5
October	8.8	76.9	2.58	5
November	3.4	77.4	1.55	5.5
December	−4.7	77.3	1.22	5.4

The post-occupancy evaluation presented in this paper focuses on energy consumption and occupant comfort. Energy simulations were completed in HOT2000 [28] and the Passive House Planning Package (PHPP) version 10 [29]. Both are commercial software used to model building energy performance. The actual energy bills from the projects were collected. With this information, the energy simulations and the actual energy consumption were compared. The occupancy for both buildings is different because the apartment building has more occupants per square meter of floor area. Furthermore, the construction methods are different. The apartment building features lightweight wood framing, whereas the Wolfe Island house has a CLT frame. The CLT walls and roof have a significant volume of solid wood, like a log house. This provides a thermal mass on the interior side of the building envelope. Secondly, simplified occupant comfort is analyzed from the sensors in the units that measure temperature. This ensures that occupant comfort is maintained. The

novelty of this study lies in the comparison of the selected buildings that have not been reported before. In addition, the methodology of analysis has not been applied to compare those types of buildings. This study also provides guidance for energy auditors to propose efficiency measures that are viable for such types of buildings in harsh climate conditions. The current paper answers the following research questions:

- Is it feasible to achieve passive house potential in single-family homes and multi-residential unit buildings in the cold Canadian climate?
- What is the difference in energy performance between the two types of buildings?
- How do the different building systems affect the building energy performance?
- What is the potential reduction in greenhouse gas emissions that can be achieved in both types of buildings?

2. Description of Analyzed Passive Buildings

2.1. Peterborough MURB

The Peterborough multi-residential building has twelve residential units. It consists of three storeys with four units per floor. Each apartment is a corner unit with windows on both sides. The building footprint is 20.68 m wide and 19.50 m deep. The ground floor features a small bump-out at the main entrance, giving the main floor a footprint of 407 square meters. The second and third floors are 403 m^2 each. Tenants began moving into the building in August 2016.

The building is designed to meet the European Passive House Standard [27]. The building is well-insulated and airtight. It is made of a 300 mm EPS foam raft slab system providing an RSI 8.13 (R-46). The walls are framed with I-beam engineered wood panels that are insulated to RSI 9.3 (R-53) with blown-in cellulose. The walls were pre-fabricated in a factory by Green Giant Design Build and then assembled on-site. The roof is insulated to RSI 16.4 (R-93) of blown-in cellulose. The building's airtightness is excellent. A preliminary blower door test during construction resulted in a value of 0.36 air change per hour at 50 Pascals (ACH @ 50 Pa).

High-performance windows and doors were installed in the building. The windows are Gaulhofer Energyline-85 units and were imported from Austria. They have a frame U-value of 0.94 W/m^2K. The glazing unit is triple-glazed with two low-e coatings. The glazing U-value is 0.5 W/m^2K, and the solar heat gain coefficient (SHGC) is 0.53. The exterior doors are Gaulhofer units with a U-value of 1.0 W/m^2K. Table 2 includes the overall heat transfer coefficient of building envelope components.

Table 2. The overall heat transfer coefficient of the building envelope components for the Peterbourough MURB.

Component	U Value (W/m^2K)
Walls	0.107
roof	0.061
Windows	0.5
Door	1.0

The mechanical system features a central natural gas boiler, which provides space heating and domestic hot water. The gas boiler is a Viessmann Vitodens 200 W from Ottawa, Canada. For ventilation, each apartment has its own independent Zehnder ComfoAir 200 heat recovery ventilator (HRV) from UK. The effective heat recovery rate is 92%, as measured by the Passive House Institute (PHI). The stairwell and hallways are also ventilated by an HRV. In August 2016, temporary 1800 BTU minisplit air conditioners of

the SENA/18HF type were installed in the occupied units. The tenants were uncomfortable inside their apartments due to very high temperatures and humidity. The LG portable cooling units have a capacity of 2.35 kW and a seasonal energy efficiency ratio of 9.2. The cooling units can cool the two-bedroom, 93 square meter apartment units. The portable units were replaced by high-efficiency wall-mounted air conditioner units in the summer of 2017. An air conditioner head unit was installed in each apartment.

2.2. Wolfe Island Passive House

The Wolfe Island passive house was completed in October 2016. The single-family house is made from CLT panels for the exterior walls, floors, and roof. It is a two-storey building built on a slab-on-grade foundation. The house has a rectangular floor plan that measures 7.5 m by 11.5 m. The building footprint is 86 m^2. The slab-on-grade foundation is a super-insulated extruded polystyrene (EPS) tray slab system provided by StyroRail in Canada. The insulation value of the foundation system is RSI 11.2 (R-64). The wall structure is made from 100 mm-thick, 4-layer CLT panels provided by Merk Timber. The CLT panels were imported from Germany. The walls are insulated with 280 mm of wood fibre board. The insulation board was made by Schneiderholz, and it was imported from Germany. The insulation value of the walls is RSI 7.7 (R-43). The roof structure is also made from CLT panels. The roof structure is a 5-layer CLT with a thickness of 130 mm. The roof is insulated to RSI 7.7 (R-43) with 280 mm of wood fibre board. The house features Optiwin Resista windows that are made in Austria. The Optiwin Resista window is a Certified Passive House Component by the Passive House Institute. The windows have a U-value of 0.72 W/m^2K. The glazing unit features triple-glazing, two low-e coatings, and a U-value of 0.5 W/m^2K. The entry door is supplied by Optiwin from Germany. The sliding door on the south elevation is the Optiwin Motura model. Table 3 includes the overall heat transfer coefficient of building envelope components.

Table 3. The overall heat transfer coefficient of the building envelope components for the Wolfe Island house.

Component	U Value (W/m^2K)
Walls	0.13
roof	0.13
Windows	0.5
Door	0.8

The energy for the house is provided exclusively by electricity. Space heating is supplied by a 2 kW thermoelectric heating element located in the supply ductwork of the energy recovery ventilator (ERV). Fresh air is supplied by a Zehnder ComfoAir 200 ERV. The effective heat recovery rate is 92% as measured by the Passive House Institute (PHI). Domestic hot water is provided by a standard electric hot water tank with a capacity of 181 L. A preliminary blower door test during construction resulted in a value of 0.48 air change per hour at 50 Pascals (ACH @ 50 Pa).

3. Data Acquisition System

Data loggers were installed in both buildings to collect indoor temperature. This ensures that indoor temperature does not exceed 25 °C more than 10% of the time during the year, according to the standard [27]. The data loggers are made by Structure Monitoring Technology (SMT), located in Vancouver, British Columbia. The measured temperatures can range from −20 °C to 70 °C. They have an accuracy of 0.2 °C. Two models of SMT data loggers were installed: the A2 Wireless Data Logger and the A3 NEMA Data Logger. The

A2 and A3 are both wireless data acquisition units with integrated temperature sensors. The data loggers connect to the SMTs Building Intelligence Gateway (BIG). The BIG gateway collects the sensor data from the data loggers. The data are exported from the BIG system into a spreadsheet format.

Six data loggers were installed at the Peterborough apartments. The first floor has data loggers in units 101 (north-west) and 104 (south-east), as shown in Figure 3. The second floor has data loggers in units 202 (north-east) and 204 (south-east), as shown in Figure 4. The third floor has data loggers in units 302 (north-east) and 303 (south-west), as shown in Figure 5. This allows data to be collected on every floor. The data loggers are also placed on the north and south sides of each floor. The data loggers were installed in a central area between the living room and kitchen. The units were placed 1.6 m from the floor, as shown in Figure 6.

