Low Energy Monitoring Research Report

North Park Passive House, Victoria, B.C.

BC HOUSING
RESEARCH CENTRE

Acknowledgements

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Executive Summary

The Passive House concept provides a framework for high-performance buildings that is growing in popularity in Canada, and particularly on the west coast. Certification to the Passive House label requires its buildings to achieve specific performance values for heating energy use intensity, total energy use intensity, spatial temperature variation, ventilation performance and air leakage rate. The promised co-benefits of Passive Houses include thermal comfort and indoor air quality.

Passive House performance requirements are being mandated in several European Union countries and the adoption of Passive House is growing in popularity worldwide. However, the potential benefits of Passive House and other low energy design approaches are not as well understood in Canada, and there are limited data on the actual performance of low energy residential buildings in various Canadian climates.

The goal of this research project was to rigorously evaluate the real-world performance of a multi-family Passive House[1] building in British Columbia's coastal region. The main aspects that were evaluated include:

- → Moisture durability and thermal performance of the high-R-value enclosure using heat and moisture sensors;
- → Occupant comfort through both quantitative and qualitative evaluation;
- → Energy and water use;
- → Financial analysis based on utility and capital costs, and
- → Theoretical performance of the same building in representative climates across Canada.

This assessment was completed for a new spec-built, six-unit Passive House complex located in Victoria, BC, known as the North Park Passive House (North Park). The building was constructed in 2014/2015, and has been occupied since September 2015.

Enclosure Performance

This aspect of the research was intended to evaluate the hygrothermal performance of the deep-stud wall assembly with interior service wall. Primarily, the moisture durability of the exterior sheathing was of principle interest, followed by other parameters such as the impact of solar heating and inward driven moisture.

The monitoring and analysis indicates that the north facing exposures were generally wetter than the south facing ones, but all monitored locations showed drying over time, with a low risk of long term mould growth.

[1] While the Passive House Institute U.S. (PHIUS) has developed a version of Passive House adapted for US climates, many projects in North America still follow the German-developed Passive House International (PHI) certification protocol. The project evaluated in this study was designed and certified under PHI.

Thermal Comfort and Air Quality

Interior temperatures were generally within a comfortable range throughout the monitoring period. However, one suite experienced 13% of hours greater than 25° C during warm periods in the summer, and some temperatures lower than 17.5° C in the winter. Indications supported by the occupant interviews suggest that some occupants are still learning how to best operate the heating and ventilation systems, as well as when to open windows and use operable shades. This feedback indicates an opportunity to further improve both comfort conditions and energy consumption in the building.

Relative humidity was well managed at all monitored locations throughout the year.

CO_2 levels are generally very good, and occupants reported either good perceived air quality, or made no comment about air quality, suggesting that the HRV was providing acceptable air exchanges. Some spikes and variation between suites were observed, likely due to different occupancy patterns, activity levels and pet ownership.

Qualitative interviews indicated that all participating occupants were satisfied with their experience living at North Park, but learning opportunities likely still exist to improve operation and comfort.

Energy and Water Consumption

The measured, normalized annual energy consumption of the whole building was found to be 33,570 kWh, or 72 $kWh/m^2 \cdot yr$.

The modeled annual energy consumption predicted a value of 43 $kWh/m^2 \cdot yr$ for the whole building for a typical weather year. The measured, normalized consumption was therefore found to be 66% higher than the model predicted. Also, the analysis showed that the actual heating demand was close to the PHPP modeled demand, indicating that the source of divergence is in base loads (plug loads, domestic hot water, etc). In other words, occupant preferences and behaviours have a significant impact on the final energy consumption. Suite level utility data suggests a broad range in consumption between suites, further supporting this observation.

Table 0.1 below summarizes the breakdown results.

TABLE 0.1: SUMMARY OF END-USE ENERGY BREAKDOWN

	PHPP Modeled Energy		Actual Energy ($kWh/m^2 \cdot yr$)	
	kWh	$kWh/m^2 \cdot yr$	kWh	$kWh/m^2 \cdot yr$
Heating	4,130	8.8	4,690	10.0
Baseline	16,040	34.2	28,880	61.6
TOTAL	**20,170**	**43**	**33,570**	**72**

The overall building water consumption for 2016 was found to be approximately 669,000 litres. The annual usage based on the building's GFA is 1,426 litres/m^2. This includes all six suites and common areas. Water usage is also typically expressed in litres per person per day. Based on occupant interviews, it is estimated that there were 10 occupants in the building during 2016, resulting in an average daily water use of 183 litres per person.

The building was not specifically designed to be water efficient beyond good standard practice. However, water consumption is lower than the average per person consumption in Canada, which was 251 L/person in 2011[2]. This likely reflects current code requirements for low flow plumbing fixtures, in combination with a small landscaped area and minimal irrigation needs at the building.

Financial Analysis

The estimated incremental cost to upgrade a building of comparable quality to Passive House was 4.2%. Annual energy savings over a typical code compliant building were estimated to be 28,370 kWh per year, or 60 kWh/m^2.

The financial analysis suggests that based on the factors considered, the additional incremental capital cost is marginally cost effective. The NPV is slightly negative; the IRR is close to the assumed discount rate, and the discounted payback period is between 11 and 20 years. Consistent with the theoretical analysis completed previously, energy cost savings alone are therefore not sufficient to offset the additional upfront investment in the shorter term.

However, this basic financial analysis paints only part of the picture. There are several financial components that were not included in this analysis, including a perceived competitive sales price and resale value; cost offset of net metering, and ongoing savings realized after the analysis period.

This research also documented several non-monetary benefits to living at the North Park Passive House, including a high level of occupant comfort, perceived building durability, improved air quality, and the ability to live in a home that reflects one's personal values.

[2] https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=7E808512-1

1 Project Introduction

The Passive House concept provides a framework for high-performance building that is growing in popularity in Canada, and particularly on the west coast. Certification to the Passive House label requires its buildings to achieve specific performance values for heating energy use intensity, total energy use intensity, spatial temperature variation, ventilation performance and air leakage rate. The promised co-benefits of Passive Houses include superior thermal comfort and indoor air quality.

Passive House performance requirements are being mandated in several European Union countries and the adoption of Passive House is growing in popularity worldwide. However, the potential benefits of Passive House and other low energy design approaches are not as well understood in Canada, and there are limited data on the actual performance of low energy residential buildings in various Canadian climates.

The goal of this research project was to rigorously evaluate the real-world performance of a multi-family Passive House[3] building in British Columbia's coastal region. The main aspects that were evaluated include:

- Moisture durability and thermal performance of the high-R-value enclosure using heat and moisture sensors;
- Occupant comfort through both quantitative and qualitative evaluation;
- Energy and water use;
- Financial analysis based on utility and capital costs, and
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This assessment was completed for a new spec-built, six-unit Passive House complex located in Victoria, BC, known as the North Park Passive House (North Park). The building was constructed in 2014/2015, and has been occupied since September 2015.

[3] While the Passive House Institute U.S. (PHIUS) has developed a version of Passive House adapted for US climates, many projects in North America still follow the German-developed Passive House International (PHI) certification protocol. The project evaluated in this study was designed and certified under PHI.

2 Design

The North Park Passive House was developer-built on a small urban infill site within walking distance of downtown Victoria. The developer/builder's intention was to build a Passive House at a market-competitive price point in a desirable location.

2.1 Form and Layout

The building was constructed on a constrained urban site with a south facing entry. The six units are stacked on three levels side-by-side with exterior entries for all suites. As such, all suites have a south exposure at the front, a north exposure at the rear, and either west or east exposure on their long side.

Total (conditioned) floor area is 424 m^2 (4,560 ft^2). Gross Floor Area (GFA) including exterior walls is 469 m^2 (5,050 ft^2).[4] The floor plate is a simple rectangular shape, with one cut-out in the rear, as shown in *Figure 2-1* below.

Figure 2-1: Typical floor layout

Figure 2-2 below shows the roof layout. The design is complex, with dormers added in response to neighbours' preference for a "traditional" design. The complex roof shape added significant cost to the project, as well as significant heat loss. The builder reported that two-thirds of the construction cost and two-thirds of the energy losses were concentrated on the upper one-third of the building. Based on this experience, the builder has implemented simpler roof shapes on subsequent projects.

[4] "Total (conditioned) floor area" refers to the sum of the areas of all floors, measured from the interior face of the exterior walls. Definition excerpted from City of Victoria Schedule A – Definitions. Gross Floor Area is typically measured to include exterior walls.

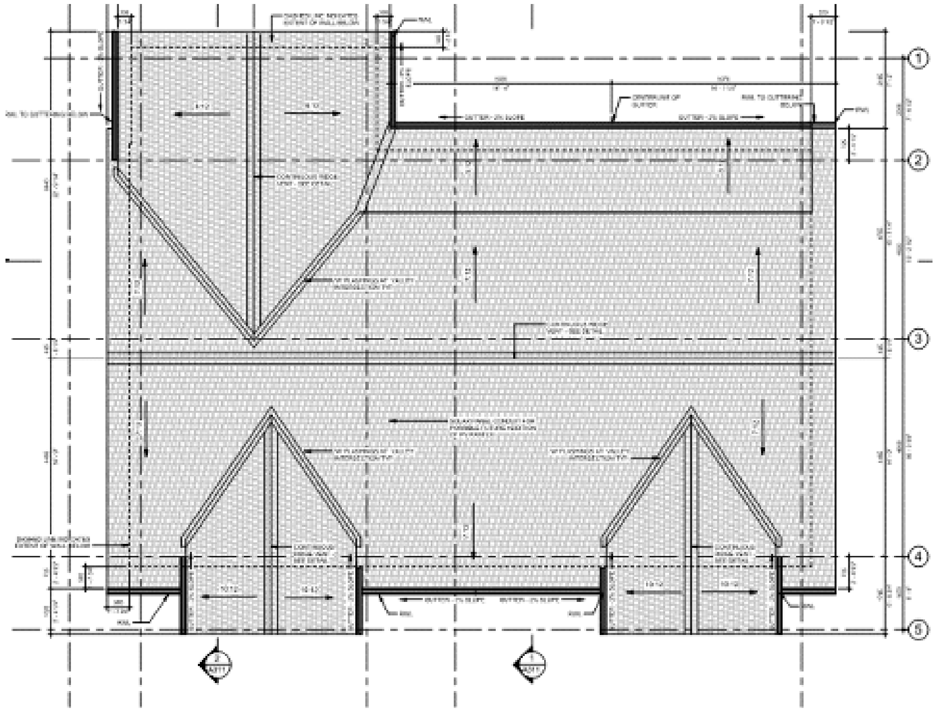


Figure 2-2: Roof Plan

2.2 Enclosure Elements

The North Park Passive House utilizes a deep stud wall system consisting of an outer 38 x 184 mm (2x8) stud wall filled with 64 kg/m^3 (4 lb/ft^3) dense pack blown-in cellulose and a 38 x 89 mm (2x4) interior service cavity filled with mineral wool batts. The effective opaque wall assembly USI-Value is 0.154 W/m^2K, or a thermal resistance of approximately RSI-6.5 (R-37). The 280 mm (11-inch) vented cathedral roof and 38 x 89 mm (2x4) service cavity are both insulated with mineral wool batts. The effective roof assembly USI-Value is 0.102 W/m^2K, or a thermal resistance of approximately RSI-9.8 (R-56).

Triple pane vinyl Passive House certified windows and patio doors are used, with installed average USI-value of 0.87 W/m^2K, or RSI-1.1 (R-6.5) (varies by dimension). Passive House certified wood entry doors have an installed USI-Value of 0.93 W/m^2K, or RSI-1.06 (R-6).

Key barriers include a sheet-applied, vapour permeable membrane applied to the exterior of the plywood sheathing and a sheet-applied air and vapour barrier installed between the 38 x 184 mm (2x8) stud wall and the interior service wall.

The east and west exposures are equipped with exterior mounted, manually operated mechanical shades.

The key building enclosure elements are described and shown in Table 2-1 below.

<table>
<tr><th colspan="2">TABLE 2-1: BUILDING ENCLOSURE ELEMENTS</th></tr>
<tr><td>Foundation: Slab on Grade with 200 mm (8”) EPS Type 2 foam; Insulated Concrete Form (ICF) foundation walls

Effective U-value basement slab: USI-0.176 W/(m²K
(RSI-5.7) (R-32)

Effective U-value foundation wall: USI-0.125 W/(m²K
(RSI-8.0) (R-45)</td><td></td></tr>
<tr><td>Exterior Above-Grade Wall: 38 x 184 mm (2x8) wood stud wall 600 mm (24”) OC, filled with 64 kg/m³ (4 lb/ft³) dense pack blown-in cellulose + 38 x 89 mm (2x4) service cavity filled with mineral wool batts.

Effective Assembly U-value: USI-0.154 W/(m²K) (RSI-6.5) (R-37)</td><td></td></tr>
</table>

TABLE 2-1: BUILDING ENCLOSURE ELEMENTS	
Roof: Insulated, vented cathedral roof with 280 mm (11”) rock wool between roof trusses + 38 x 89 mm (2x4) service cavity filled with mineral wool batts. Effective Assembly U-value: USI-0.102 W/(m^2K) (RSI-9.8) (R-56)	
Windows: Passive House certified triple glazed, argon filled vinyl windows and patio doors Installed average U-value: USI-0.87 W/(m^2K) (RSI-1.1) (R-6.5), varies by dimension Solar Heat Gain Coefficient (SHGC): 0.39	
Entry Doors: Passive House certified wood exterior glazed doors Installed U-value: USI-0.93 W/m^2K (RSI-1.1) (R-6)	

TABLE 2-1: BUILDING ENCLOSURE ELEMENTS	
Air & Vapour Barrier: SIGA Majpell on interior of deep stud wall and on interior truss framing in roof. All transitions taped with SIGA Rissan.	

2.3 Heating, Ventilation, and Solar PV Systems

The building is all-electric and is heated by in-floor electric resistance heat at each suite's entry and bath. Heating is controlled by the occupants via wall-mounted thermostats.

Ventilation is provided by a Zehnder ComfoAir 200 Heat Recovery Ventilator (HRV) in each suite. The HRVs have three operating modes (low, medium, high) that are controlled manually by the occupant. There is one main HRV control panel for the suite, plus a "boost" mode switch in the bathroom that manually boosts the fan into "high" mode for a selected time period.

Supply air is ducted from the HRV to the living room and bedrooms, and returned to the HRV from the bathroom, kitchen, and laundry closet. The range hood is recirculating and equipped with a grease and charcoal filter. Total outdoor supply air volumes to each suite, as documented in the HRV commissioning report, are generally between 0.85 m^3/min and 1.1 m^3/min (30 and 40 CFM) in low mode and up to 2.8 m^3/min (100 CFM) in high mode. The air supply has neither a pre- nor post-heater.

A 7 kW photovoltaic solar array is installed on the south facing roof, and equipped to feed into BC Hydro's grid for net metering.

The key mechanical system elements are described and shown in Table 2-2 below.

