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PERFORMANCE MONITORING OF AN ENERGY EFFICIENT SIX- STOREY WOOD-FRAME BUILDING

Hygrothermal Performance,
Thermal Comfort, and Space
Heating Energy

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March 2026

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**PERFORMANCE MONITORING OF AN
ENERGY EFFICIENT SIX-STOREY WOOD-
FRAME BUILDING**

Project number: 250

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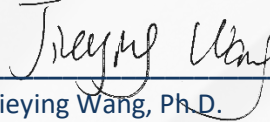
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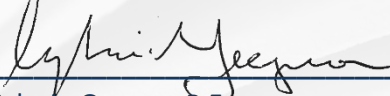
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EXECUTIVE SUMMARY

Mid-rise wood-frame buildings, often designed and built to target high energy performance, have become popular in residential construction across Canada over the past decade. Gathering the 'As Built' performance through in-situ testing and monitoring can help compare field measurements with design expectations to improve the designs of future buildings, validate various modelling to improve design tools, and support regulatory and market acceptance for innovative (e.g., taller, larger, energy efficient) wood buildings.

This monitoring study aims to collect performance data from an energy-efficient, six-storey, wood-frame residential building in Victoria, located in climate zone 4 of British Columbia. The building was designed and built to meet the energy requirements for Step 4 of the BC Energy Step Code, with energy targets similar to those of the Passive House standard. It was built with highly insulated and airtight building envelope assemblies to minimize space heating needs in the winter. For example, its wood-frame exterior walls were split-insulated assemblies, with R14 batt insulation installed in the 2 by 4 stud cavities and R24 rigid stone wool insulation boards installed outboard of the plywood exterior sheathing, reaching approximately effective R37. Its low-slope roof was built with "I" joist with cavity insulation, together with R40 rigid insulation above the plywood roof sheathing, achieving approximately effective R70.

This monitoring study focuses on assessing durability performance of the building envelope assemblies (exterior wall, roof), indoor thermal comfort, and electricity use of space heating for this energy efficient building. Eighteen suites in total, ranging from studio, one-bedroom, to three-bedroom suites were selected for instrumentation. They were located on levels 1, 3, and 6, respectively, to cover different building heights, exterior wall orientations (with and without exterior shading at windows), and occupants. The measurements cover:

- the service environment (i.e., temperature and relative humidity (RH)) and wood moisture content (MC) of the plywood exterior sheathing at seven exterior wall locations in five suites and two roof locations in two suites.
- the indoor environment, i.e., the temperature and RH inside 11 suites including 32 living spaces (studio, bedroom, living room) in total.
- electrical consumption of the baseboard space heaters in 12 suites including 17 living spaces in total.

The sensors were installed during the construction from 2020 to 2021. Data collection started in February 2021 when the building was near completion. Unfortunately, severe data loss occurred due to premature failure of many sensors. Only about one third of the sensors installed have generated data continuously since 2021 for at least a year. The following conclusions are made, based on the collected data:

- The plywood exterior sheathing has remained dry at all measurement locations of the building envelope. The split-insulated exterior wall and roof assemblies with thick exterior insulation keep the sheathing warm in cold weather. The highly vapour-permeable exterior insulation and self-adhered membrane in the exterior wall will also allow drying towards the exterior if there is



incidental wetting. These design measures will contribute towards long-term durability of the building envelope.

- The measured indoor temperature and RH from several suites indicate overall comfortable indoor space. Use of exterior shading appears to be effective to reduce solar heat gains, especially for the south-facing suites. Among the five suites with relatively complete data collected from the sensors installed, two west-facing suites have the largest hours with indoor temperature exceeding 25°C; one of the suites has 15.7% of the yearly hours with indoor temperature exceeding 25°C, not meeting the Passive House requirement.
- Electricity consumption for space heating ranges from 23.0 to 0.1 kWh/m²/yr for the five suites with data available. Two suites have space heating energy consumption exceeding the energy step code requirement of 15 kWh/m²/yr. The other three suites show much smaller amounts of space energy use, far below the code requirement. Occupant behaviour including occupants' tolerance for a cooler environment in the winter and a warmer environment in the summer appears to be critically important for achieving energy efficiency. The energy data also reflect the high energy efficiency and climate resiliency of the building, which have become increasingly important to battle climate change.

The following best practices may be taken into consideration when designing and installing highly insulated, wood-frame buildings to improve their thermal performance and long-term durability, based on the monitoring results of this study.

- Using prefabricated panels can speed up construction and thereby reduce the time of exposure during construction. It helps prevent construction wetting to improve long-term durability.
- For building envelope design, specify a high level of exterior insulation to keep the wood warmer and drier in service, whenever possible.
- Vapour-permeable exterior membrane and exterior insulation facilitate drying of the wood towards the exterior in a heating climate and helps ensure long-term durability.
- If overheating occurs, measures, such as providing shading at windows, increasing ventilation by adjusting ventilators or opening windows when it is cooler outside, and providing cooling (e.g., by using portable air conditioners) in a warm season may become necessary to improve indoor thermal comfort.