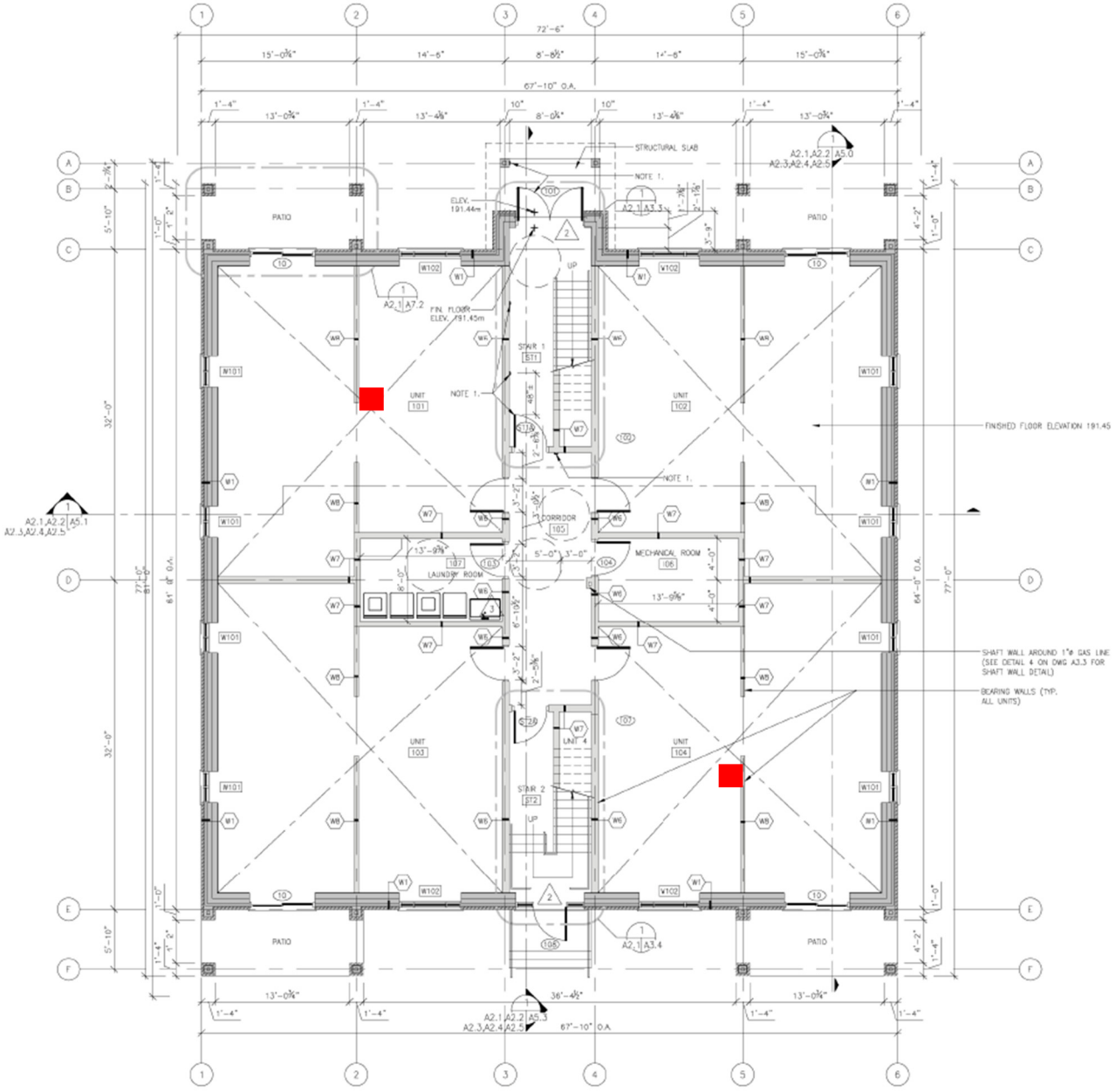

Figure 3. Location of dataloggers on first floor of Peterborough MURB.

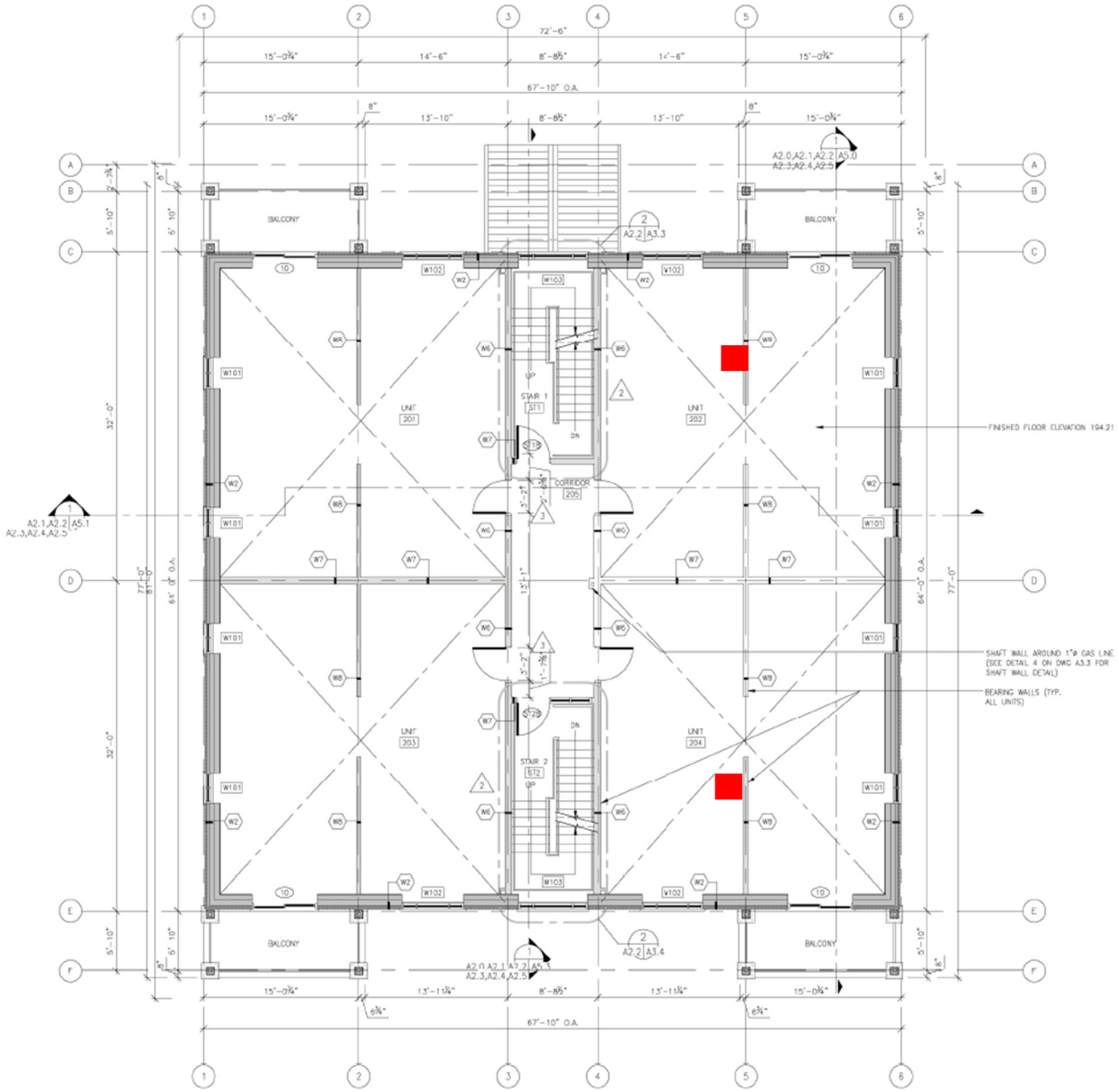

Figure 4. Location of dataloggers on second floor of Peterborough MURB.

The Wolfe Island house had two data loggers installed, one on each floor. The first-floor data logger was installed to the east of the stairs, between the kitchen and dining room, as shown in Figures 7 and 8. It is mounted 2.0 m from the floor. The second-floor data logger was also installed to the east of the stairs. It is in the hallway next to the bathroom, the second bedroom, and the sitting room, as shown in Figure 9.

The coming sections include a validation of the simulation package's results used in the analysis against real-time data. It is followed by the simulation results for building energy performance and its comparison to the current building code and passive house standards. Then, different energy end uses have been presented in both buildings. Finally, temperature readings from the data loggers have been analyzed to ensure that it is within the recommendations of the passive house standard.