TABLE 2-2: HEATING, VENTILATION AND SOLAR PV ELEMENTS	
Passive House certified HRV; one Zehnder ComfoAir 200 unit per suite: Nominal efficiency: 92%	 
7 kW rooftop photovoltaic solar array on the south facing roof, with net metering to BC Hydro	

2.4 Plumbing and Domestic Hot Water System

Each suite has its own 3kW of a 114-liter (30 gallons) domestic hot water heater/tank.

Plumbing fixtures are as follows:

- Toilets: American Standard “Studio” LXP Dual Flush toilet, 6 LPF/4.1 LPF.
- Showerheads: Moen Rizon with 9.5 liters/min (2.5 gallons/min) flow rate
- Bath and Kitchen Sink faucets: Moen Rizon/Align with 5.7 liters/min (1.5 gallons/min) max flow rate

In-suite appliances include a dishwasher, clothes washer and ventless condensing dryer.

3 Enclosure Performance

A highly insulated enclosure is a requirement for a high-performance building such as a Passive House. The assembly type, choice of materials and their position within the assembly can all affect the long-term performance of the enclosure.

This aspect of the research was intended to evaluate the hygrothermal performance of the deep-stud wall assembly with interior service wall. Primarily, the moisture durability of the sheathing was of principle interest, followed by other parameters such as the impact of solar heating and inward driven moisture. The following factors were evaluated:

→ Durability of the exterior sheathing

→ Hygric buffering capacity of the densepack cellulose

→ Impacts of solar radiation on the hygric profiles through the assembly

→ Interior surface temperature impacts on mean radiant temperatures

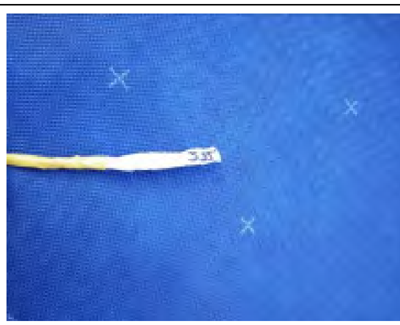
3.1 Methodology

The critical layers of the enclosure were monitored for heat and moisture (both relative humidity and moisture content) and compared with known durability metrics and empirical models.

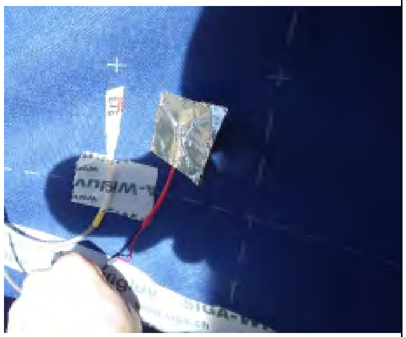
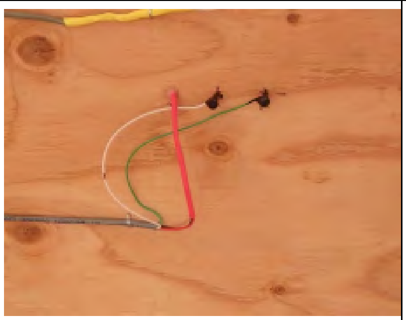
Details on the instrumentation plan and sensor locations within the building are provided below.

3.1.1 Instrumentation Plan

The wall assemblies were monitored using relative humidity sensors, electrical resistance moisture content sensors, and temperature sensors[5], as summarized in Table 3-1 below.

TABLE 3-1 – SENSOR DESCRIPTIONS AND DATA- ENCLOSURE PERFORMANCE			
Sensor Type		Description	Accuracy
Relative Humidity Sensor		Thermoset polymer capacitive sensor with onboard signal conditioning	±3.5%, from 10%–90% RH

[5] The sensors were provided by Building Science Laboratories (BSL). The data acquisition system is a laboratory research grade CR1000 data logger system provided by Campbell Scientific Instruments (CSI). BSL has extensive experience designing and providing sensor packages that work well with the CSI equipment (Schumacher, Straube, 2005).

Temperature Sensor		10k NTC glass-encapsulated thermistor, including aluminum foil spatial heat sink (RH sensor in background).	±0.2 ˚C
Moisture Content Sensor		In-situ electrical-based resistance measurements between corrosion-resistance and electrically insulated pins, including 10k NTC thermistor	± 3%, with temperature and wood species correction.

3.1.2 Wall and Roof Assembly Sensor Packages

The sensor packages for each wall assembly were designed to provide the maximum amount of information while minimizing complexity and cost. The temperature sensors are included to provide the surface temperatures that form part of the boundary condition for the respective layers. The relative humidity sensors are used to assess the impacts of the hygric performance of the dense-pack cellulose and to provide an indication of the influence of exterior cavity humidity conditions on the insulation. The sheathing moisture content was measured with a single centre-of-cavity moisture content sensor with included temperature sensor. Note that all moisture content and relative humidity sensors also include temperature sensors.

Sensor locations within the wall and roof assemblies are shown in Figure 3-1 and Figure 3-2.

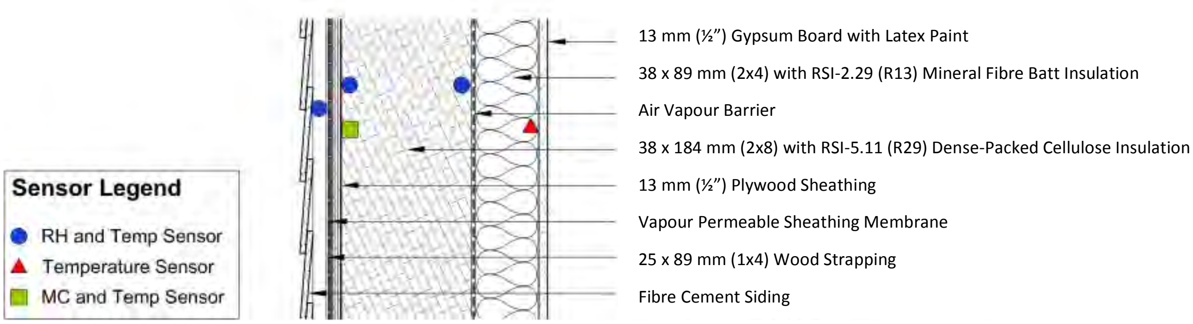


Figure 3-1 – Typical Wall Assembly Sensor Layout

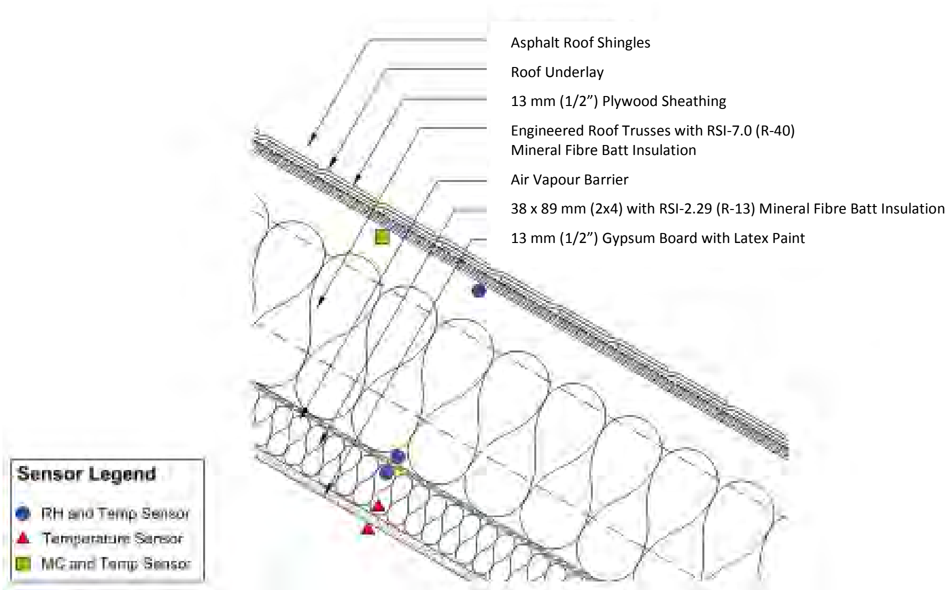


Figure 3-2 – Typical Roof Assembly Sensor Layout

Wall and Roof Instrumentation Layout

Each instrumented assembly is positioned on the north and south orientation of the building. The sensors on the south exposure are positioned near the westernmost section of the building, as shown in the floor plan and elevations in Figure 3-3 to Figure *3-5*. These locations are west of protruding balconies to capture the full impact of late afternoon sun. The sensors on the north wall are positioned at approximately the same distance from the corner and at the same height as those in the south wall. The sensor wiring was maintained in the same isothermal planes as the sensor, and was passed through into a guard bay.

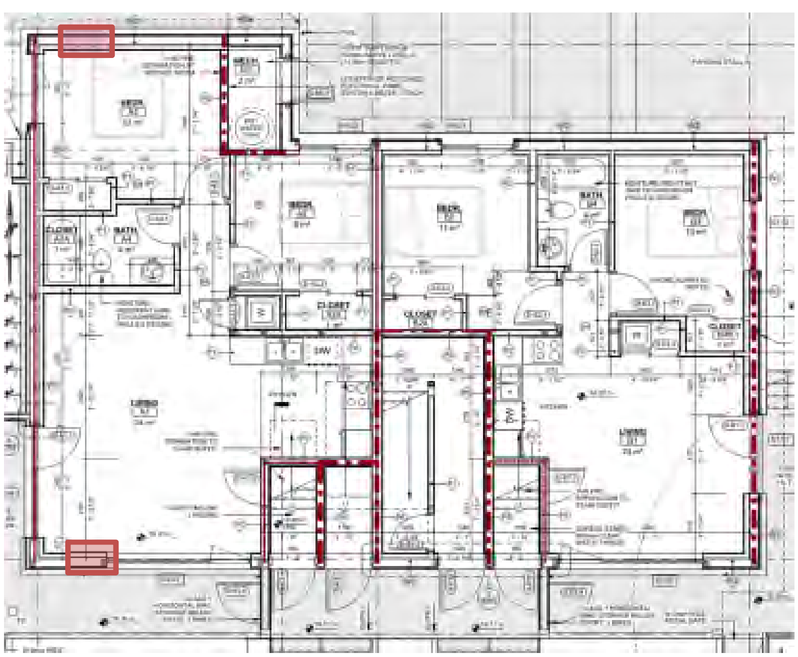


Figure 3-3 – Typical floor plan showing the location of the North and South wall sections, highlighted in red.

Figure 3-4– North and South elevations showing approximate locations for the instrumented enclosure sections.[6]

[6] The nomenclature for the assemblies follows the orientations (N or S) for the walls, followed by the floor level (2 or 3). The roofs are identified by an R and the orientation (N or S). The data acquisition system is positioned in the ground floor and is lettered by a D.

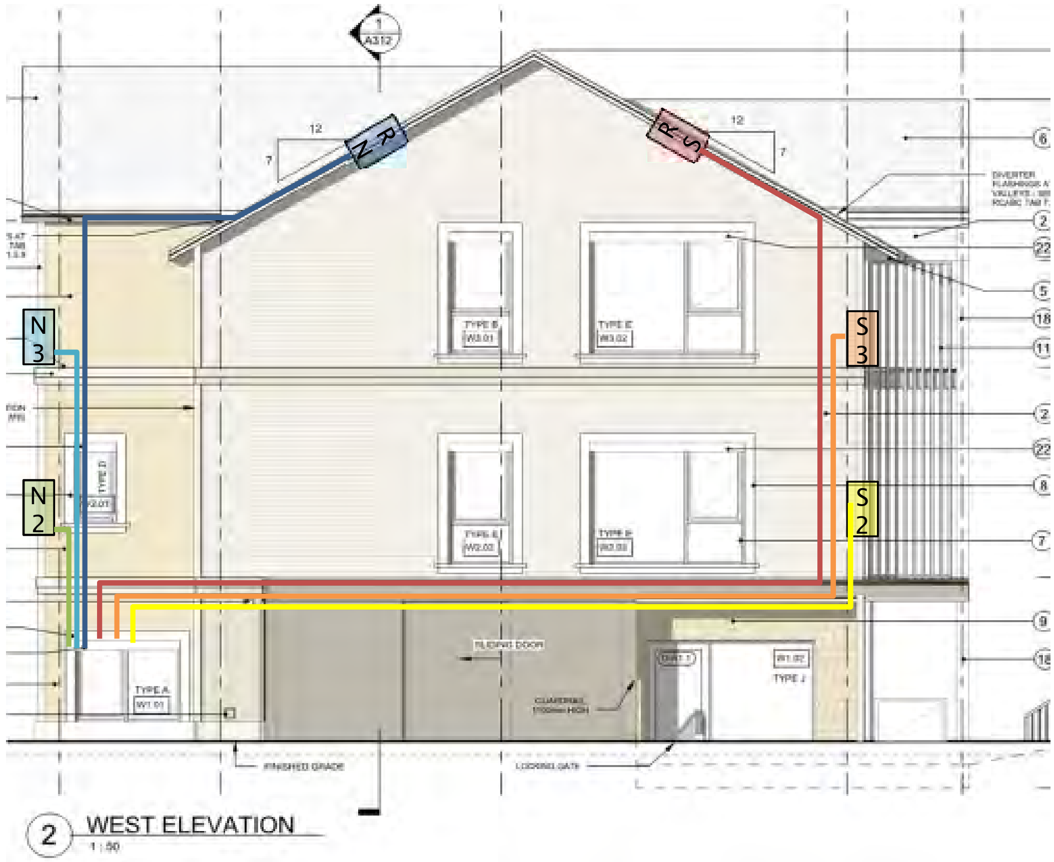


Figure 3-5 – West Elevation

A photograph of the phased sensor installation is provided in Figure 3-6.

Figure 3-6 – S2 interior relative humidity and thermistor in partial installation (awaiting insulation).

The sensors were installed into a local bus (BIX block) then routed to the central data logging systems, shown in Figure 3-7.

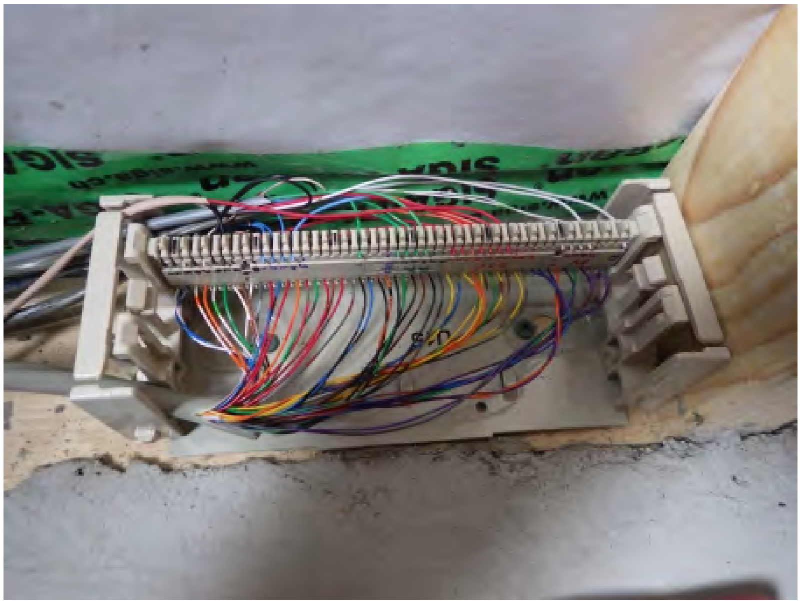


Figure 3-7 – Partially installed sensors into the local (N-2) assembly bus.