Lessons are learned from this study about instrumentation to improve future monitoring studies.



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1 OBJECTIVES

This project conducts performance monitoring of an energy efficient, six-storey, wood-frame residential building in Victoria for the following objectives:

- To assess building envelope performance of highly insulated, wood-frame exterior wall and roof assemblies with split insulation.
- To assess indoor thermal comfort by focusing on overheating potential.
- To gather information about space heating energy use.

2 INTRODUCTION

Building energy regulations have substantially changed across Canada over the past two decades to meet the mandates of governments to reduce energy consumption and greenhouse gas emissions. In British Columbia, the provincial government has committed to building a net zero economy by 2050. Energy Step Code¹ was enacted in 2017 to incrementally raise the requirements for new construction of both Part 9 and Part 3 buildings. Five incremental steps are provided for Part 9 housing and four steps for Part 3 buildings. This code adopts an overall “envelope first” approach, requiring the building envelope shall be highly airtight and thermally efficient² to reduce space heating energy consumption. Step 4, the highest step for Part 3 residential buildings, has energy efficiency requirements similar to those of the Passive House standard (Passive House Institute 2026). Design guides have been developed by BC Housing (2019a; b) to assist the industry in meeting the Energy Step Code requirements.

It is known potential durability issues may arise from increased building energy efficiency. Highly insulated assemblies can be more prone to moisture-related problems, both during construction (e.g., from trapped moisture) and in operation (e.g., from indoor/outdoor humidity, water leakage, etc.). Compared to conventional wood-frame construction, the typically thicker and highly insulated building envelope assemblies used in many high energy efficient buildings reduce the heat loss from the interior, which consequently reduces their drying capacity and increases their wetting potential. The exterior sheathing, typically as the coldest moisture-sensitive structural member in the building envelope in a heating-dominated climate, is particularly susceptible to interstitial moisture accumulation and vapour condensation, when air exfiltration and/or outbound vapour diffusion occurs. Air leakage is typically a

¹ BC Energy Step Code - Province of British Columbia.

² The thermal resistance of an assembly is often referred to as an R-value in imperial measurement ($\text{hr}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$), RSI in the metric measurement system ($(\text{m}^2\cdot\text{K})/\text{W}$) or its inverse, i.e., the overall thermal transmittance (or U-factor, in a unit of $\text{W}/(\text{m}^2\cdot\text{K})$). The calculation of effective R-values takes into account thermal bridging of framing and other components.



more severe cause than vapour diffusion in conventional buildings; however, air leakage and its moisture-related impact is expected to be reduced in an airtight building. While exterior insulation keeps the sheathing warmer in a cold climate, exterior insulation and membrane products with low vapour permeance may affect the capacity to dry towards the exterior and consequently the long-term durability performance (Wang 2021; Wang 2023; Wang 2025a). The exterior sheathing is also the most susceptible to water penetration from the exterior, if rain leaks occur.

In addition to building envelope performance, the indoor environmental conditions (temperature, humidity, etc.) and air quality (e.g., indoor pollution) are also important design considerations. Mechanical ventilation is commonly used to remove indoor pollutants and to provide fresh air for occupants in a contemporary building, with ventilation rates regulated by building codes and standards based on building use, area, and number of occupants (ANSI/ASHRAE 2025a; b). This becomes more important for buildings with airtight building envelopes. As a result, heat- or energy-recovery ventilators (HRVs or ERVs) are essential for an energy efficient building to minimize the energy loss associated with mechanical ventilation.

Indoor temperature and humidity are critically important to occupant comfort. The target indoor temperature in the Canadian building codes ranges from 18°C to 22°C for designing heating systems and 24°C for space cooling; these are the default building operation values that can be used for energy simulation [Table A-8.4.3.2.(1) in the National Energy Code of Canada for Buildings (NECB)] (NRC 2020). Based on the levels acceptable to most people, the ANSI/ASHRAE 55 standard (2017) provides guidance for passively cooled buildings to quantify the effects of environmental factors, including temperature, thermal radiation, humidity, and air speed, as well as personal factors, such as activity (metabolic rate) and clothing insulation on thermal comfort. In terms of indoor thermal comfort, the standard generally recommends the indoor temperature to stay below 25°C in the winter and 28°C in the summer³.