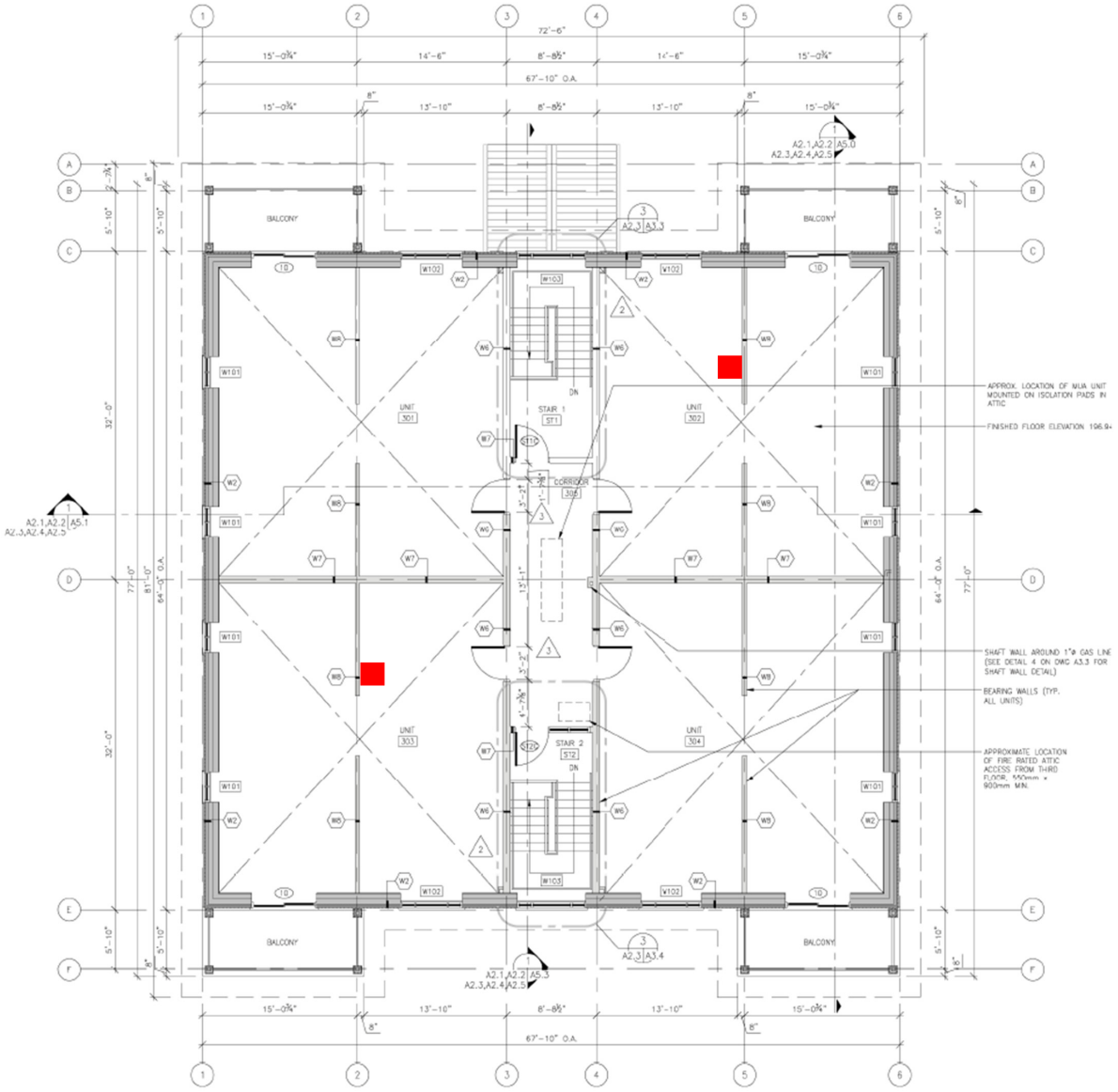

Figure 5. Location of dataloggers on third floor plan.



Figure 6. SMT A3 data logger located in Peterborough MURB.

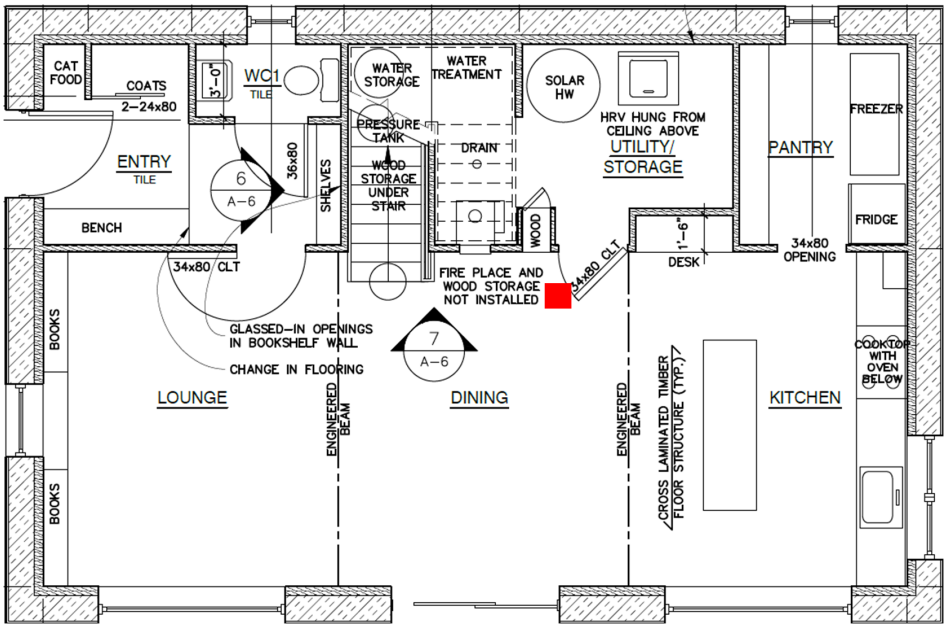

Figure 7. First-floor location of datalogger, Wolfe Island.



Figure 8. SMT A3 datalogger installed on first floor, Wolfe Island.

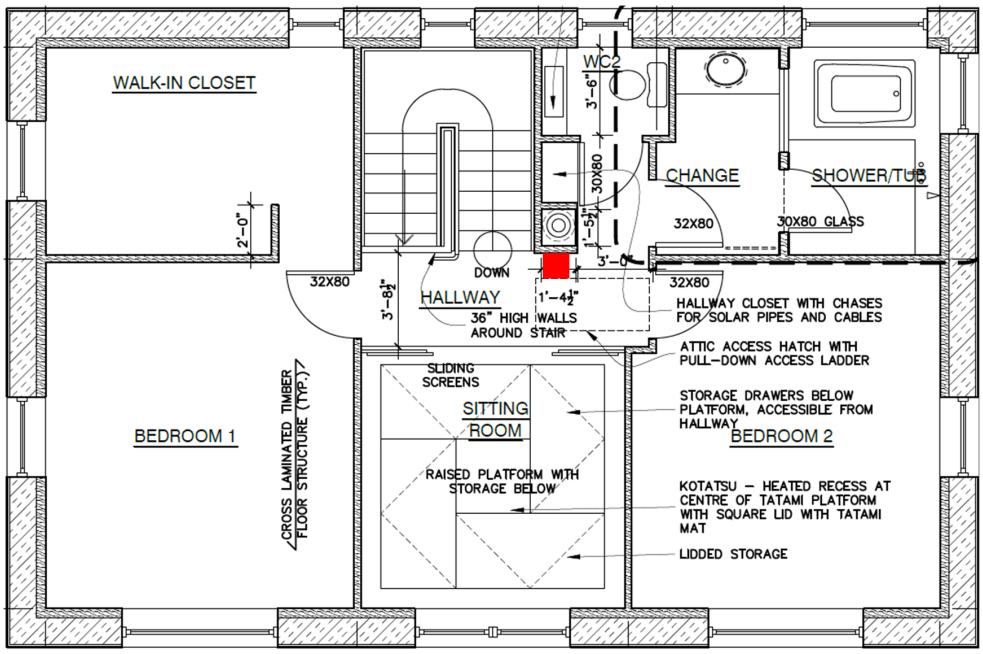

Figure 9. Second floor location of datalogger, Wolfe Island.

4. Simulation Methodology and Validation

HOT2000 version 11 [28] is a commercial package that was developed by Natural Resources Canada. It considers the building design and operating conditions to simulate the building energy performance. It is an easy-to-use software that has a straightforward graphical user interface. All building information and systems specifications are selected through drop-down menus.

The mathematical model used in HOT2000 is based on the fundamental heating and cooling load calculations. It takes into account the compliance with the recommendations of the national energy code of buildings in Canada [30].

The heating load is the power required to maintain the indoor temperature at the comfort set point for a given lower outdoor temperature. Its calculation includes the sum of the heat transmitted through building envelope elements (i.e., walls, ceilings, floors, glass, and other surfaces) and the heat required to temper outdoor air entering the building through infiltration and ventilation. The heating system should have the ability to provide enough heat at maximum capacity to compensate for peak heat losses.

The cooling load is the power required to maintain the indoor temperature at the comfort set point for a given higher outdoor temperature. Cooling load calculations need to take into account heat transfer from the building envelope, solar heat gains via fenestrations, infiltration and ventilation load, and internal gains load (occupants, equipment, and lighting). Cooling equipment should provide the needed cooling in the most adverse conditions of high outdoor temperatures. Both heating and cooling equipment should comply with section 9.36.5 of the National Energy Code of Buildings in Canada [30].

Transmission heat load through the building envelope is obtained by adding heat transfer through different components (walls, roof, floor, etc.). It is a function of the heat transfer coefficient, the area of heat transfer, and the temperature difference. It is calculated through the following equation:

$$q_t = UA\Delta T \quad (1)$$

where q_t is transmission heat load in the heating or cooling season, A is the area of heat transfer, and ΔT is the difference between indoor and outdoor temperatures.

For walls, the heat transfer coefficient U is calculated using the sum of the materials' thermal resistance values and is as follows:

$$U = \frac{1}{R_{eff}} \quad (2)$$

where R_{eff} is the effective thermal resistance of the wall assembly.

The solar heat gain through windows is calculated as follows:

$$q_s = (SHGC)A_{window}G \quad (3)$$

where SHGC is the solar heat gain coefficient, A_{window} is the area of the window, and G is solar radiation per unit area.