3.1.3 Data Logger

The data logger was installed in the common electrical room. The data logging system consisted of the data logger (CR1000) with a multiplexer (MUX), which permitted collection of 76 single-ended channels of data (shown **in** Figure 3-8). The data were recorded on a 5-minute basis and averaged over an hour. The internal program included the conversion from raw data unit into functional units, including any required corrections.

Figure 3-8 – Campbell Scientific CR1000 Data Logger and Multiplexer

3.2 Results

The results were aggregated into the respective study locations (N2, S2, etc) and reviewed for broad level performance behaviour. A 'study year' from January 1, 2016, to December 31st, 2016 was selected for all assessments. The critical relative humidity and temperature profiles for the four analyzed wall segments are provided in Figure 3-9 to Figure 3-12. The sheathing temperature, vapour barrier temperature, and interior drywall temperatures provide the through-wall temperature profile, and correlate proportionally to the level of insulation. The indoor dew-point can be compared to the vapour barrier and the sheathing temperatures to assess relative risk of concealed condensation and potential moisture damage. The exterior and interior relative humidity across the deep-stud wall provides a general indicator to the risk of moisture related damage. Most bacteria and fungi are unable to grow at a relative humidity below 80%.

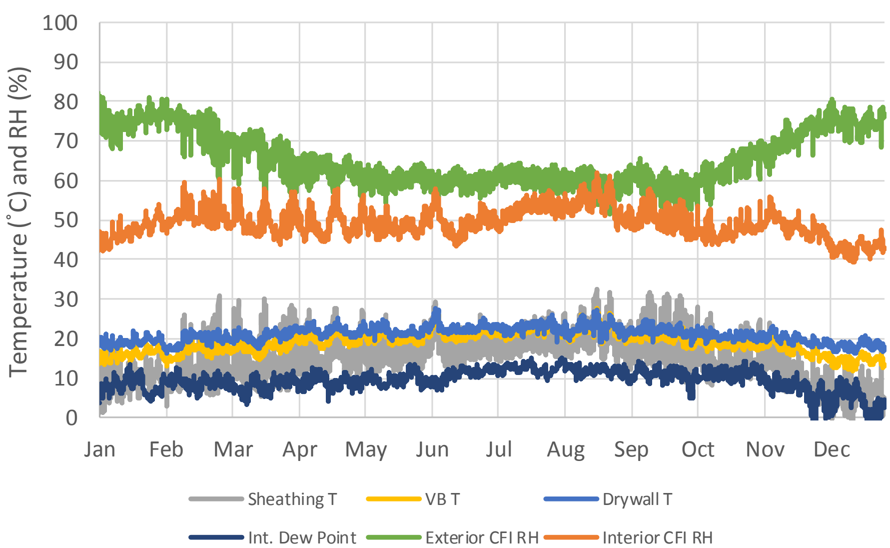


Figure 3-9 – S2 wall data for Sheathing, Vapour Barrier (VB) and Drywall temperatures, including indoor air dewpoint temperature, and the relative humidity for the outer and inner cellulose fibre insulation (CFI), from January to December 2016.

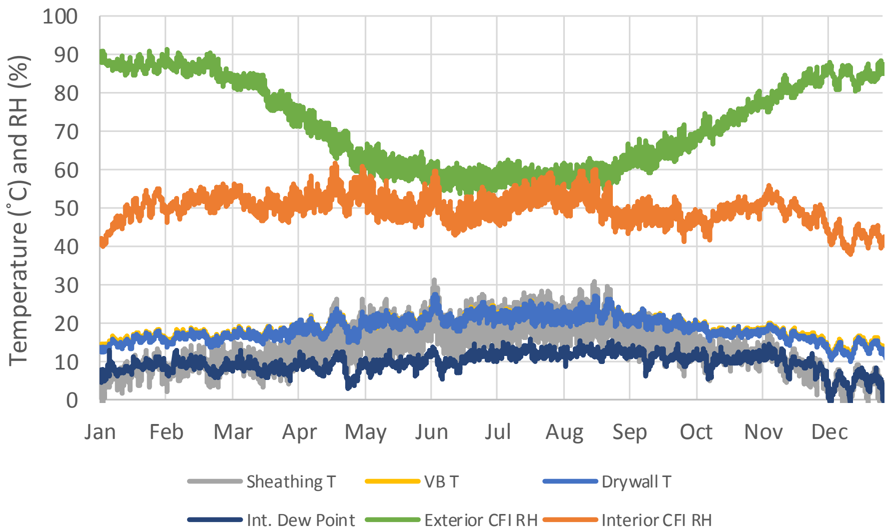


Figure 3-10 – N2 wall data for Sheathing, Vapour Barrier (VB) and Drywall temperatures, including indoor air dewpoint temperature, and the exterior/sheathing and interior cellulose fibre insulation relative humidity from January to December 2016.

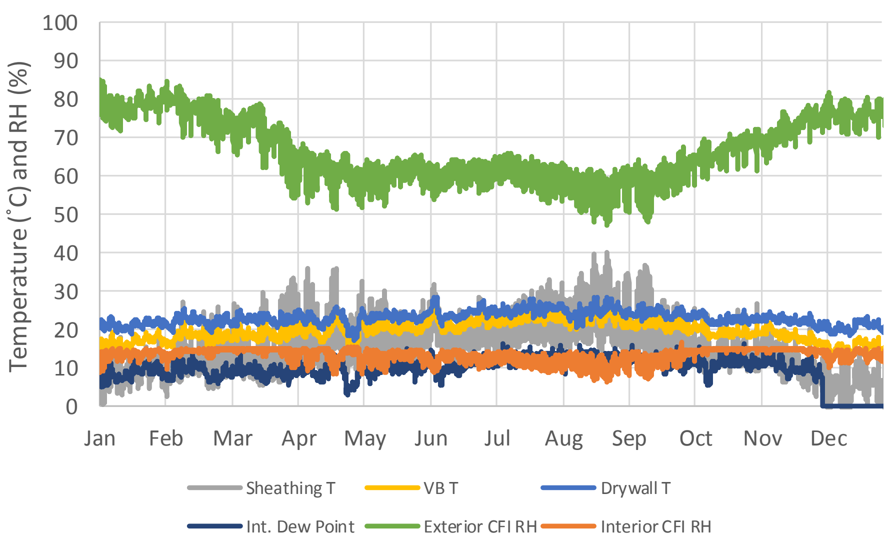


Figure 3-11 – S3 wall data for Sheathing, Vapour Barrier (VB) and Drywall temperatures, including indoor air dewpoint temperature, and the exterior/sheathing and interior cellulose fibre insulation (CFI) relative humidity from January to December, 2016. Note Interior CFI RH may have had a split in the protective coating that encapsulates the sensor, which could permit the blown-in cellulose for affecting sensor readings.

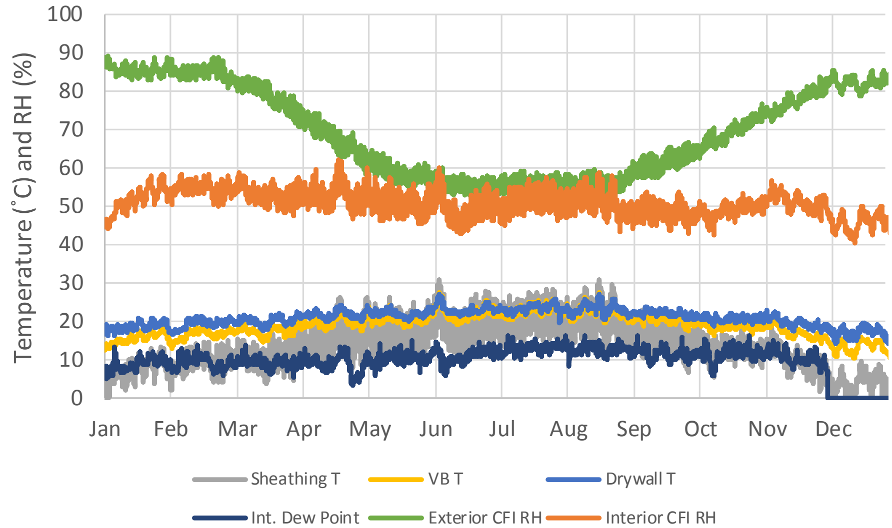


Figure 3-12 – N3 wall data for Sheathing, Vapour Barrier (VB) and Drywall temperatures, including indoor air dewpoint temperature, and the exterior/sheathing and interior cellulose fibre insulation (CFI) relative humidity from January to December 2016.

A key observation is that the temperature of the vapour barrier remains above the interior dew-point temperature at all times throughout the year. As indicated by the contractor, the insulation ratio on either side of the vapour barrier was designed based on dew-point design method, confirming that it appears to be valid.

A comparison between the South and North walls shows that the relative humidity on the inside of the cellulose insulation is higher in the North walls, but that the exterior layer of the cellulose insulation is susceptible to high spikes in the South walls. These observations hint at the effects of inward driven moisture (e.g. moisture driven through the plywood sheathing by high vapour pressures) and to the general drying effect of a warmer south elevation (i.e. with dryer cellulose insulation on the South orientation). By investigating the water vapour pressure across vapour absorbing or retarding materials (e.g. the plywood, cellulose, or vapour barrier) the direction of drying can be identified. The vapour pressure for the interior and exterior relative humidity sensors on either side of the cellulose insulation are shown in Figure 3-13. The plot shows the gradient, with negative values showing an *inward* flow, and positive values as *outward* flowing moisture.

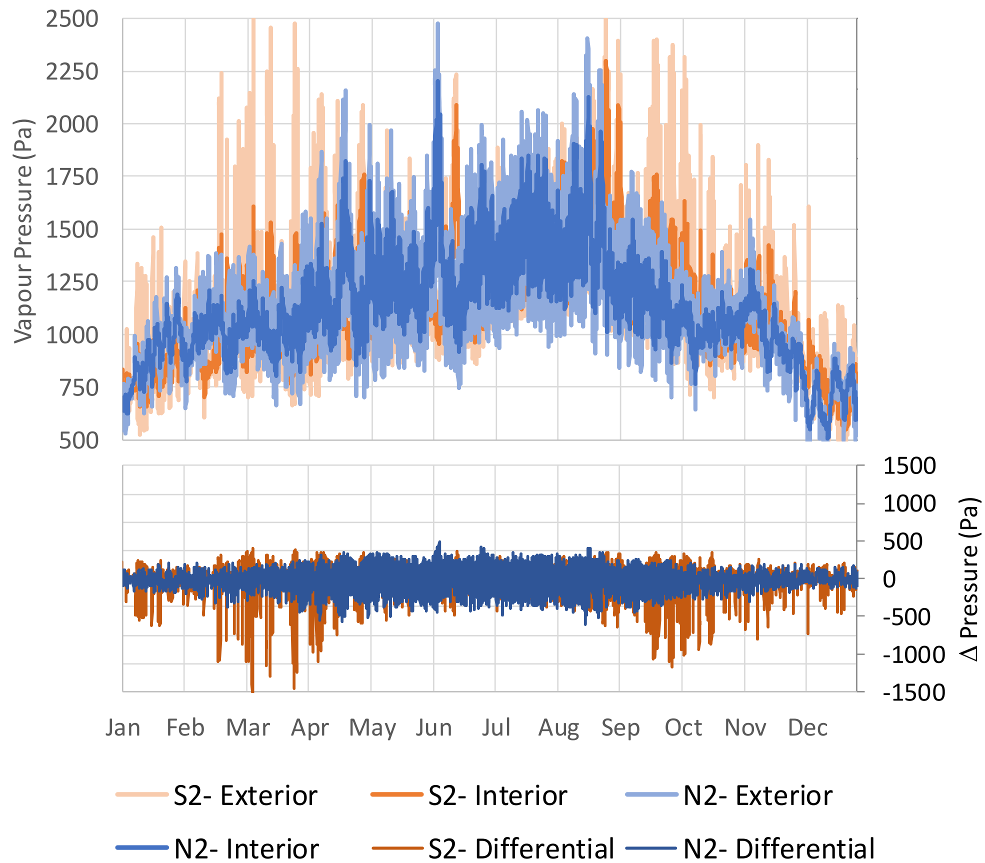


Figure 3-13 – Cellulose Insulation Vapour Pressure and Vapour Pressure Gradients, for North and South Walls on Level 2.

The south walls experience significantly higher vapour pressure peaks than do the north walls. This also translates to higher peak vapour pressures on the interior side of the cellulose insulation, though appreciably abated by the moisture storing capacity of the insulation. Review of the pressure gradients provides an indication of direction of drying. In the winter, the south orientation appears to have strong inward vapour gradients. These correspond to wetting events followed by sunny periods, which create high vapour pressure differentials forcing water through the sheathing and into the cellulose insulation. The North elevation also tends to a neutral pressure gradient, with a slight diurnal variation likely caused by temperature differences. These drying and wetting patterns affect the plywood sheathing moisture levels, and consequently the durability of the assembly.

A review of the sheathing temperature shows similar behaviour as previously identified: higher average and peak temperatures on the South elevation than on the North. Local temperature and relative humidity can have an appreciable impact on the sheathing moisture content, and thus its inherent durability. A plot of the sheathing moisture content for both the North and South orientation is provided in Figure 3-14.

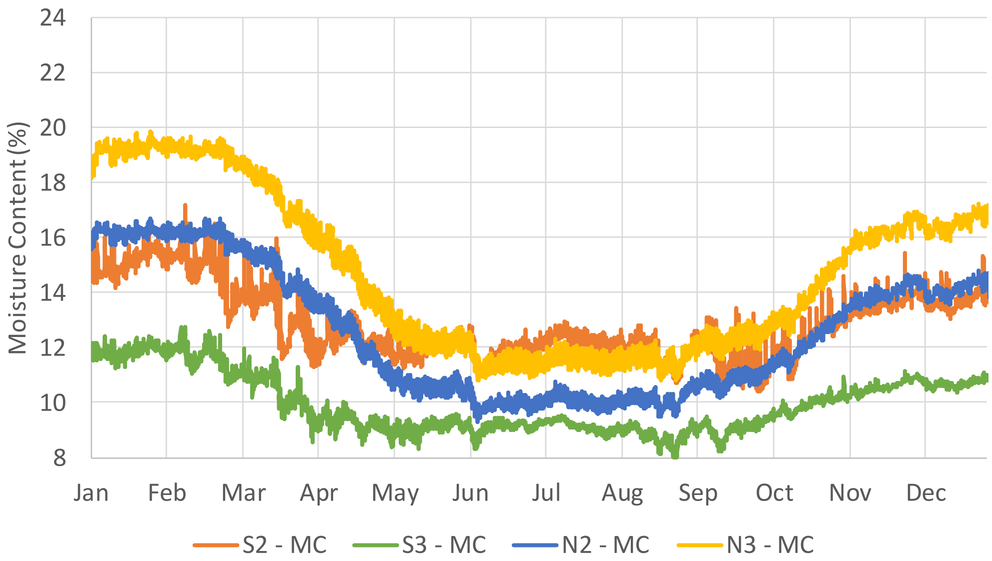


Figure 3-14 – Sheathing moisture content for north and south walls, on floors 2 and 3.