The ventilation and infiltration heat load need to be taken into account when sizing the heating and cooling equipment. The ventilation is the fresh air that must be admitted to the building to ensure occupant comfort. However, infiltration is the unwanted air that enters through building cracks and different joints. Both loads are calculated by the following equation:

$$q_{\text{ventilation or infilteration}} = \frac{\dot{Q}}{v_o}C_p\Delta T \quad (4)$$

where $q_{\text{ventilation or infilteration}}$ is the ventilation or infiltration heat load, $\dot{Q}$ is ventilation or infiltration volumetric flowrate, v_o is the specific volume, C_p is the specific heat of air, and

ΔT is the temperature difference between indoors and outdoors. For fan sizing, HOT2000 correlates it to the required air flow rate and efficiency. For fan and heat recovery ventilators sizing, section 9.32.3 in the National Energy Code for Buildings in Canada is used [30].

Internal loads include the occupants' heat gain, lights, and equipment. HOT2000 considers the steady state method in the calculation of average values recommended by the National Energy Code for Buildings in Canada for residential applications [30]. Both sensible and latent components are considered in the analysis.

For domestic hot water system, the temperature set point is assumed as 57 °C, which is suitable for residential applications. The schedule of hot water demand is assuming an average distributed occupancy throughout the daytime, as per the National Energy Code for Buildings in Canada [30].

HOT2000 [28] was used to model the two considered buildings. Figure 10 compares the actual billed electricity consumption of the Peterborough building with the HOT2000 simulation. In August, the actual consumption is lower than the simulation because some of the apartments were not occupied yet. In September, October, and November, the actual consumption is very close to the simulation, within 0.1 or 0.2 MWh. From December to March inclusive reveals that the actual consumption is higher than the simulation. The actual consumption is higher by from 0.6 to 0.8 MWh for those months. Overall, there is very good agreement between simulated data and real consumption. This agrees with the conclusions of previously published results [4]. Others have reviewed the sensitivity of occupant behavior on energy use and identified the relationship between space heating load and behavioral variables. They found that, in general, passive houses are less sensitive to occupant behavior than initially anticipated.

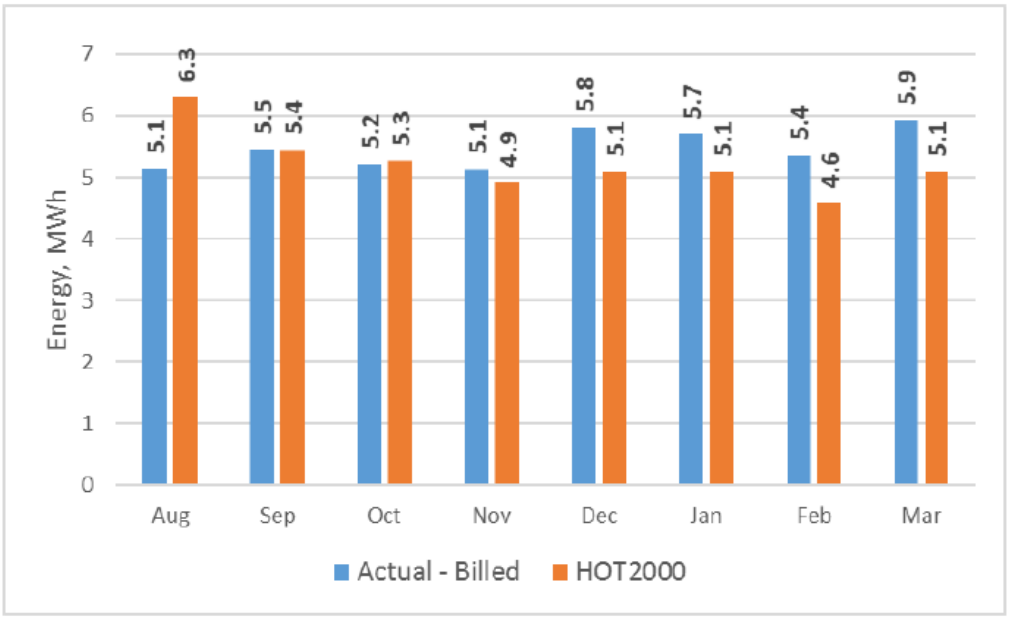

Figure 10. Monthly electricity comparison, billed versus simulation for Peterborough MURB.

Figure 11 compares the actual billed consumption with the HOT2000 and PHPP simulations for the Wolfe Island building. In November and April, HOT2000 overestimated the consumption (maximum of 25% deviation). From December to March, HOT2000 underestimated the billed consumption (10% deviation). The PHPP estimates are very close to the billed consumption during November, December, January, and February. However, PHPP underestimated consumption in March and April. The highest deviation observed is 28% from the billed consumption. There is an overall good agreement between the simulated data and the real consumption.

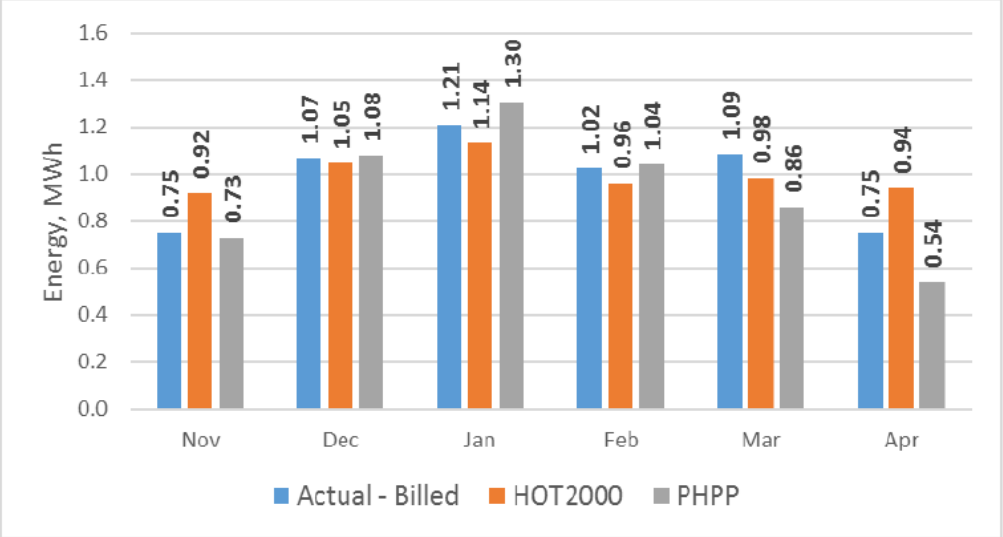

Figure 11. Comparison of actual billed consumption with HOT2000 and PHPP for Wolfe Island house.

5. Detailed Building Energy Model

5.1. Peterborough MURB Model

Four HOT2000 models were created for the Peterborough building to compare the passive house (as-built) version with the 2017 version of the Ontario Building Code (OBC) [31]. It includes the guidelines that the building needs to follow in the province of Ontario. Furthermore, both versions were modeled with shading (as-built) and without shading to compare the difference in heating and cooling energy. Passive houses, designed to minimize heat loss and maximize solar gain, with high airtightness and limited ventilation, can overheat. This can be mitigated with external shading, night cooling, cross-ventilation, and thermal mass, among other strategies. In this case, we are using shading as a basis for comparison. The specifications of the building models are shown in Table 4. Since the MURB building includes both above-grade and below-grade walls, their thermal resistances are included. The table also includes the heat transfer coefficient of windows and doors. In addition, it includes mechanical system specifications. The glazing distribution area percent and shading overhang depth on different building orientations are given in Table 5. The highest window percent is on the south side in order to make use of daylight. This corresponds to the highest overhang depth to prevent overheating. This is followed by east and west. The lowest percentage of glazing is on the north side.

Table 4. Peterborough MURB specifications: passive house and OBC 2017 [31].

Component	Specification	Passive House	OBC 2017 Package A4
Ceiling with attic space	Effective RSI	16.4 (R93)	10.43 (R60)
Walls above grade	Nominal RSI	- -	3.87 + 0.88 ci (R22 + R5 ci)
	Effective RSI	9.26 (R53)	3.77 (R21.4)
Slab < 600 mm below grade	Effective RSI	8.13 (R46)	1.96 (R11.13)
Edge of slab < 600 mm below grade	Nominal RSI	8.13 (R46)	1.76 (R10)
Windows and sliding glass doors	U value SI (W/m^2K)	0.65	1.6
Exterior doors	Effective RSI	1 (R5.7)	0.7 (R4)

Table 4. *Cont.*

Component	Specification	Passive House	OBC 2017 Package A4
Space heating equipment	AFUE	96%	96%
HRV	SRE	92%	75%
Air leakage	ACH @ 50 Pa	0.36	3.57

Table 5. The glazing distribution area percent and shading overhang depth on different building orientations for Peterborough MURB.

Orientation	Glazing Percent (%)	Shading Overhang Depth (m)
North	11	0.5
East	12.2	0.75
South	66	2.3
West	10.8	0.7

5.2. Wolfe Island Model

Four HOT2000 models were created for the Wolfe Island passive house to compare the passive house (as-built) version with the 2017 version of the Ontario Building Code (OBC). Furthermore, both versions were modeled with shading (as-built) and without shading to compare the difference in heating and cooling energy. The specifications of the building models are shown in Table 6. The single-family home included both above-grade and below-grade walls. Their thermal resistances are included. The table also includes the heat transfer coefficient of windows and doors. In addition, it includes mechanical system specifications. The glazing distribution area percent and shading overhang depth on different building orientations are given in Table 7.

Table 6. Wolfe Island building specifications: passive house and OBC 2017 [31].

Component	Specification	Passive House	OBC 2017 Package A4
Ceiling without attic space	Effective RSI	7.7 (R43)	5.46 (R27.65)
Walls above grade	Nominal RSI	- -	3.34 + 1.76 ci (R19 + R10 ci)
	Effective RSI	7.7 (R43)	3.77 (R21.4)
Slab < 600 mm below grade	Effective RSI	11.3 (R64)	1.96(R11.13)
Edge of slab < 600 mm below grade	Nominal RSI	8.5 (R48)	1.76 (R10)
Windows and sliding glass doors	U value SI (W/m^2K)	0.72	1.4
Exterior doors	Effective RSI	1.56 (R8.9)	0.7 (R4)
Space heating equipment	Electric	Direct resistance	Direct resistance
HRV	SRE	92%	81%
Air leakage	ACH @ 50 Pa	0.4	3.57

Table 7. The glazing distribution area percent on different building orientations for the Wolfe Island house.

Orientation	Glazing Percent (%)	Shading Overhang Depth (m)
North	11.6	0.4
East	14.2	0.6
South	60.7	1.6
West	13.5	0.55

6. Results and Discussion

The annual heat loss by component for the Peterborough building is shown in Figure 12. The largest reduction in heat loss is by the reduction in air leakage. The reduction in energy loss by air leakage is 87%. The heat loss reduction is 35% for the ceiling, 58% for the walls, 37% for the doors, and 43% for the slab. The north and south elevations have a larger surface area of windows. Therefore, their contribution to heat loss is higher than the east and west windows.

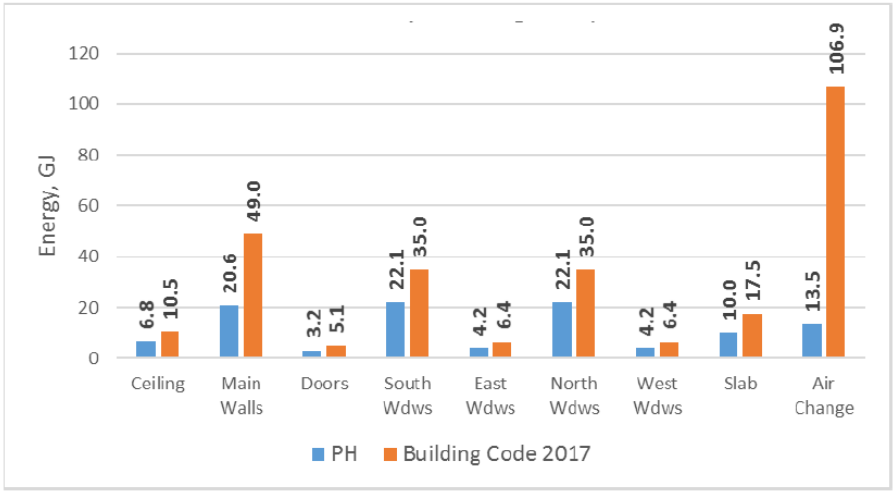

Figure 12. Annual heat loss by building component for Peterborough MURB.

The annual heat loss by building component for the Wolfe Island house is shown in Figure 13. The passive house has lower heat loss in all categories. The largest reduction in heat loss is the air change, with a reduction of 13.9 GJ, which is about an 86% reduction.

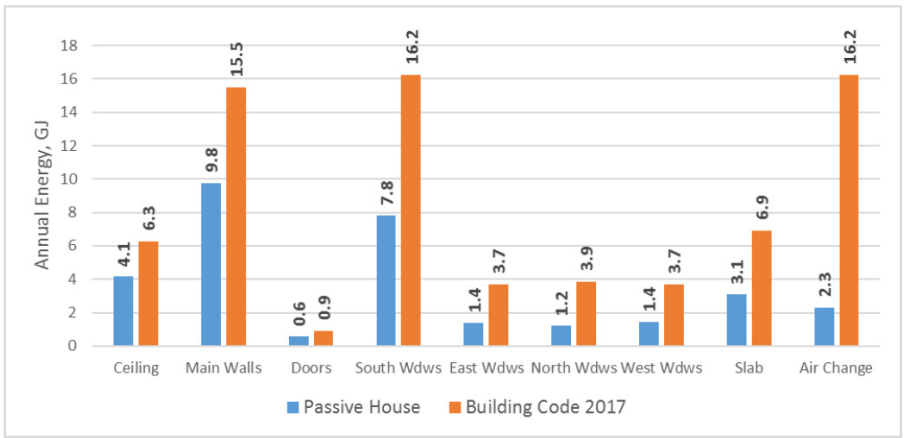

Figure 13. Annual heat loss by building component for Wolfe Island house.

The monthly space heating consumption for the Peterborough house is shown in Figure 14. The passive house model has a significantly lower space heating consumption. Furthermore, it only requires heating for three months, from December to February inclusive. The code model requires heating from November to April inclusive. The passive house is more sensitive to shading than the code model. However, in all cases, the passive house requires less heating than the code model.

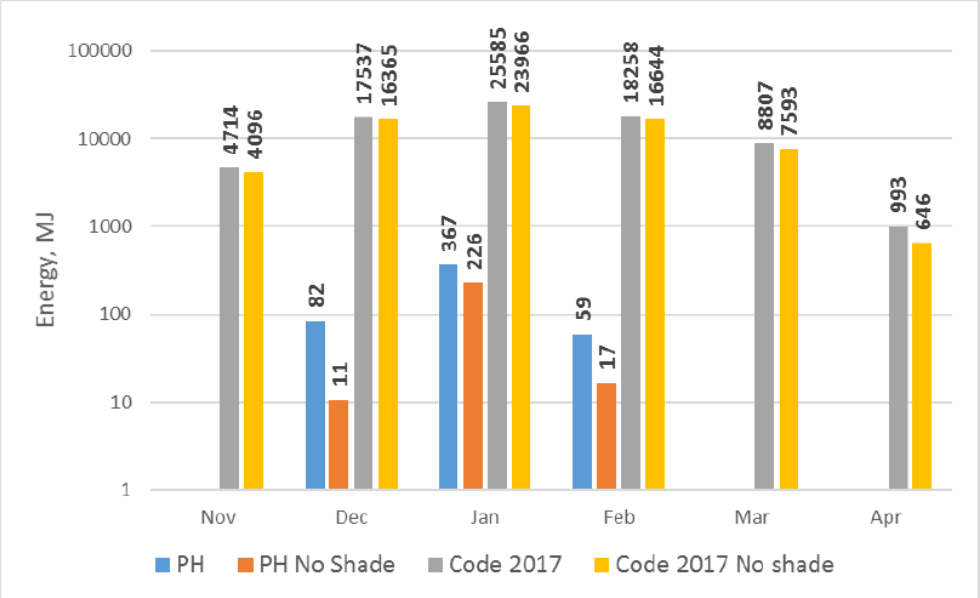

Figure 14. Monthly space heating consumption for Peterborough MURB.

The monthly space heating consumption for Wolfe Island's passive house is shown in Figure 15. The passive model only requires heating from December to February inclusive. The code model requires heating from October to April inclusive.

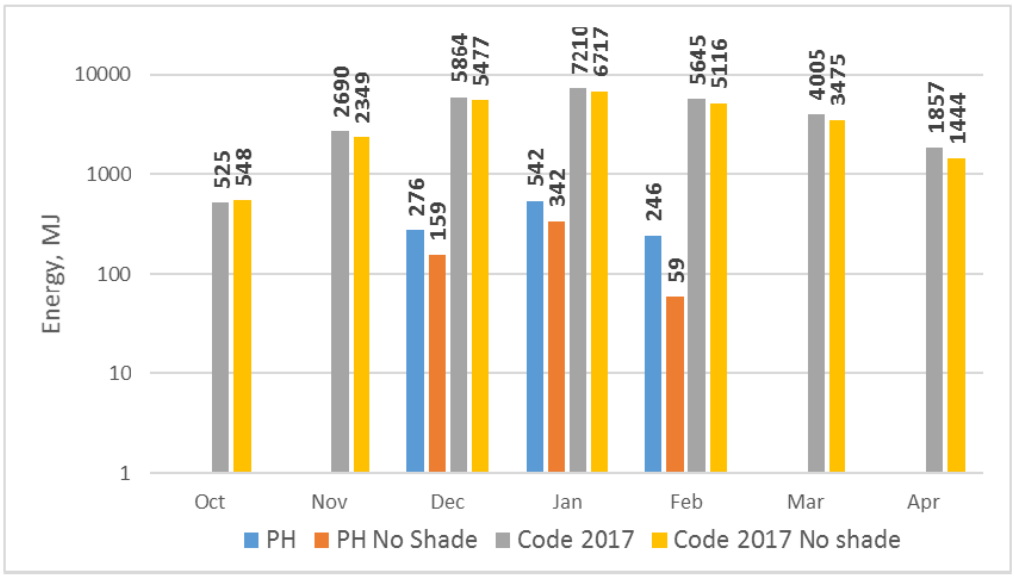

Figure 15. Monthly space heating consumption for Wolfe Island house.