Peak sheathing moisture contents are prevalent on the South orientation in the Winter and swing seasons but are dampened in the summer as a result of solar angles and shading from nearby deciduous trees. The sheathing moisture contents are also generally reduced on the South orientation than the North, due to higher temperatures which permit increased drying. An exception to this is the S2 assembly, which may experience greater run-off than the S3 wall, which may yield greater solar vapour drives. The recommended limit for sheathing moisture content is 20% MC; the lowest threshold for mould growth is around 16% MC whereas rot is known to occur when the plywood reaches the fibre saturation point, at around 25-28% MC. The sheathing moisture content therefore does not appear to be at risk of rot.

3.3 Discussion

There are multiple methods to evaluate the durability of wall assemblies. As the main risk of deterioration to this wall is fungal growth, the use of a calibrated mould model was used. This model is based on the work of the Finnish Forest Products Laboratory (VTT), which describes a mould index as a function of fluctuating temperature, relative humidity and substrate type. The ratings for the mould index are provided in Table 3-2.

Table 3-2 – Mould Index Score and Description (Ojanen et al. 2010)[7]

Index	Description of Growth Rate
0	No growth
1	Small amounts of mold on surface (microscope), initial stages of local growth
2	Several local mold growth colonies on surface (microscope)
3	Visual findings of mold on surface, < 10% coverage, or **< 50% coverage of mold (microscope)**
4	Visual findings of mold on surface, 10%–50% coverage, or **> 50% coverage of mold (microscope)**
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

[7] Ojanen, T. et al., 2010. Mold Growth Modeling of Building Structures Using Sensitivity Classes of Materials. *Thermal Performance of the Exterior Envelopes of Buildings XI.*

A mould index of less than 1 would therefore be deemed acceptable, as this constitutes only microscopic levels of mould which are not likely to generate spores that can affect human health. By incorporating the temperature and relative humidity data and assuming pristine plywood (mould growth index of 0), Figure 3-15 was produced.

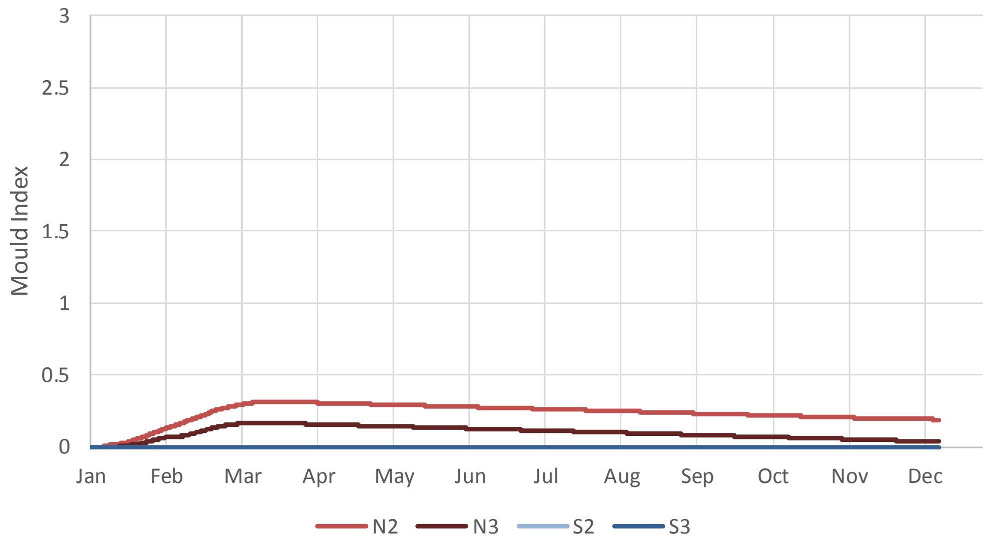


Figure 3-15 – VTT Mould Index for N2, N3, S2, and S3 walls

Both the 2nd and 3rd storey south walls were unable to grow any mould from a lack of moisture. However, the North walls were sufficiently cool and humid that in theory, microscopic mould growth could occur. Over the 1 year monitoring period, a slight increase in predicted microscopic growth was calculated in the spring season as the humidity increased concurrently with temperatures suitable for mould growth. Despite the N3 wall having a higher moisture content, the combination of temperature and cellulose relative humidity were sufficiently high that the N3 wall appears to have a marginally higher mould index. The summers were sufficiently dry that the plywood sheathing dried out and the mould went into stasis in both northern wall assemblies. This simulation assumes that the original mould growth is zero, so to determine the maximum mould growth condition, the model was run iteratively until the starting and final mould indices for the modeled year were approximately equal. The results, including the number of iterations (i.e. years), are provided in Figure 3-16.

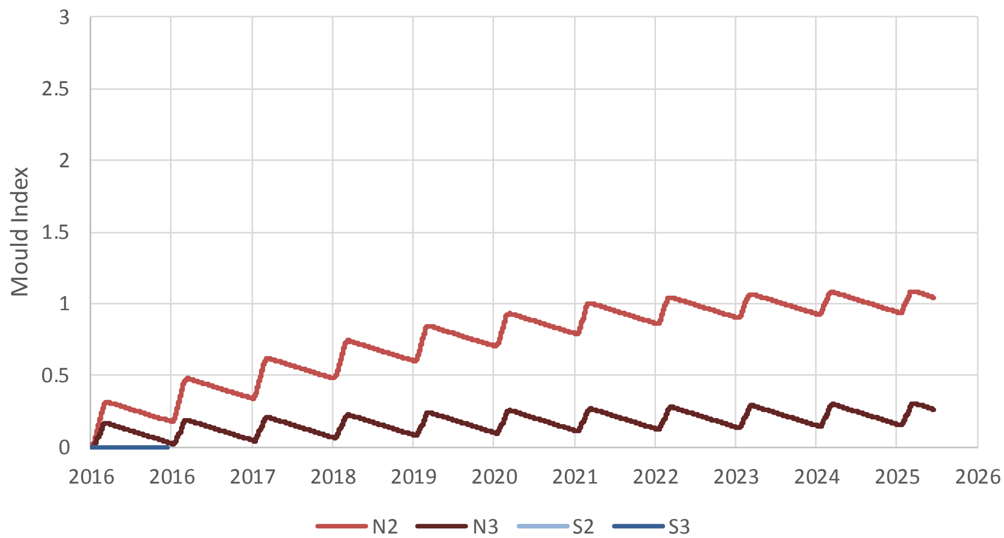


Figure 3-16 – Maximum Supportable Mould Conditions for North and South Walls on the 2nd and 3rd Storeys

The iterative simulations suggest that after about a decade, a steady state condition with a mould grow index of around 1 could be anticipated, provided the assumption that each year is approximately identical to the measured year holds. This would suggest that localized initial stages of growth may be found microscopically, but would not pose a durability risk to the structure. Risks to human health would also be limited, as the air barrier system of a passive house is rigorously tested and would thus significantly inhibit any spore or fungal cell laden air movement across the air barrier assembly.

A strategy to help further minimize this risk of mould growth is to keep the sheathing slightly warmer. The slight temperature increase of the South elevation was sufficient to have virtually zero risk of mould growth, and a similar effect could be replicated by adding insulation to the exterior of the sheathing. This was investigated and supported in a research paper by Smegal et al. (2016)[8].

3.3.1 Air Leakage Testing

Air Leakage testing of the building was a requirement of achieving Passive House Certification. This test measures the efficacy of the air barrier system and is indicative of the air leakage of the completed building. The testing methodology generally complied with standard CGSB 149.10-M86, with air volume calculated to Passive House requirements. The building was tested as a single volume, with testing conducted under both pressurization and depressurization (not required by ASTM or CGSB, but required for Passive House certification), with the average of both tests determining the air change rate at 50 Pa (ACH_{50}).

Two blower doors were used and controlled centrally to pressurize the building. The easternmost door leading to unit 301 was connected to four additional suites through wall openings that were sufficiently large to not restrict air flow. Pressure measurements

8 Smegal, Jonathan, Robert Lepage, and Chris Schumacher. 2016. “Moisture-Related Durability of In-Service High-R Wall Assemblies in Pacific Northwest Climates.” In Thermal Performance of the Exterior Envelopes of Whole Buildings XIII International.

across the suites were conducted to ensure uniformity of the pressure field. The westernmost door was used to pressurize unit 201. Stair configuration and firewalls made wall openings infeasible for this unit, so a parallel pressurization approach with two fans was employed.

The maximum allowable air leakage rate to achieve Passive House certification is 0.6 $ACH_{50.}$ As a point of comparison, the BC Step Code for Part 9 buildings targets 2.5 ACH_{50} as its 'Step 3 – 20% Beyond Code' target and 1.0 ACH_{50} as its most stringent Step 5 target[9]. The Canadian Home Builders Association's Net Zero Ready Home program requires a maximum of 1.5 ACH_{50}, so the Passive House target is much more aggressive than most other residential building standards or codes to date.

The results of the air leakage test are summarized in Table 3.3 below.

TABLE 3.3 AIR LEAKAGE TEST RESULTS	
Air Changes per Hour, ACH_{50}, depressurization	0.47
Air Changes per Hour, ACH_{50}, pressurization	0.58
Average ACH_{50}	0.53

The average equivalent leakage area (ELA) at 10 Pa is 206 cm^2 for the whole building, which in visual terms can be represented by a square with approximate dimensions of 14 cm by 14 cm.

[9] Stretch Code Implementation Working Group: Energy Step Code Implementation Recommendations Final Report, August 2016. http://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/construction-industry/building-codes-and-standards/reports/step_code_sciwg_report_final.pdf

4 Occupant Comfort and Air Quality

The Passive House certification path has several criteria for minimum acceptable interior conditions. An evaluation of both adherence to the quantitative Passive House comfort requirements and of the occupants' qualitative experience were included in this part of the research.

4.1 Quantitative Evaluation

The quantitative evaluation for comfort was based on temperature, relative humidity, and carbon dioxide readings of the indoor spaces of two units at North Park. The interior measurements form part of the larger data logging efforts for this research project. The requirements for comfort are cross referenced with the Passive House Institute (PHI) standard requirements and with ASHRAE-55: *Thermal Environmental Conditions for Human Occupancy*.

4.1.1 Methodology

The metrics for indoor air quality and comfort included ambient air temperature, relative humidity, and Carbon Dioxide (CO_2). Additional comfort metrics included analogues to the mean radiant temperature, as measured by the surface temperature of the drywall.

The CO_2 sensor details are provided in Table 4-1. The temperature and RH sensors were the same as those used within the building enclosure and are described in Section 3.1.1.

TABLE 4-1 – SENSOR DESCRIPTION			
Sensor Type		Description	Accuracy
CO2	 (from co2meter.com)	Carbon dioxide sensor (COZIR 2K)	±50ppm or ±3%

The temperature, RH, and CO_2 sensors were installed in a hollowed out smoke detector on the underside of the ceiling in the two critical locations for the suites: the living room and the master bedroom. The locations are shown in Figure 4-1.

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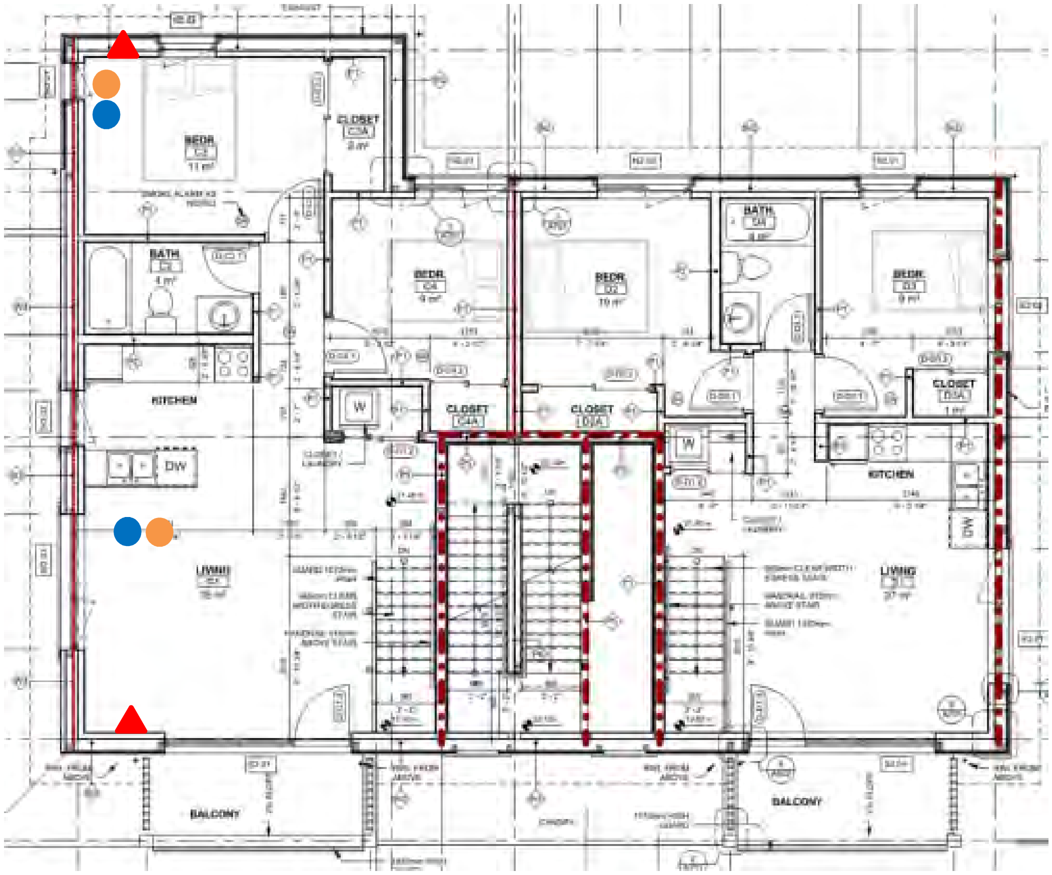

Figure 4-1 – Typical floor plan showing the approximate locations for surface temperature sensors and indoor air quality sensors.

Surface Temperature Sensor

Relative Humidity and Temperature Sensor

CO_2 Sensor

4.1.2 Results

The hourly temperatures for the living room and bedroom for Suite A and Suite B are provided in *Figure 4-2*.[10] The living rooms all have southern exposures, while the bedrooms face north.