The monthly cooling consumption in Peterborough MURB is shown in Figure 16. Both models require cooling from May to October inclusive. The passive house model demonstrates the lowest cooling requirements. The highly insulated and air-tight building envelope reduces heat gain from the exterior. Both passive house and code models require

more cooling when the shading is removed from the building. The code built with no shading requires the most cooling. In general, building codes do not prioritize maximizing solar heat gain or enforce strict airtightness, unlike passive houses. While recent updates to energy codes, like the BC Step Code [32] and NECB [30], are improving efficiency, code-built homes are not optimized for passive solar gain. The BC step code aims to position British Columbia to meet its emission target by 2032. The National Energy Code of Buildings (NECB) in Canada positions the country to meet its emission target in the coming decade. As a result, shading has a lesser impact on their energy consumption compared to passive houses, which rely on solar heat gain and airtightness for energy efficiency.

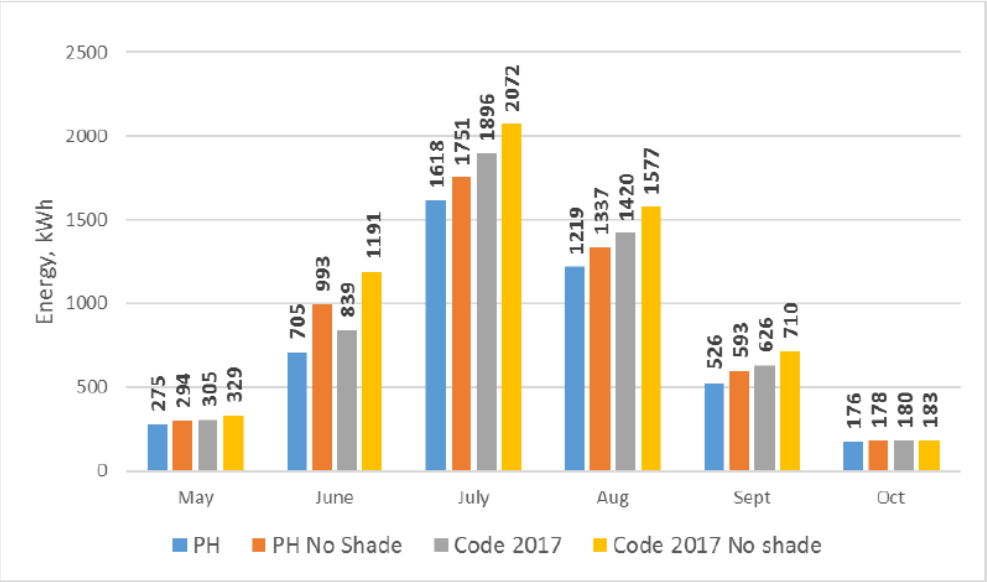

Figure 16. Monthly cooling consumption for Peterborough MURB.

The monthly cooling consumption in the Wolfe Island passive house is shown in Figure 17. The openable window area is 40%, and this was included in the HOT2000 model. The passive model requires the lowest amount of cooling in all months. The code model without shading requires the most cooling. The peak cooling month is July due to it having the hottest weather. The passive model with shading consumes significantly less energy than the code model without shading.

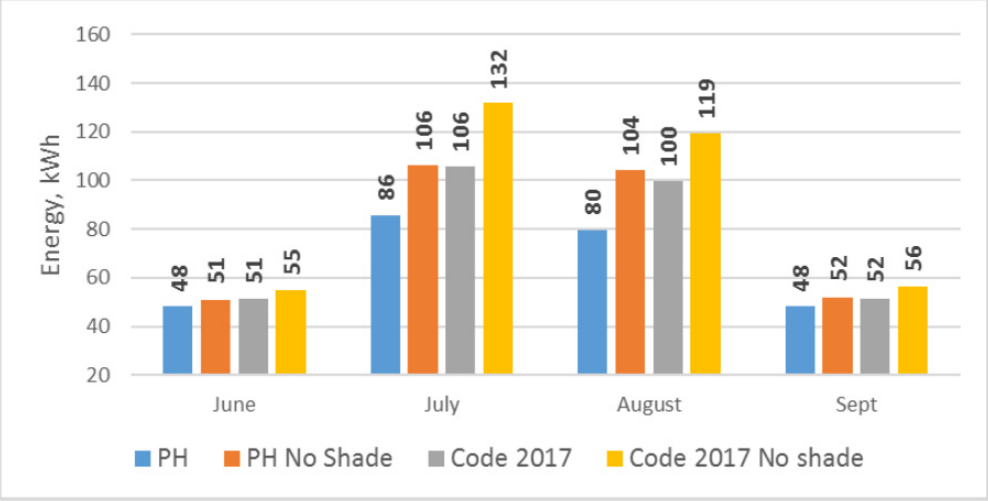

Figure 17. Monthly cooling consumption for Wolfe Island house.

The annual heating and cooling consumption for Peterborough MURB is shown in Figure 18. The passive house with shading has significantly less heating consumption. The cooling consumption for the passive house is 14% less than the code model. The heating consumption is 99% less than the code model. Overall, the passive house consumes 82% less energy for heating and cooling. While overheating can occur in passive houses, well-designed ones typically manage heat more effectively than conventional buildings. The Passive House Institute (PHI) sets a strict overheating threshold, ensuring indoor temperatures do not exceed 25 °C (77 °F) for more than 10% of the year. This limit is more stringent than many building codes, requiring passive houses to be designed to prevent overheating.

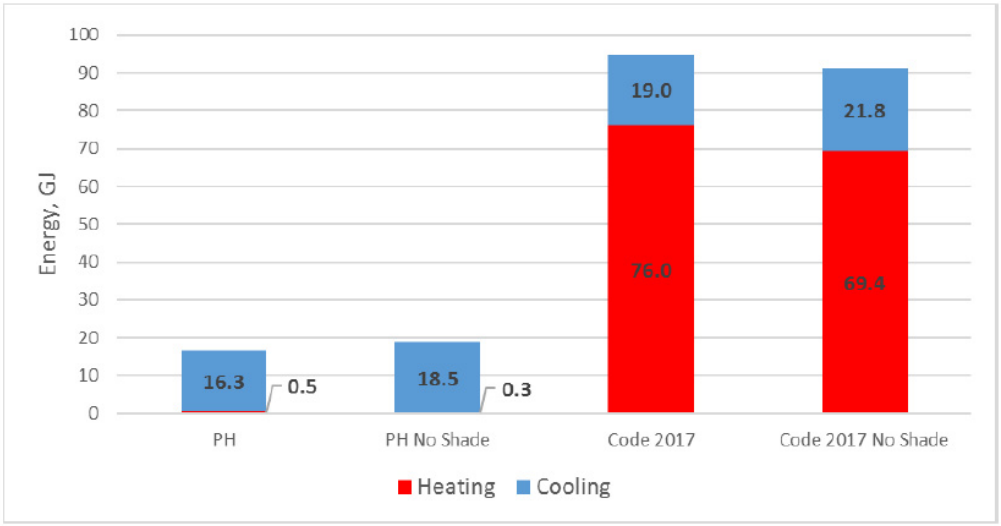

Figure 18. Annual consumption, heating, and cooling for Peterborough MURB.

The annual consumption of both heating and cooling in the Wolfe Island passive house is shown in Figure 19. The passive model requires 96% less heating energy than the code model. The passive model requires 8% less cooling energy than the code model. For both heating and cooling, the passive house model requires 90% less energy than the code model.

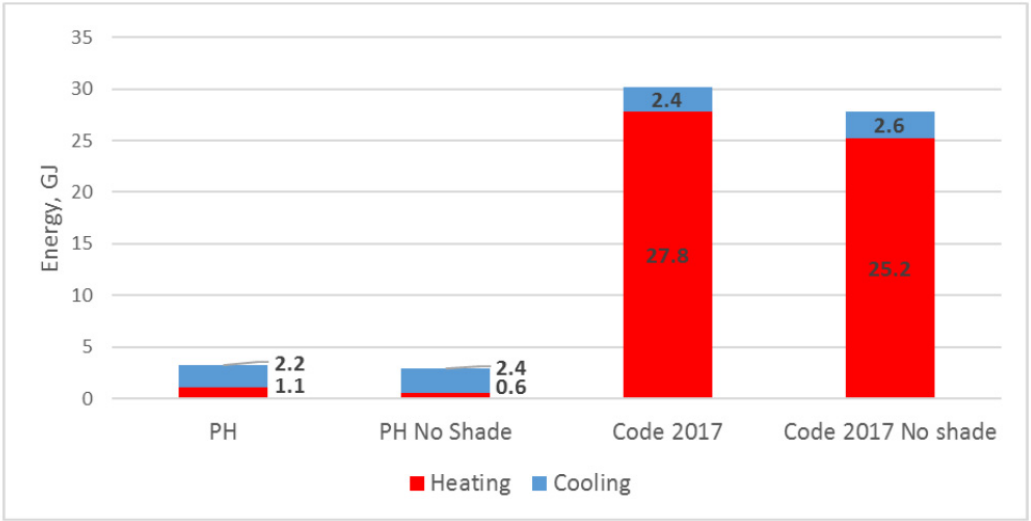

Figure 19. Annual consumption, heating, and cooling energy for Wolfe Island house.