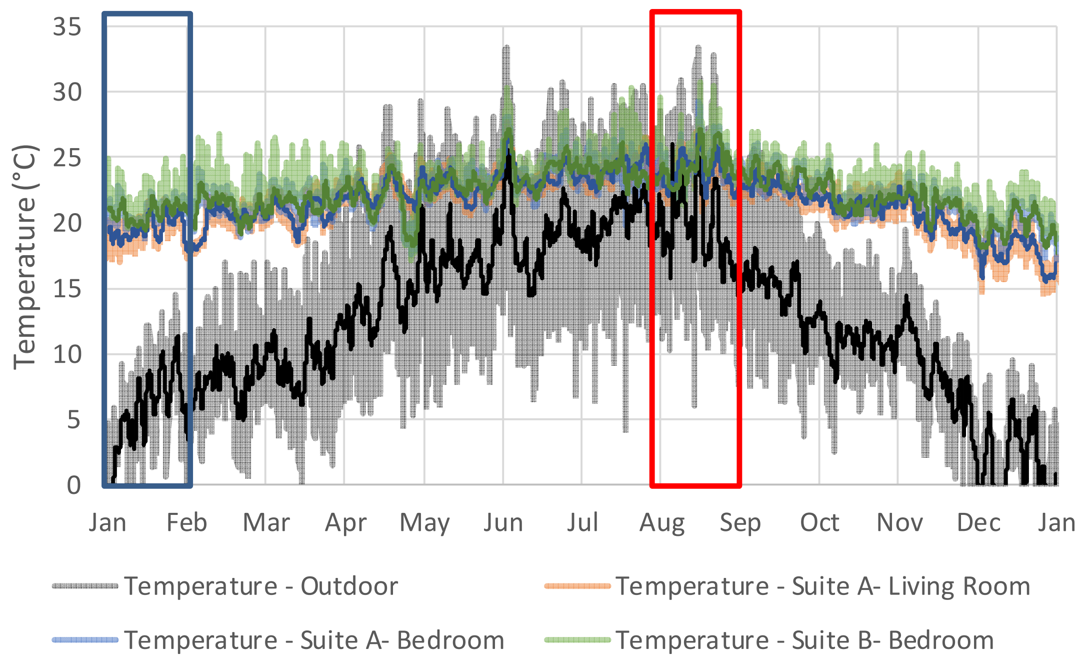

Figure 4-2 – Hourly Interior Temperature Living Room in Suite A and B, and Bedroom in Suite A, including Outdoor Temperature for Reference with 24-hr Running Average in Bold.

In general, the interior conditions remain close to the designed 20°C target. The two boxed areas of *Figure 4-2* above, one blue and the other red, representing a typical cold month (January) and hot month (August), are enlarged in *Figure 4-3* and *Figure 4-4*, respectively.

[10] Due to instrumentation problems, the indoor IAQ package for Suite B Living Room could not be used.

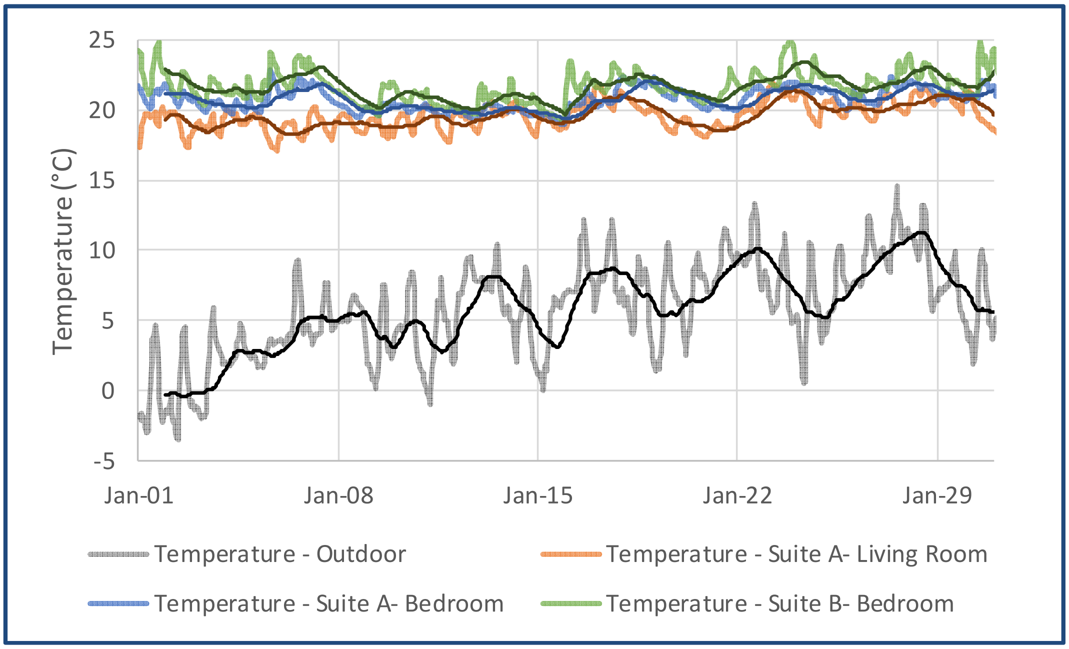

Figure 4-3 – January Hourly Temperatures, with 24-hr Running Average in Bold.

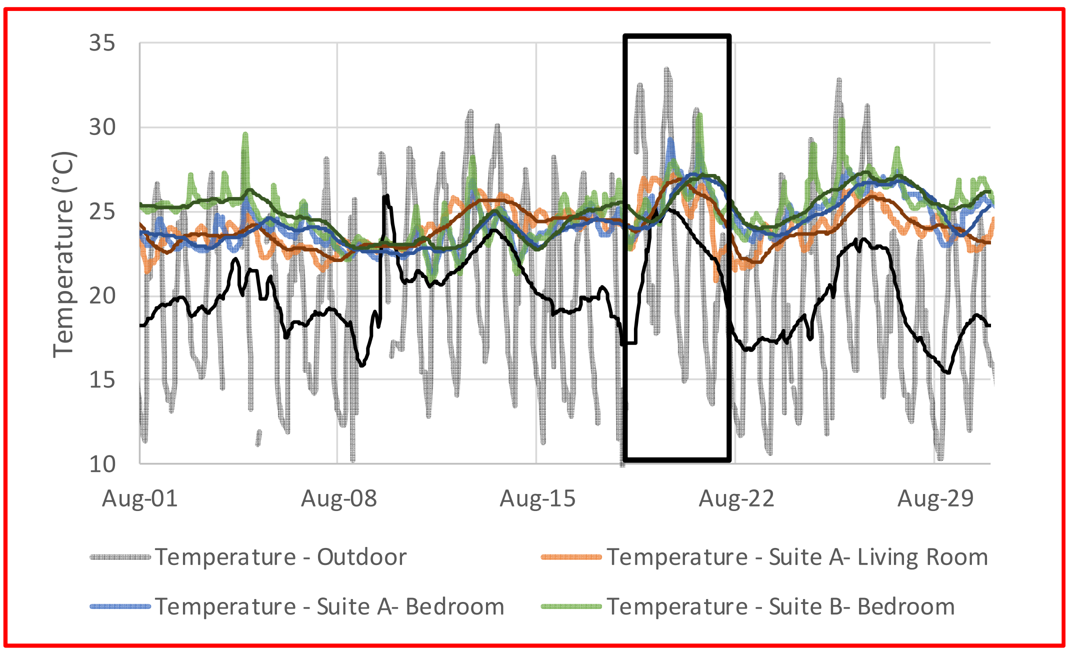

Figure 4-4 – August Hourly Temperatures, with 24-hr Running Average in Bold.

A review of the month of August indicates several hours that exceed the 25°C upper limit for interior temperatures recommended by the PHPP design tool. A 3-day break-down is for the warmest period in August, including outdoor temperature, is provided in *Figure 4-5* below.

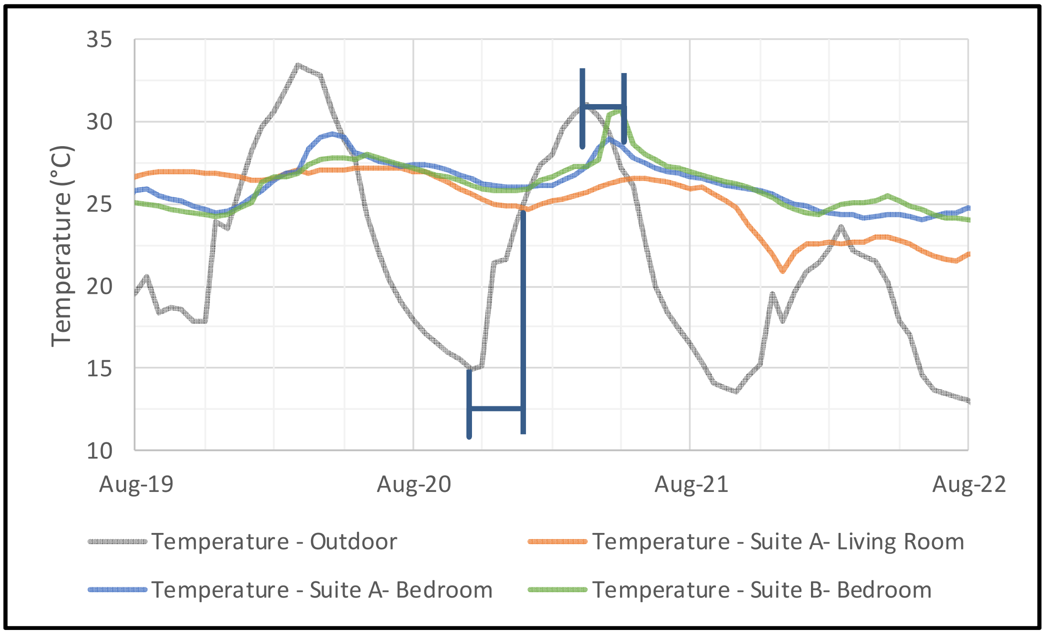

Figure 4-5 – Warmest 3-Day Hourly Temperature Conditions for August, 2016. The timelapse between peaks is approximately 6-hrs, with a faster response exhibited in the bedrooms, possibly due to operable window use.

A review of these conditions shows that elevated interior temperatures track elevated exterior temperatures. However, as the nightly outdoor temperature falls, so too does the interior temperature.

To show the range in temperatures, a series of monthly boxplots were prepared to help analyse the results (*Figure 4-6* and *Figure 4-7*). The solid box represents the 25% to 75% percentile, with the "whiskers" representing the 5% and 95% conditions; the line connects to the 50% mean. The hourly outliers are represented by coloured circles.

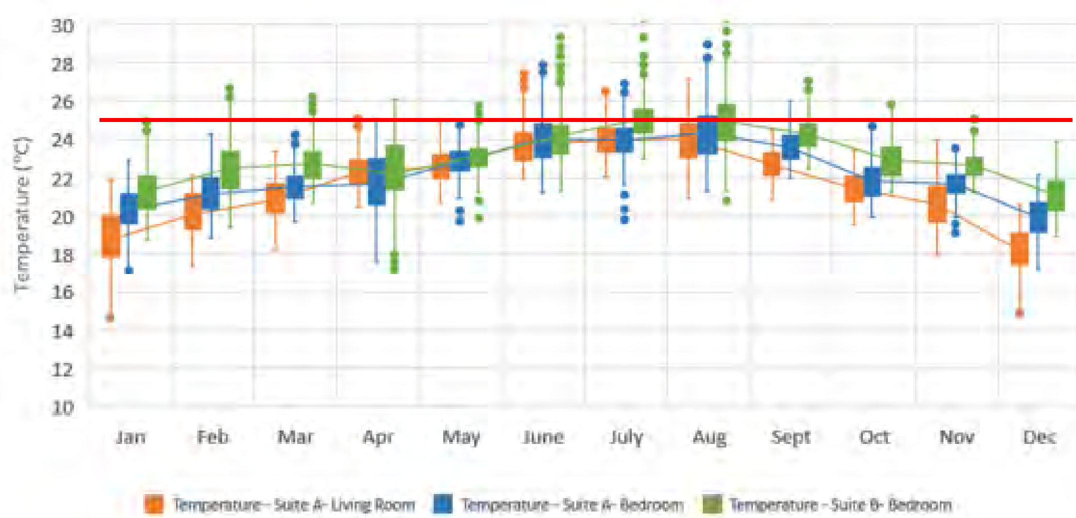

Figure 4-6 – Monthly Temperature Boxplots. The 25°C Threshold Line is Shown in Red.

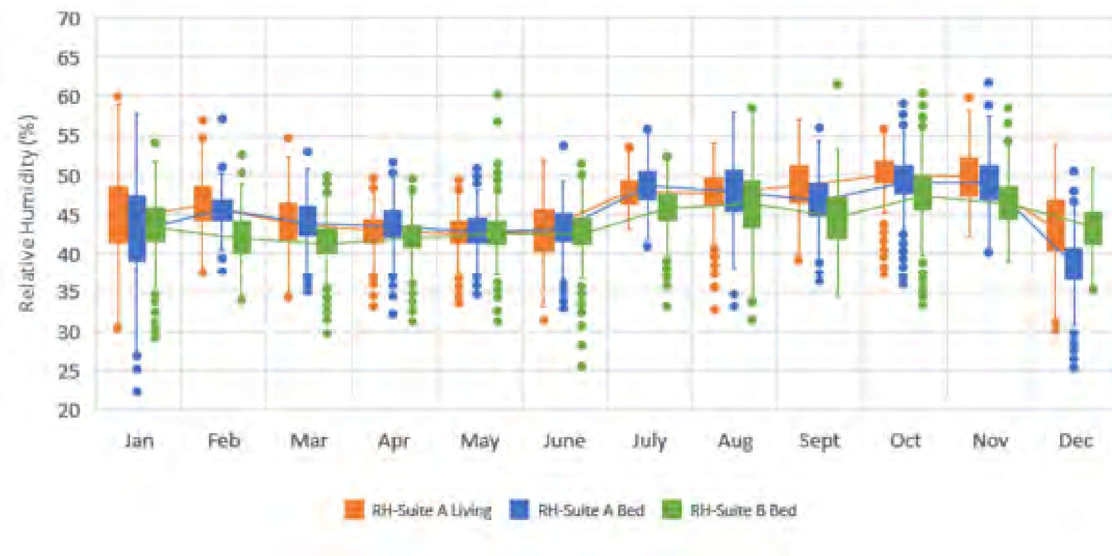

Figure 4-7 – Monthly Relative Humidity Boxplots.

The average monthly temperatures in the bedrooms appear to be higher than the living room/kitchen throughout the year, but for most of the year, are not statistically different. A distinctive seasonal trend, which would be expected for a building with a strong passive heating aspects, is also apparent. The relative humidity appears to be well controlled and falls below 50% for most of the year, which helps minimize risks of moisture related damage to the building enclosure. It also suggests effective air exchange from the HRV.

Similar to what the hourly data suggests, there are a statistically significant number of hours in which the indoor temperatures exceed 25°C. To demonstrate the number of hours in a year that exceed the threshold, a cumulative distribution with the number of hours exceeding a given temperature is shown in *Figure 4-8*.