The annual energy consumption by device in the Peterborough MURB obtained from the HOT2000 simulation is shown in Figure 20. The total annual energy consumption for

the passive house is 356 GJ, and, for the code model, it is 434 GJ. Therefore, the passive house consumes 18% less total energy per year. The savings are mostly due to a 75 GJ reduction in heating, and also a 3 GJ reduction in cooling. The lighting, appliance, HRV, fan, and domestic hot water consumption are the same for both models because they are not affected by the building envelope.

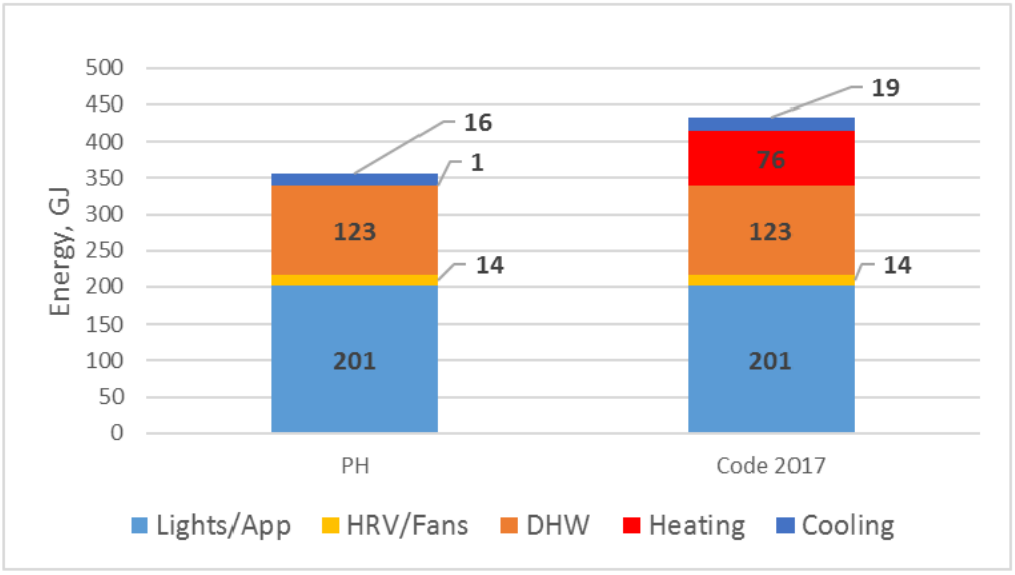

Figure 20. Annual energy consumption by device for Peterborough MURB.

The annual energy consumption by device in the Wolfe Island passive house is shown in Figure 21. The largest saving provided by the passive model is in the heating season. There is also a small saving in cooling and HRV/fan energy. In total, the passive house model requires 39% less energy than the code model.

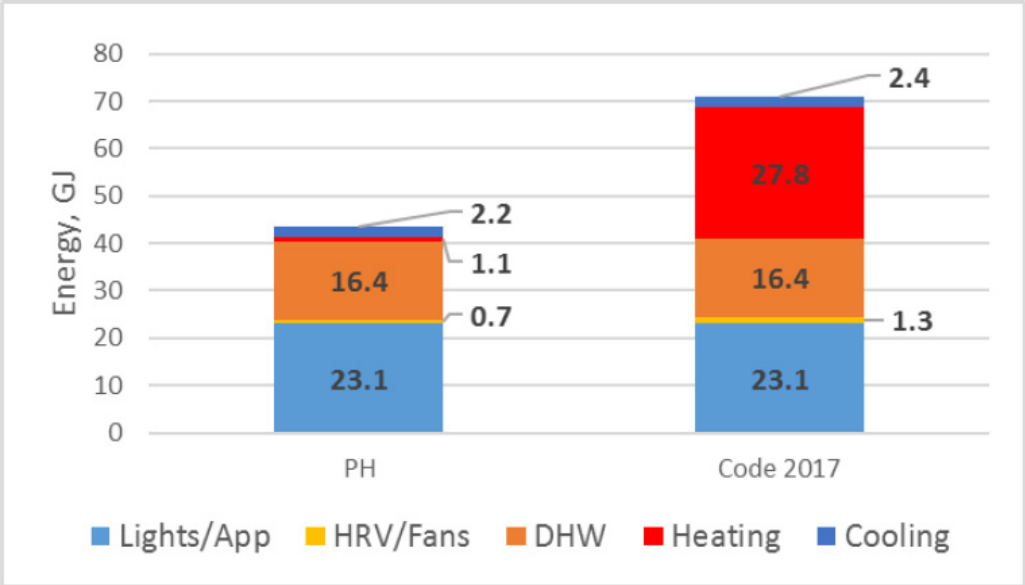

Figure 21. Annual energy consumption by device for Wolfe Island house.

The estimated greenhouse gas (GHG) emissions in the Peterborough MURB, as calculated by HOT2000, are shown in Figure 22. The passive house GHG emissions are 3.8 tonnes per year lower than those of the code model. This is a reduction of 8%.

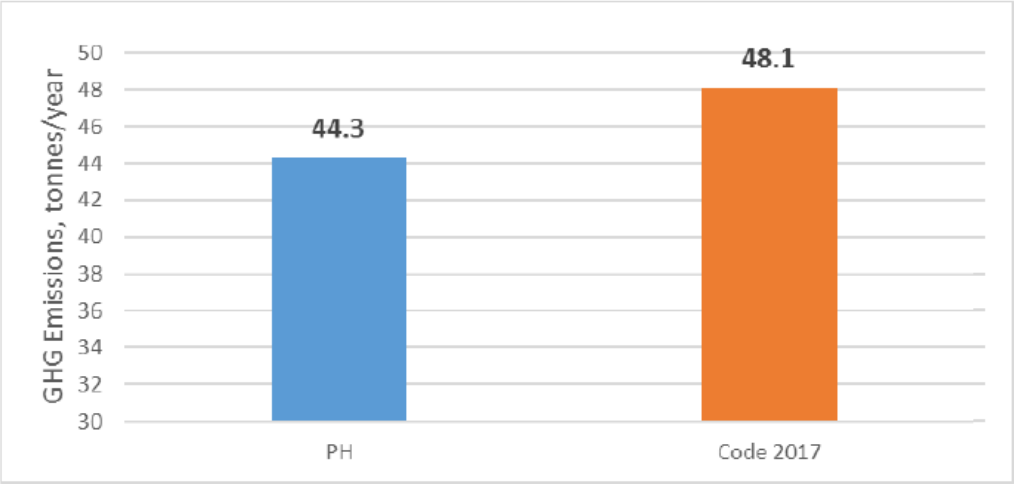

Figure 22. Estimated greenhouse gas emissions for Peterborough MURB from HOT2000 simulation.

The estimated greenhouse gas emissions, as calculated by HOT2000 in the Wolfe Island passive house, are shown in Figure 23. The passive model creates 1.0 tonnes per year less GHG emissions than the code model. This is a reduction of 39%.

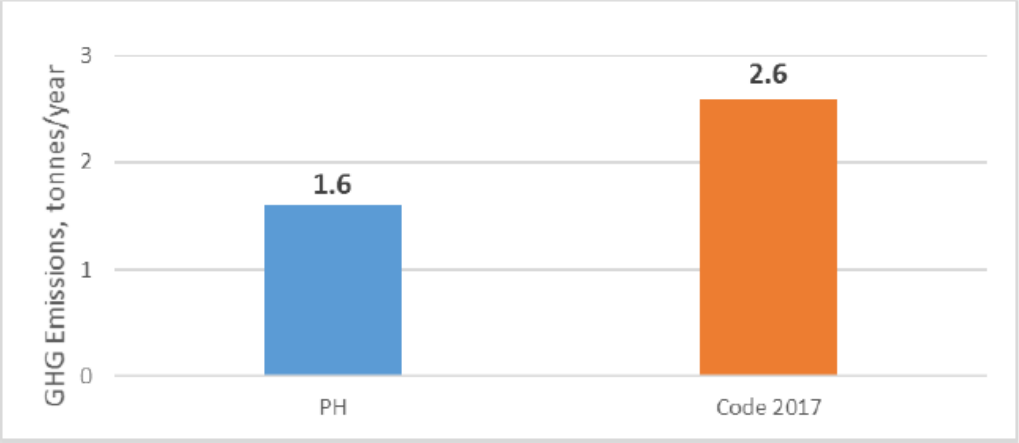

Figure 23. Estimated greenhouse gas emissions for Wolfe Island house from HOT2000 simulation.