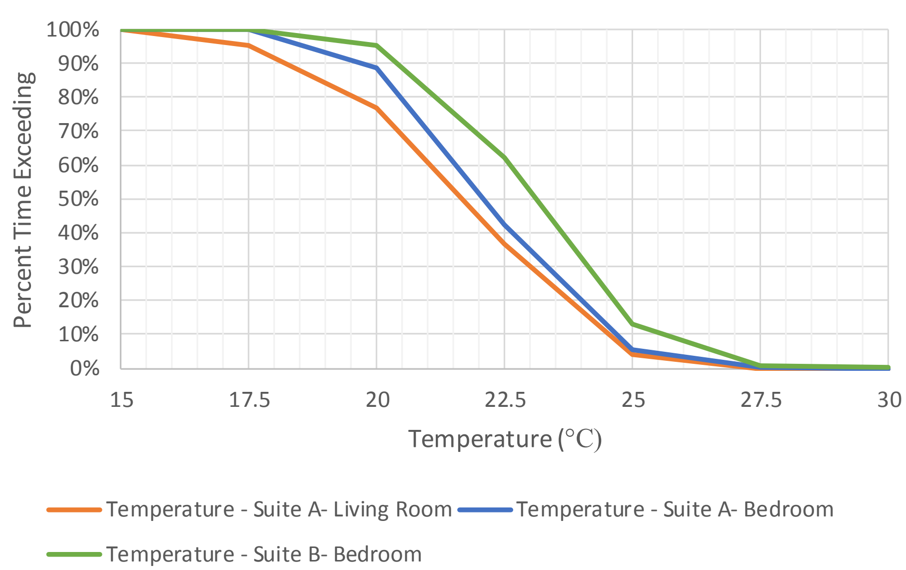

Figure 4-8 – Cumulative Distribution Plot of Percent Hours Exceeding Limiting Temperatures

For most of the year, the interior temperatures did not dip below 20°C and did not exceed 25°C.

However, in the bedroom of suite B, approximately 13% of the total hours in the year exceeded 25°C, while both monitored rooms in Suite A did not experience much more than 6% of total annual hours in this range. The Passive House criteria is that no more than 10% of total hours are greater than 25°C.

During the heating season, the living room of suite A experienced about 5% of hours below 17.5°C. These variations may be indicative of occupant preference, or potentially an ongoing learning curve to optimize operation of the suites' heating, ventilation system, and/or exterior shading devices.

Carbon Dioxide

Carbon dioxide is used as a general indicator of the quality of the interior air. While it is not considered to be toxic to humans (occupational exposure limit to not exceed 5,000 ppm daily average), higher levels of CO_2 do correlate with undesirable indoor air quality. The hourly CO_2 are plotted for the interior air monitoring packages, shown in *Figure 4-9*. The hourly data were corrected for CO_2 sensor slope error by regressing against the minimum 24-hr reading throughout the year and then applying a linear translation correction to meet a 400 ppm outdoor level.

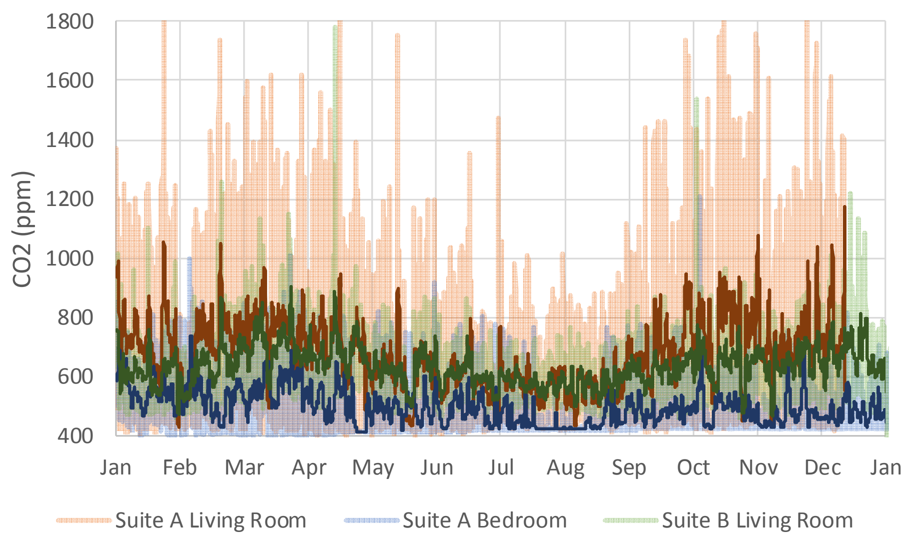

Figure 4-9 – Hourly CO_2 Readings in Living Rooms in Suite A and Bedrooms in Suite A and B, with Running 24hr- Average in Bold.

- Short term spikes exceeding 1400 ppm are not uncommon, particularly in the living room where the occupants' use of space can raise interior CO_2 levels, but the 24-hr running average appears to maintain conditions below 800 ppm. The large difference in peaks to valleys appears to be a result of the HRV providing fresh air to the interior space once the CO_2 source has been removed or the HRV flow being manually increased. Due to the high-performance enclosure, proximity to potential ducts is not believed to cause undue influence on readings. The cumulative plot of the percent time that the interior CO_2 levels exceed the threshold is shown in *Figure 4-10*.

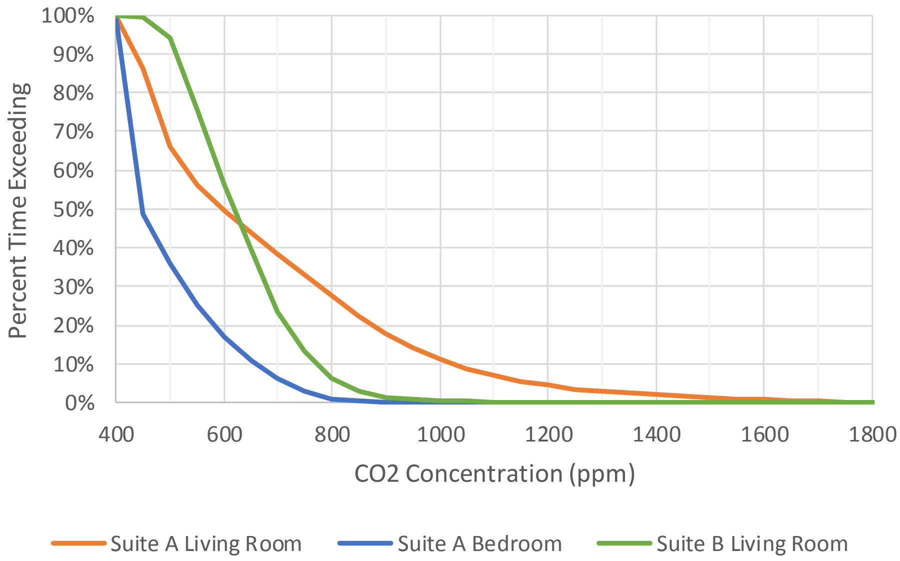

Figure 4-10 – Percent Hours Exceeding Limiting CO_2 Values.

The CO_2 levels in Suite A's bedroom and Suite B's living room fall below 800 ppm more than 95% of the time. The CO_2 level in Suite A's living room rises above 800 ppm about 27% of the time. While CO_2 is a good indicator of occupant use and air quality, qualitative data provided by occupants supplements the CO_2 data with their experiences and patterns living in the space. Occupant interviews indicate a significant range in occupancy pattern and pet ownership between Suite A and B, which likely accounts for the observed differences. Factors such as whether the bedroom door is kept open overnight could also impact these results.

Mean Radiant Temperatures

Mean radiant temperatures combine air temperature with the effect of surface temperatures radiating to the body, and are considered to provide a more complete indicator of occupant comfort. Location of the radiating bodies as well as blocking materials, such as clothing, can affect the functional mean radiant temperature. The prescriptive requirement of the Passive House Standard is that interior surface temperatures shall not be greater than 4.2°C below ambient[11]. Using the drywall thermistor data from the monitored wall assemblies, a plot of the interior surface temperature was created, shown in *Figure 4-11*. The secondary y-axis shows the difference between the wall surface temperature and the ambient air. Despite the location of the air temperature sensors being situated near the ceiling, the high-performance enclosure would minimize stratification effects.

[11] Passive House, EnergPHit, and PHI Low Energy Building Standard, version 9f, revised 15.08.2016

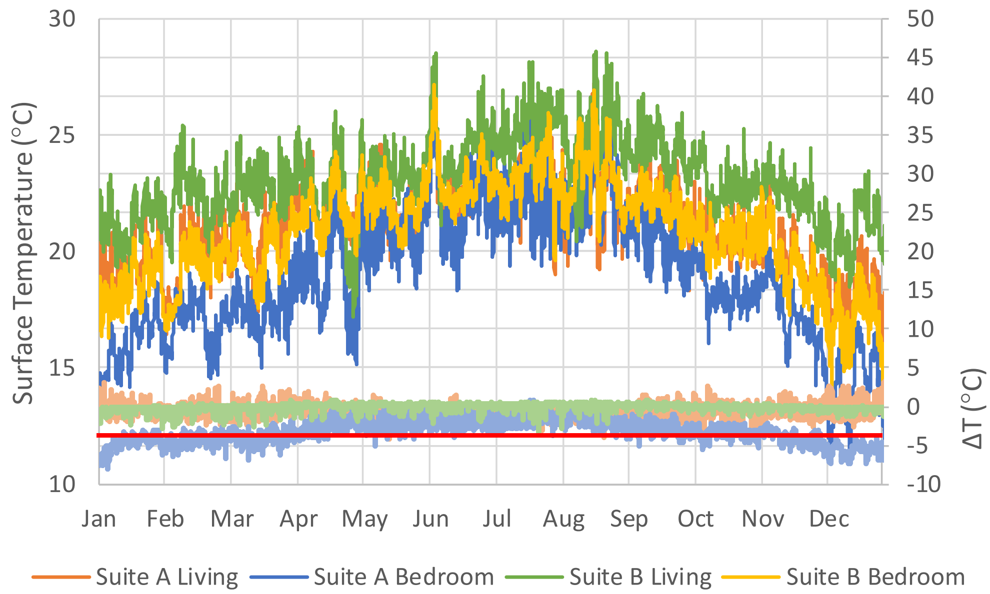

Figure 4-11 – Drywall Surface Temperature (Above) and Temperature Differential with Interior Air Conditions (Below) – Red Line Indicates 4.2°C Threshold.

For most of the year, the surface temperatures fall within ±5°C of the room air temperature. However, Suite A's Bedroom seems to be an exception, where very cold temperatures (<16°C) combined with temperature differences exceeding 6°C occur in the winter months. These differences could be caused by an opened window, or interior furniture placed against the wall. The placement of dressers, bookshelves, or beds against a wall will insulate the drywall from the room-side environment, causing it to be colder than it otherwise would be when exposed to conditioned interior air.

4.1.3 Discussion

Interior comfort is dependent on several variables extending beyond just interior temperature, relative humidity, and CO_2, including metabolic activity, clothing, and even interior paint colour and lighting.

The quantitative data suggests that the interior air is of good quality, with low instances of odour or elevated humidity, as based on CO_2 readings. The HRV balancing report also confirms that, during initial commissioning, the HRV was delivering adequate ventilation air to both bedrooms and living room spaces. However, it appears that several hours exceeded standard comfort levels for warmth during the summer in Suite A. Investigation into these occurrences show that when outdoor conditions exceed 25°C and the night time temperatures do not fall below 18°C, the interior temperatures may become uncomfortably warm for some occupants. Use of exterior shading devices and night-time outdoor air flushing techniques as modeled by the PHPP software may not match the strategies used by the occupants. As will be seen in the qualitative evaluation section that follows, several of the occupants were still learning how to best operate their systems several months into the monitoring period.

The qualitative evaluation of comfort provides information about how occupants *feel* about their living space.

4.2 Qualitative Evaluation – Occupant Surveys

In addition to perceptions of comfort, the overall objective of the qualitative research was to gain insight on various elements of living in a low energy home like the North Park Passive House by interviewing the homeowners/occupants about their expectations at two different points in time: first, prior to moving in and second, after they have lived in their homes for some time. More specifically, the interviews sought to address the following objectives:

- To identify why the homeowners chose to buy at North Park.
- To understand the initial expectations of the homeowners/occupants.
- To gain feedback on the overall experience of homeowners/occupants after living in their homes through their first fall and winter seasons.
- To assess homeowners'/occupants' level of knowledge of sustainable housing technologies and features including operating and maintenance needs.
- To understand the features that the homeowners/occupants like the most and like the least, as well as challenges and surprises that came up since moving into their homes.
- To determine how occupant behavior is affected or changed by living in a Passive House.
- To ascertain homeowner/occupant perceptions of specific benefits – and costs - of living in a Passive House.

4.2.1 Methodology

All occupants of North Park were invited to participate in qualitative interviews. The first round of interviews was conducted immediately after move-in, in September 2015. The second round was conducted in February 2016, after occupants had spent several months living in their homes and had lived through their first fall and winter.

Semi-structured interviews were conducted in person, in the occupants' homes. Where possible, and where two adults shared a suite, they were interviewed at the same time. Interview format and guiding questions are included in Appendix A, with an open-ended format to explore the occupants' perceptions and experiences. Detailed notes were taken and coded from each recorded interview. Common themes were extracted from the results using an inductive process.

4.2.2 Results

At least one occupant from all six suites participated in the "Pre-Occupancy" interviews. Occupants from four of the six suites participated in the "Post-Occupancy" interviews.

Table 4-2 below summarizes key themes that were touched on by the occupants.

TABLE 4-2: SUMMARY QUALITATIVE INTERVIEW RESPONSES – PRE-OCCUPANCY		
		# of suites (of 6 interviewed)
1. Factors in choosing to buy at North Park:		
	Location	All suites

TABLE 4-2: SUMMARY QUALITATIVE INTERVIEW RESPONSES – PRE-OCCUPANCY		
	Aligned with values (environmentally conscious and/or low impact lifestyle)	All suites
	Expected low energy costs	5/6 suites
	Affordable price point	4/6 suites
	Expected low strata fees	4/6 suites
	Layout/size/appearance	4/6 suites
	Quality of construction/durability	2/6 suites
	Parking spot	2/6 suites
	Other responses expressed by only 1 suite: expected high level of air quality; being rentable; expected investment/resale value	
2. Expectations:		
	Learning curve to learn to operate the HRV, external shades etc	4/6 suites
	No major change in lifestyle expected	3/6 suites
	Some change in lifestyle expected	2/6 suites
	High level of comfort/no drafts	2/6 suites
	Other responses expressed by only 1 suite: less maintenance and repairs; potentially cold feet? Potentially stuffy?	

TABLE 4-3: SUMMARY QUALITATIVE INTERVIEW RESPONSES – POST-OCCUPANCY		
		# of suites (of 4 interviewed)
1. Overall experience so far:		
	Satisfied or very satisfied	All suites
	Reasons cited:	
	Warmth/comfort/interior conditions	3/4 suites
	Quietness	3/4 suites
	Low electricity bills	3/4 suites
	Low strata fees	3/4 suites
	Design/layout	2/4 suites
	Other responses expressed by only 1 suite: indoor air quality; in-suite hot water	
2. Challenges and issues:		
	Learning to operate the ventilation and/or heating system, when to open windows (varying responses: too warm in winter; too cold overnight; air dry overnight, cold floor; managing the heat with lots of people over)	All suites
	Quality of interior finishes below expectations/issues with resolving cosmetic issues	All suites

TABLE 4-3: SUMMARY QUALITATIVE INTERVIEW RESPONSES – POST-OCCUPANCY		
	Energy monitoring system not working/not end-user friendly	3/4 suites
	Internal noise more noticeable than expected, particularly for lower suites	2/4 suites
	Energy bills very good but higher than expected	2/4 suites
	Difficulty/cost associated with re-keying the European exterior door	2/4 suites
	Other responses expressed by only 1 suite: noise from adjacent electrical room; cost of window coverings for custom windows; drainage issues from slab construction; loss of closet space to HRV; lack of light in north facing room; commissioning-related issues; getting used to condensing dryer	
3. Lifestyle change resulting from living at North Park?		
	No/not really	3/4 suites
4. Perceived investment/resale value:		
	Passive House factor will be a benefit for resale value	3/4 suites
5. Would you recommend a Passive House based on your experience?		
	Yes	All suites

4.2.3 Discussion

Overall, the interviewed occupants at North Park were satisfied or very satisfied with their experience of living in a Passive House so far, and all would recommend it based on their experience.

A key takeaway from the pre-occupancy interviews was that the market appeal to the buyers, many of whom were first time home buyers and young urban professionals, was a combination of sustainable design, location, and price point.

Most occupants expressed a prior level of commitment to a low impact and/or environmentally conscious lifestyle, but Passive House was a new concept for most. Most buyers therefore had an expectation going in that there would be a learning curve to understanding how the building and system works. Post-occupancy, some occupants were still struggling to understand how best to operate the system, while others felt it was simple.

More detailed guidance on how to operate the HRV, heating system, when to open windows etc, would likely be of benefit to new occupants.

> 'A good owner's manual would help,' offered the occupants of one suite who were still struggling to understand their heating and ventilation system.

> 'It's a Passive House, not a magic house,' said the occupants of another suite who felt their expectations may have been unreasonably high prior to moving in.

There was some variation in the experience of internal noise between occupants of upper and lower suites, with lower suites experiencing more internal noise (e.g. from people walking up their stairs). With respect to thermal comfort, one upper suite reported being “almost too warm” while the other “had some very cold nights”. This could be due to varying amounts of heat migrating up from lower floors, as well as potential operational issues; for example, with the settings on the HRV, the use of operable windows and/or the use of operable exterior shades.

The variation in responses around energy use correlates with the wide range in suite level energy data. This range may be due to both the living habits and preferences of the occupants, but the responses also indicate that some occupants may still be figuring out how to operate their suites in the most efficient and comfortable way.

5 Energy and Water Consumption

5.1 Methodology

To analyse the energy and water consumption of the building, utility data was collected for a minimum of one full year post-occupancy. Results presented as consumption per square metre were calculated based on the building's GFA (469 m^2).[12]

Whole building energy data for the six suites plus one common account was provided by BC Hydro, from September 2015 to February 2017. The data was normalized to average weather data based on Canadian Weather for Energy Calculations (CWEC). The normalized consumption was compared against the consumption modeled by the Passive House Planning Package (PHPP) software used to document and certify Passive Houses. Heating demand vs. base loads were also analysed to better understand where the model and actual consumption diverged.

Electricity consumption from individual suites was also collected to provide insight in the range of suite-level consumption and the impact of occupant behaviour. Limited circuit-level metering was collected using a "The Energy Detective" (TED) Pro Home residential electricity monitoring system, with Spyder multiplexer, which enabled end use monitoring of up to eight individual circuits at a suite's electrical panel.

Water consumption data for the whole building was provided by the City of Victoria. While data was provided from July 2015 to November 2016, the data prior to full-occupancy in September 2015 was incomplete and not used in our analysis. Readings were provided in three month intervals. To reflect monthly consumption, the raw billing data was adjusted to calendarized data. The measured consumption for 2016 was used to calculate the total annual water consumption. Due to the nature of the billing period, water consumption from December 2015 was included in the yearly 2016 total (data from December 2016 was not available at the time of this study).

5.2 Results

5.2.1 Energy Consumption

The measured, normalized annual energy consumption of the whole building was found to be 33,570 kWh, or 72 $kWh/m^2 \cdot yr$.

The modeled annual energy consumption predicted a value of 43 $kWh/m^2 \cdot yr$ for the whole building for a typical weather year. The measured, normalized consumption was therefore found to be 66% higher than the model predicted. A comparison chart of the monthly consumption between the actual energy and modeled energy is presented in Figure 5-1 below.

[12] Passive House modeling uses Treated Floor Area, TFA, in its calculation of heating demand, which is a smaller area than Gross Floor Area, which includes exterior walls, and Total (conditioned) Floor Area, which excludes exterior walls but includes interior partition walls. To enable comparison across the industry, the more commonly used GFA was used.

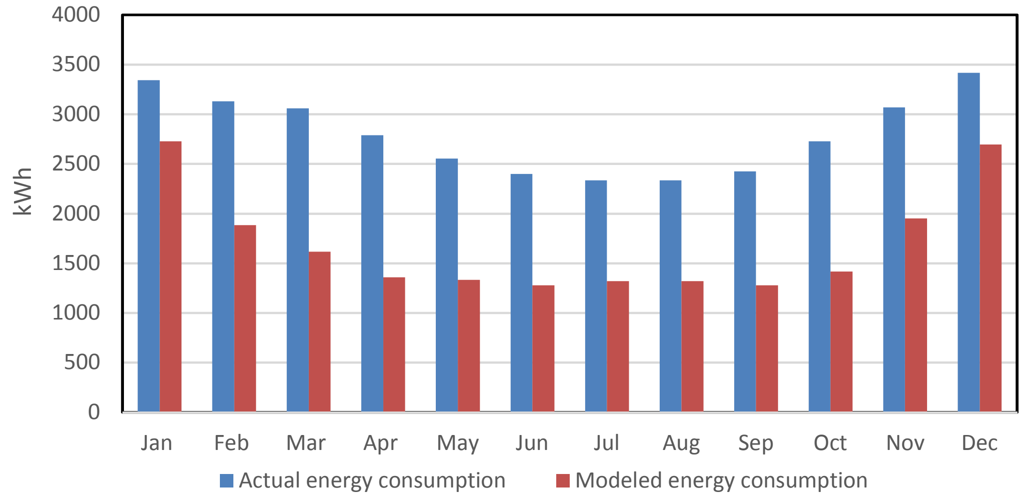

Figure 5-1 – Actual and Modeled Monthly Whole Building Energy Consumption

Further analysis was conducted to investigate the breakdown of the building's energy consumption. The metered results were broken down into heating consumption and baseline consumption (everything other than heating). An estimate of the heating consumption was determined by comparing the PHPP model monthly heating demands. The model indicated that the building would have zero heating demands during the warmer months of June, July, August and September. The assumption that no heating was used for these months was, in turn, adopted for the metered results to estimate a baseline consumption. The two graphs below present the results of the modeled energy breakdown (Figure 5-2) and the actual energy breakdown (Figure 5-3).

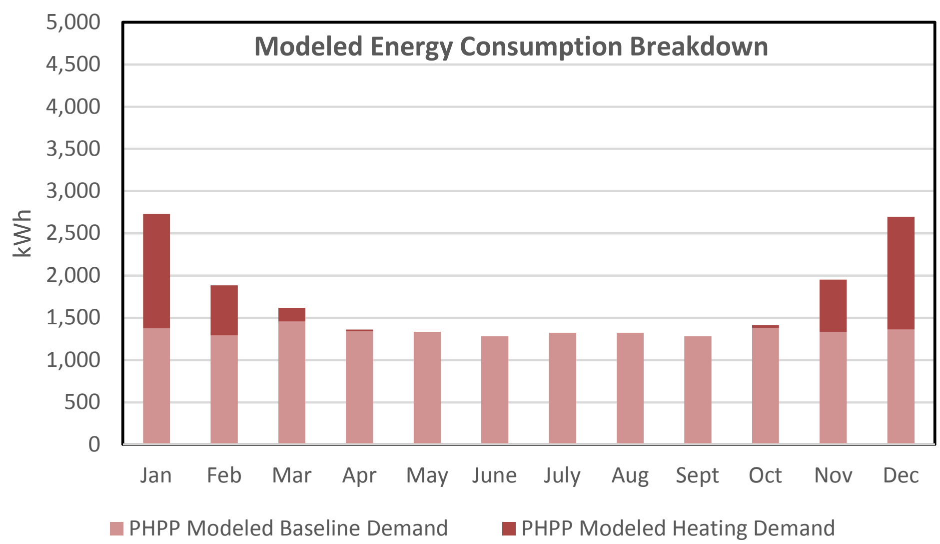

Figure 5-2 – PHPP Modeled Energy Consumption Breakdown

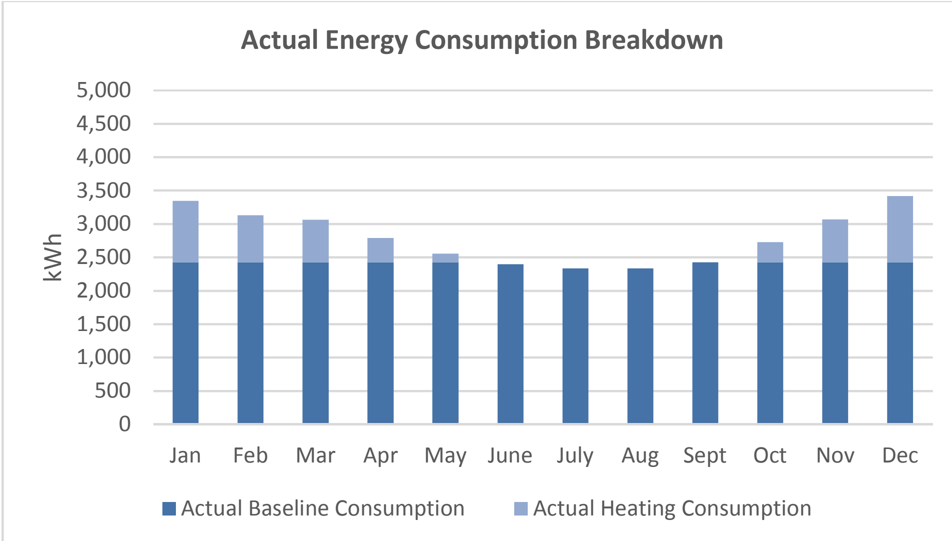

Figure 5-3 – Actual Energy Consumption Breakdown

Table 5.1 below summarizes the breakdown results.

TABLE 5.1: SUMMARY OF END-USE ENERGY BREAKDOWN				
	PHPP Modeled Energy		Actual Energy (kWh/m²·yr)	
	kWh	kWh/m²·yr	kWh	kWh/m²·yr
Heating	4,130	8.8	4,690	10.0
Baseline	16,040	34.2	28,880	61.6
TOTAL	**20,170**	**43**	**33,570**	**72**

While the total actual energy consumption was found to be significantly higher than the total modeled consumption, the breakdown shows that most of this can be attributed to baseline consumption. The building's heating more closely reflects the modeled heating demand, further illustrated in Figure 5-4 below.

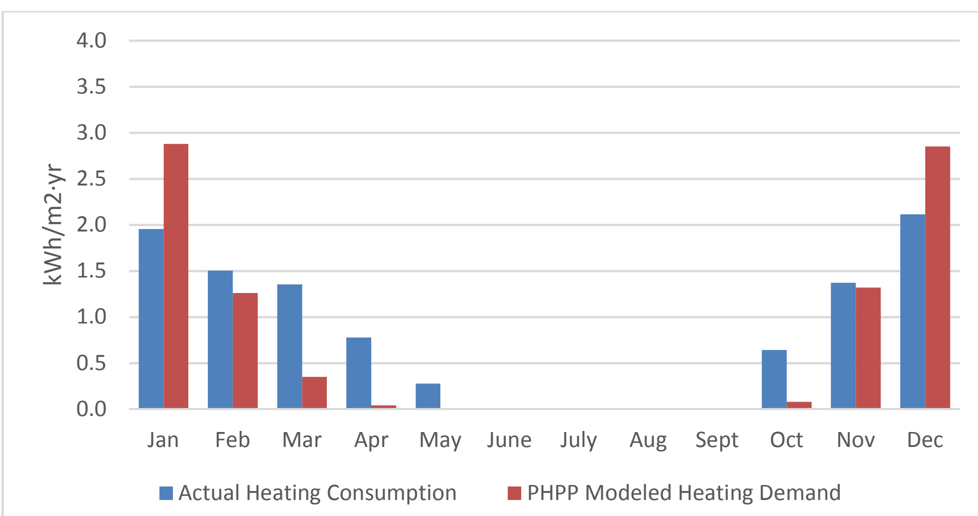

Figure 5-4 – Comparison of Actual and PHPP Modeled Heating Demand

Further analysis was conducted for suite consumption. All suites are two-bedroom, but do range in size. The average annual suite consumption was found to be 5,375 kWh/yr, with 4 out of the 6 suites falling within one standard deviation of the mean. The data suggest a wide range in energy consumption at the individual suite level. If all suites maintained consumption at rates similar to the lowest consuming suite (3,530 kWh/yr), total building energy consumption would be approximately 46 kWh/$m^2 \cdot$yr, very close to the modeled 43 kWh/$m^2 \cdot$yr.

5.2.2 Sub-metered energy consumption

Sub-metered data from one unit, representing electrical consumption between October 20th, 2015, to January 6th, 2016, was collected and used to validate our assumptions about heating versus base loads. It also provided additional information on the base load end uses for a limited time period. The power at the circuit breaker was recorded, in addition to the total electrical consumption of the suite. The daily energy consumption for the monitored unit is shown in Figure 5-5, with the dark bands representing the weekends.

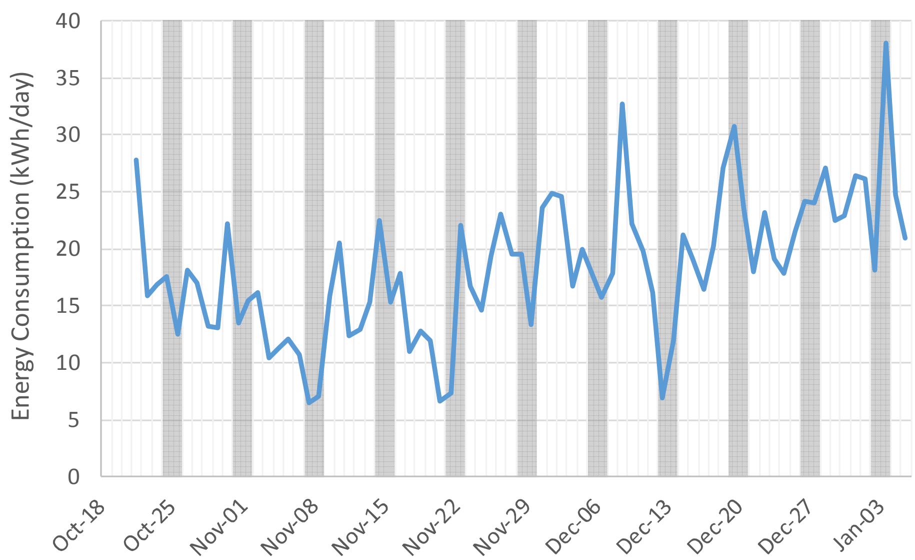

Figure 5-5 – Daily Energy Consumption for Monitored Suite.