The temperatures of the apartments in the Peterborough MURB were collected every two hours. Figure 24 demonstrates the indoor temperature of the apartments on a monthly basis. Overall, the warmest apartments are 104 (south-east) and 202 (north-east). For the months of September and October, unit 303 (south-west) is the coolest unit. Unit 302 (north-east) is cooler from November to February. Therefore, the third-floor units have a lower average temperature than the first- and second-floor units. The third floor is directly under the roof, which tends to be less insulated than the walls and floors of the building and is more exposed to wind and weather than lower floors. In winter, this can lead to significant heat loss through the roof, causing the third-floor units to be colder. Northeast-facing units receive very limited solar radiation in the winter months. The NE third-floor unit is the one with the lowest temperature. Another effect to consider is that heat naturally rises, and the third floor may have higher internal gains coming from the lower floors (the third floor SW has a higher temperature than the first floor NW). For unit 302 NE, there was a significant reduction in temperature in December as occupants had taken a long vacation before and around the Christmas holidays.

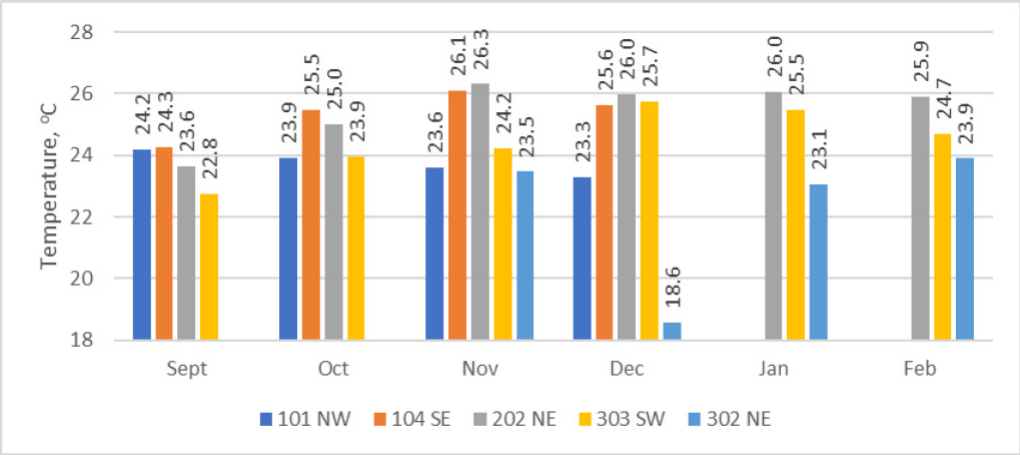

Figure 24. Apartment units: monthly average indoor temperature for Peterborough MURB.

The indoor temperature was measured at the Wolfe Island house every two hours. The temperature data are shown in Figure 25. The homeowners were just starting to occupy the house in early November. The temperature is higher upstairs than downstairs, which is expected in a typical two-storey house. The homeowners moved in full-time in mid-November. From that point until mid-February, the temperature is higher on the first floor. This is due to the kitchen, dining, and living room being located on the first floor. The homeowners would turn on the portable electric heater in the morning to warm up that local space. At the end of December, the homeowners went away for the holidays. The graph indicates that the lowest temperature was 13 °C on 29 December. The figure shows that thermal comfort was maintained the majority of the time (from the temperature perspective) when occupants were present in the house [27]. The dip in temperature in December was during their vacation. The temperature was kept below 25 °C more than 90% of the time, according to the standard [27]. As the thermal resistance of the passive building envelope is high, the temperature evolution does not experience noticeable instantaneous variations.

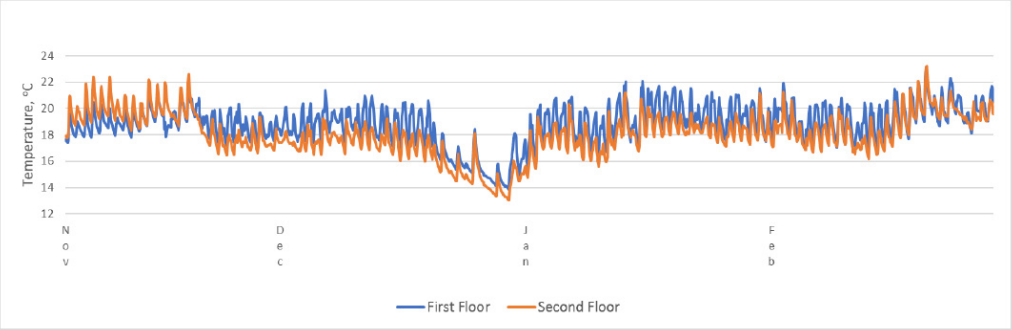

Figure 25. Indoor temperatures, first-floor and second-floor of Wolfe Island house.

6.1. Peterborough MURB Summary of Results

Energy modeling has shown that a passive house requires 99% less heating and 14% less cooling than the code model (OBC 2017 [31]). Overall, the passive house consumes 82% less energy for both heating and cooling. The total energy consumption for the entire building is 18% less than the code model. The reduction of energy cost of the passive house is 11%. The reduction in GHG emissions for the passive house model is 8%. Although the reduction in space heating is 99%, both the passive and code models utilize natural gas for domestic hot water heating. The data loggers indicate that the average indoor temperature ranges from 22.8 °C to 26.3 °C. This is comfortable and above the Ontario Building Code

requirement of 22 °C indoor temperature for heating capacity. It is worth mentioning that there are other internal and external environmental factors that influence occupant comfort. However, the current study focuses on the explicit criteria listed in the standard [27].

6.2. Wolfe Island Passive House Summary of Results

The passive house model requires 96% less heating energy and 8% less cooling energy than the code model. For both heating and cooling, the passive house model requires 90% less energy than the code model. For the total building energy consumption, the passive house model requires 39% less energy than the code model. Similarly, the cost of energy is 39% less than code because the house is 100% powered by grid electricity. Furthermore, the reduction in GHG emissions is 39%, which is directly related to the energy savings from the electrical grid. The Wolfe Island home was kept at lower average monthly temperatures ranging from 18.1 °C to 19.4 °C throughout the year. The homeowners set the thermostat to 20 °C and found the house to be very comfortable.

7. Conclusions

The current paper presents the energy analysis of two different buildings: the Peterborough MURB and the Wolfe Island house. The simulations were performed on HOT2000 and PHPP software, offering new insights into the influence of occupancy, ventilation strategies, and fuel sources on energy efficiency and greenhouse gas (GHG) emissions. The simulated results were validated against real consumption. The validation of HOT2000 and PHPP simulations against real consumption data strengthens the reliability of predictive modeling for passive house design in Canada. The main conclusions of the work are highlighted as follows:

- The Wolfe Island house offers greater total energy savings (39%) versus the Peterborough MURB (18%) when both are compared to the Ontario Building Code. This is due to the occupancy load. The Peterborough MURB has twice as many occupants per square meter as the Wolfe Island house. The house has less exterior surface area per unit volume, leading to less heat loss. The baseload and domestic hot water require a greater percentage of the total energy consumption.
- As a percentage, the Wolfe Island house has a GHG emission reduction of 39%. This is directly linked to electricity consumption because the house is 100% electric. The Peterborough MURB has a GHG emission reduction of 8%. Although the space heating from natural gas is greatly reduced, the domestic hot water is still provided by natural gas.
- The Peterborough MURB had comfortable temperatures, with average indoor temperatures ranging from 22 °C to 26 °C. The Wolfe Island house had cooler with average temperatures of around 19 °C. The homeowners did not feel any discomfort and simply turned on a small portable heater when needed. The temperatures in both buildings were within the criteria explicitly listed in the passive house standard. They were kept below 25 °C more than 90% of the time. It is worth mentioning that there are other internal and external environmental factors that influence occupant comfort. However, the current study focuses on the explicit criteria listed in the standard.
- This paper has shown the great potential of passive house buildings in terms of sustainability. It is worth noting that the results presented in this paper are specific to the building conditions under consideration.

Future passive house designs need to consider more efficient hot water solutions (e.g., heat pump water heaters, drain water heat recovery). This can contribute to better energy efficiency. In addition, the occupant comfort should be considered to avoid any overheating

problems that might occur. A non-dimensional analysis will be very important in order to reach general recommendations for passive houses.

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Nomenclature

ACH	Air changes per hour
AFUE	Annual fuel utilization efficiency
BC Step Code	British Colombia Code for energy efficiency
CLT	Cross laminated timber
EPS	Expanded polystyrene
GHG	Greenhouse gas emissions
HOT2000	Energy Efficiency Software developed by Natural Resources Canada
HRV	Heat recovery ventilator
NECB	National Energy Code of Buildings
OBC	Ontario Building code
PH	Passive house
PHPP	Passive House Planning Package
R	Thermal resistance in metric system
RSI	Thermal resistance in SI system
SHGC	Solar heat gain coefficient

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