The sub-metered data permitted a further breakdown of the major components of energy consumption within the suite. Due to a problem with the circuit transfer for the HRV, and the use of an additional heater on a non-monitored circuit, the heating loads could not be confirmed with the data logger configuration.

However, an estimate of the heating load can be calculated by considering that the total baseline energy consumption of the suite when unoccupied should consist mostly of HRV, domestic hot water and other electrical system stand-by losses, and any required heat. The installed HRV is stated to use around 1.5-2kWh per day when running continuously and data from the breakdown suggest a baseline refrigerator load and hot water tank losses of around 0.4 and 0.6 kWh per day, respectively. Consequently, subtraction of the assumed loads permits an estimate of the baseline heating load. This yields a breakdown shown in Figure 5-6.

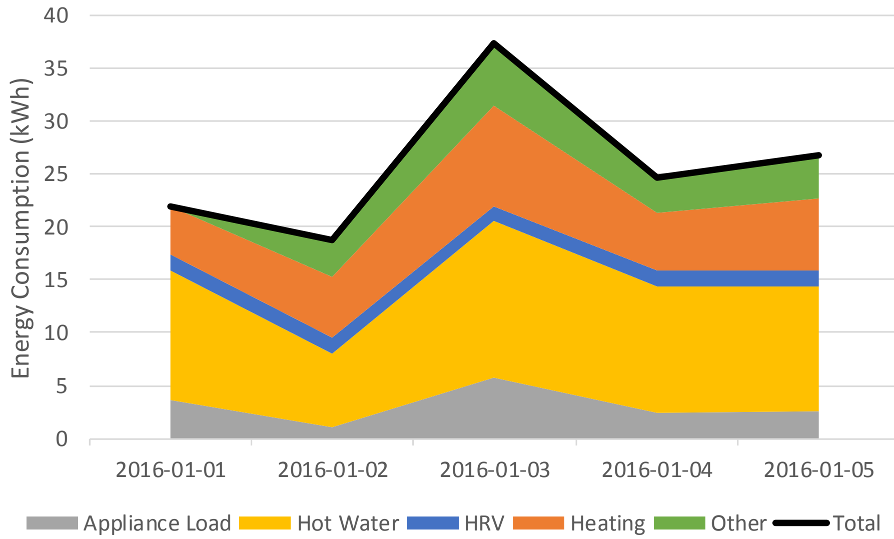

Figure 5-6 – Refined Energy Consumption with HRV and Heating Load Assumptions, from January 1st to January 5th, 2016

The average estimated heating requirements over this monitoring period averaged around 6.8 kWh per day, which is slightly more than the average suite value calculated from the actual energy consumption for the month of January. This result is consistent with this suite's larger size and higher than average overall energy consumption.

5.3 Discussion

Consistent with other measurement and verification studies, the PHPP model underestimated the non-heating energy demands. The range in consumption across the six suites was also significant. If all six suites performed at the level of the lowest consuming suite, the energy demand per square foot would be very close to the modeled energy demand.

These results point to the significant impact that occupant behaviour has on the actual energy consumption of even a building like a Passive House that is intentionally built to dramatically reduce heating demand.

With improved enclosure performance, a lesser component of energy consumption is required for space heating or cooling. Thus, the fraction of energy consumption used for occupant related operation increases as a proportion of total energy use. The fraction of the daily energy use just for domestic hot water amounts to approximately 45% of total energy consumption, whereas supplemental space heating is estimated in to range in the 25% range. Consequently, in higher performance buildings, greater focus will be required to minimize occupant related operation loads on the building, requiring higher efficiency appliances and domestic hot water heating strategies to minimize electrical use.

Having said this, the actual energy consumption of the building is still well below that of buildings meeting the requirements of local building and energy codes.

There is limited available data on the actual metered energy consumption of *new* low-rise residential buildings. However, a recent study[13] completed detailed whole building modeling of new residential buildings built to ASHRAE 90-1-2010 prescriptive requirements (i.e., consistent with the energy requirements in the current BC Building Code (2012)). This study modeled an electrically heated wood-frame building at 132 $kWh/m^2 \cdot yr$ - nearly double North Park's EUI of 72. Another study[14] measured performance of existing low-rise residential buildings in south-west BC, with construction dates ranging from 1970s to 2000s, and found an average EUI of 171 kWh/m^2.

5.3.1 Water Consumption

The overall building water consumption for 2016 was found to be approximately 669,000 litres. The annual usage based on the building's GFA is 1,426 $litres/m^2$. This includes all six suites and common areas. Water usage is also typically expressed in litres per person per day. Based on occupant interviews, it is estimated that there were 10 occupants in the building during 2016, resulting in an average daily water use of 183 litres per person.

The building was not specifically designed to be water efficient beyond good standard practice. However, water consumption is lower than the average per person consumption in Canada, which was 251 L/person in 2011[15]. This likely reflects current code requirements for low flow plumbing fixtures, in combination with a small landscaped area and minimal irrigation needs at the building.

[13] Carbon Neutral 4-6 Storey Multifamily Buildings, March 2016, by RDH for the City of Vancouver Sustainability Group, including updates.

[14] Energy Consumption in Low Rise Multifamily Residential Buildings, March 2017, by RDH Building Science for BC Housing.

[15] https://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=7E808512-1

6 Financial Analysis

This section summarizes actual construction cost and summarizes the financial analysis to determine the Net Present Value (NPV), Internal Rate of Return (IRR) and Discounted Payback of the additional investment to build a Passive House.

6.1 Construction Cost

Construction cost data was collected as part of a separate study, The Business Case for Passive House[16], which is excerpted here. The builder reported that final construction and soft costs were approximately $2519/m^2$ ($234/ft^2), or $1,134,000 total. The incremental increase above a non-Passive House building of *similar build quality* was approximately 4.2%.

Key differences in construction costs were estimated for the major building components, as summarized in Table 6-1 below.

TABLE 6-1: SOURCES OF COST DIFFERENCES		
Building Component	**$ Diff.**	**Description**
Architecture	+$10,000	More detailed design and advanced planning of details to eliminate thermal bridging
Certification	+$5,000	Cost for achieving Passive House certification
Foundation and Slab	+$10,900	Thicker insulation and additional rebar reinforcement
Walls & Insulation	+$7,500	Additional lumber and labour for 2x8 stud wall and service cavity
Air Sealing & Acoustics	+$10,000	Additional labour and higher quality tape to achieve very tight air barrier
Ventilation	+$16,000	Compared to a lower efficiency/lower cost HRV for each suite
Heating	-$30,000	Compared to in-floor radiant heating system to achieve comparable level of thermal comfort
Plumbing & Electrical	No change	
Windows & Doors	+$17,900	Compared to double paned windows and glass doors with similar quality and functionality (e.g. tilt-and-turn windows)
Total incremental cost	**$47,300**	

6.2 Energy Cost

Average weather normalized energy consumption at North Park was 72 kWh/m^2·yr, or 33,570 kWh total. The whole building base electricity cost was estimated at $2,676 at January 2016 electricity rates, or approximately $446 per suite per year (~$37/month per suite for all electricity). This excludes the contribution of net metering from the solar PV array, which was not available at the time of completing this research.

[16] Business Case for Passive House report, dated May 27, 2015, by Synergy Sustainability Institute.

To determine the savings over a more conventional build, an estimate of the energy consumption of a conventional build was needed.

Previously cited whole building modeling of new multifamily residential buildings built to ASHRAE 90-1-2010 prescriptive requirements benchmarks a new electrically heated wood-frame multifamily building at 132 $kWh/m^2 \cdot yr$[17], or 61,940 kWh per year for a building of the same size as North Park. This metric was used for this analysis.

6.3 Financial Analysis

Cost-effectiveness indicators used for the financial analysis were as follows:

- → Net present value (NPV) = discounted future benefits from lower energy bills, minus incremental capital cost. Benefits and costs were considered for a period of 30 years. A positive NPV indicates a “profitable” investment, whereby benefits exceed costs after applying the discount rate.
- → Internal Rate of Return (IRR) = the rate of return that corresponds to an NPV of zero; or a “break-even” point for the investment. This IRR can be compared to the discount rate or required rate of return. If the IRR is larger than the discount rate, then the investment is considered economically attractive.
- → Discounted payback period = the number of years (rounded up for decimals) after which the discounted benefits exceed the incremental capital costs.

The following parameters were used for the financial analysis:

- → BC Hydro Residential electricity prices as of January 2016:
  - → Step 1 $0.0797 per kWh (up to 1,350 kWh in a two-month billing period). All consumption was assumed to fall within Step 1.)
- → Energy escalation per BC Hydro scheduled increases through 2019, and 2% net of inflation for the remainder of the analysis period, as follows:
  - → 2016: 4% increase
  - → 2017: 4% increase
  - → 2018: 3.5% increase
  - → 2019: 3% increase
  - → 2% increase net of CPI thereafter
- → Discount rate 6% (real, net of normal inflation)
- → CPI 1.1%

[17] Carbon Neutral 4-6 Storey Multifamily Buildings, March 2016, by RDH for the City of Vancouver Sustainability Group, including updates.

The results are summarized in Table 6-2 below:

TABLE 6-2: FINANCIAL ANALYSIS SUMMARY			
Annual Energy Savings	Net Present Value (NPV)	Internal Rate of Return (IRR)	Discounted Payback Period
(kWh/m^2)	($\$/m^2$)	(%)	(Years)
60	-$13.93	5%	17

The financial analysis suggests that based on the factors considered, the upfront investment is marginally cost effective. The NPV is slightly negative; the IRR is close to the assumed discount rate, and the discounted payback period is between 11 and 20 years. Consistent with the theoretical analysis completed previously, energy cost savings alone are therefore not sufficient to offset the additional upfront investment in the shorter term.

However, this basic financial analysis only paints a part of the picture. There are several financial components that were not included in this analysis, including the following:

- Most owners report that their strata fees are lower than other buildings they considered buying into, suggesting that the incremental cost was not borne by the buyers, or that the perceived value for the money was equal to or better than other options.
- Cost offset by on-site solar PV and net metering
- Potential increased resale value
- Most owners believed the price was comparable or better than other condos they looked at
- Additional savings beyond the 30-year analysis period

This research also documented several non-monetary benefits to living at the North Park Passive House, including perceived building durability, improved air quality and perceived comfort, and the ability to live in a home that reflects one’s personal values.

7 Conclusions

7.1 Enclosure Performance

The monitoring and analysis indicates that the north facing exposures were generally wetter than the south facing ones, but all monitored locations showed drying over time, with a low risk of long term mould growth.

7.2 Thermal Comfort and Air Quality

Interior temperatures were generally within a comfortable range throughout the monitoring period. However, one suite experienced 13% of hours greater than 25° C during warm periods in the summer, and some temperatures lower than 17.5° C in the winter. Indications supported by the occupant interviews suggest that some occupants are still learning how to best operate the heating and ventilation systems, as well as when to open windows and use operable shades. This feedback indicates an opportunity to further improve both comfort conditions and energy consumption in the building.

Relative humidity was well managed at all monitored locations throughout the year.

CO_2 levels are generally very good, and occupants reported either good perceived air quality, or made no comment about air quality, suggesting that the HRV was providing acceptable air exchanges. Some spikes and variation between suites was observed, likely due to different occupancy patterns, activity levels and pet ownership.

Qualitative interviews indicated that all participating occupants were satisfied with their experience living at North Park, but learning opportunities likely still exist to improve operation and comfort.

7.3 Energy and Water Consumption

The actual energy consumption at North Park is higher than modeled but still much lower than a conventional new building, and significantly better that a typical existing building. Also, the analysis showed that the actual heating demand was close to the PHPP modeled demand, indicating that the source of divergence is in base loads (plug loads, domestic hot water, etc). In other words, occupant preferences and behaviours have a significant impact on the final energy consumption. Suite level utility data suggests a broad range in consumption between suites, further supporting this observation.

Water consumption is lower than the Canadian average, but not unexpectedly so for a building with limited landscaping and standard low flow fixtures.

7.4 Financial Analysis

The estimated incremental cost to upgrade a building of comparable quality to Passive House was 4.2%. Annual energy savings were estimated to be 28,370 kWh per year, or 60 kWh/m^2.

The financial analysis suggests that based on the factors considered, the upfront investment is marginally cost effective. The NPV is slightly negative; the IRR is close to the assumed discount rate, and the discounted payback period is between 11 and 20 years.

Consistent with the theoretical analysis completed previously, energy cost savings alone are therefore not sufficient to offset the additional upfront investment in the shorter term.

However, this basic financial analysis paints only part of the picture. There are several financial components that were not included in this analysis, including a perceived competitive sales price and resale value; cost offset of net metering, and ongoing savings realized after the analysis period.

This research also documented several non-monetary benefits to living at the North Park Passive House, including a high level of occupant comfort, perceived building durability, improved air quality, and the ability to live in a home that reflects one's personal values.

7.5 Lessons Learned

In addition to the construction lessons that the builder shared, there were several lessons learned by the research team that can inform future monitoring and verification projects.

Design & Construction

The key lesson learned from the design and construction process was the importance of keeping the building form simple. Because of the complicated dormer roof shape, the builder reported that two-thirds of the construction cost and two-thirds of the energy losses were concentrated on the upper one-third of the building. In future projects, the builder has insisted on a simpler roof shape.

Partial pre-fabrication of the deep stud wall was also explored early on in this project, but found to be cost-prohibitive for a project of this small scale.

No supply chain issues were reported by the builder. All materials and products were readily available through local or regional suppliers.

Instrumentation

Challenges were encountered as part of the instrumentation of the building that manifested in erroneous sensor readings, unidentifiable and unlocatable sensors, and issues in tracing sensors back to their locations. These instrumentation problems created data reliability concerns and alternative solutions and assumptions were required to achieve the research objectives. While an intentional degree of redundancy was provided in the initial sensor layout in anticipation of potential problems, some of the critical and non-duplicatable sensors (i.e. indoor CO_2 and T&RH sensors) were non-functional.

As this research project was an addendum to the construction of the building, the sensor installation had to be phased in whenever an opportunity presented itself in the contractor schedule. This exposed many sensitive sensors to the rigors of a construction environment for prolonged durations. Despite careful attention by the construction crew, it is nonetheless inevitable that damage to the sensors could occur.

In the interest of efficiency, the contractor assisted with some of the instrumentation installation. An electrician was provided with the bus cables to run back to the central electrical room. However, upon investigation, the ordering of the cables did not appear to match the monitoring locations. This led to challenges in tracing back sensors and resulted in significant time troubleshooting problem sensors. Closer monitoring and guidance during the installation would alleviate some future troubleshooting issues.

APPENDIX A: Occupant Interview Protocol and Questions

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