Overheating is understood to be the accumulation of warmth within a building to an extent that it causes discomfort to occupants (NHBC Foundation 2012). Highly energy efficient buildings in a heating-dominated climate have conventionally been focused on minimizing the amount of energy needed for space heating over the winter and thereby tend to trap heat with airtight and thermally efficient building envelopes. Moreover, occupants may have higher expectations about the indoor thermal comfort of energy efficient buildings, which are typically touted as high-performance buildings. The Passive House standard has a criterion for avoiding overheating by requiring that not more than 10% (i.e., 876 hrs) of the total hours each year should exceed 25°C and recommends targeting less than 5% in design (Passive House Institute 2026). The BC Energy Step Code has more stringent criteria to prevent overheating (BC Housing 2019b). For indoor spaces without mechanical cooling, for example, the indoor temperature

³ Overall, most people feel “warm” at 25°C and “hot” at 28°C.



cannot exceed “80% acceptability limits⁴” for more than 200 hours, and the limit is reduced to 20 hours for vulnerable populations. To meet the requirements of the BC Energy Step Code for indoor spaces without mechanical cooling, the upper limit of temperature roughly falls in the range of 25-26°C for the coastal climate in which this building is located, using the calculations specified in the ASHRAE standard 55 (2017). Overheating was recently confirmed with field data for a six-storey wood-frame residential building and a three-storey mass timber office building in Vancouver, both designed to meet the Passive House standard (Wang 2019; 2025b). A similar energy efficient six-storey wood-frame residential building in a northern BC climate prevented overheating by integrating mechanical cooling in the building (Wang and Ngo 2021).

This study aims to gather performance data about durability of the building envelope, indoor thermal comfort, and space heating energy use of an energy-efficient, six-storey wood-frame building, designed and built to meet the energy requirements for Step 4 in the coastal climate of British Columbia.

3 STAFF

The following FPInnovations staff are directly involved in this monitoring study:

- Jieying Wang, Senior Scientist, Building Systems
- Mohammad Sadegh Mazloomi, Senior Scientist, Building Systems
- Neal Holcroft, Scientist, Building Systems (until March 2024)
- Ramandeep Ramandeep, Technologist, Advanced Manufacturing (until June 2024)
- Victor Cheung, Technologist, Building Systems
- Dorian Tung, Manager, Technology Assessment
- Sylvain Gagnon, Manager, Building Systems

4 BUILDING INFORMATION AND INSTRUMENTATION

The building is a six-storey wood-frame residential building in Victoria, British Columbia, located in climate zone 4 with heating degree days over 3000 as defined in the NECB (NRC 2020). Providing 102 units of non-market housing units ranging from studios, one bedroom, two bedrooms, to three bedrooms, it has been used as a rental building since the fall of 2021. The building was designed and built to meet the energy requirements for Step 4 of the BC Energy Step Code. The detailed energy targets are similar to those of

⁴ The 80% acceptability limit of temperature is 25.5°C for May, 26.5°C for June, 27.5°C for July, 28.4°C for August, 26.5°C for September, and 25.2°C for October for Vancouver, slightly increased from the provisions in the previous version of the Energy Modelling Guidelines (City of Vancouver 2025).



the Passive House standard including a Thermal Energy Demand Intensity (TEDI) below 15 kWh/m²/yr and airtightness below 0.6 ACH @ 50 Pa. The airtightness was confirmed to be 0.55 ACH @ 50 Pa by testing upon substantial completion of the building in early 2021.

The building has an “L” shape with suites facing different orientations, designed to provide optimal solar gains as well as natural light for the entire building (Figure 1). Its building envelope includes highly insulated light-wood-frame wall and roof assemblies and high-performance windows to minimize space heating needs in cold weather. For example, with wall panels prefabricated in a factory located in Metro Vancouver, the wood-frame exterior walls achieved about effective R37 with split-insulated assemblies. They were built with 2 by 4 (actual 38 mm by 90 mm) dimension lumber wall studs, with R14 batt insulation installed in the stud cavities and R24 rigid stone wool insulation boards [6 in. (152 mm) in thickness] installed outboard of the 1/2 in. (actual 13 mm) thick plywood exterior sheathing. A vapour-permeable sheathing membrane was pre-installed in the factory also to provide protection during the installation on site. The low-slope roof was built with “I” joist [11 7/8 in. (actual 302 mm) deep] with batt insulation installed inside the joist cavities and rigid exterior insulation of R40 installed above the plywood roof sheathing, approximately achieving effective R70. The prefabricated panels were installed from October 2019 to February 2020. Exterior sunshades were installed at major windows facing south, west, and east to block unwanted solar gains to keep the indoor temperature comfortable in the summer. The building has electrical baseboard heaters in each living space (i.e., studio, bedroom, or living room) to provide space heating when needed by occupants. Mechanical cooling is not provided.



Figure 1. Building under construction.



4.1 Instrumentation

This monitoring study focuses on assessing durability performance of the envelope assemblies (i.e., exterior wall, roof), indoor thermal comfort, and space heating energy consumption to address the most critical concerns related to high building energy efficiency. A monitoring system using wireless sensors and data loggers was installed during the construction from 2020 to 2021. Eighteen suites in total, ranging from studio, one-bedroom, to three-bedroom suites were selected from levels 1, 3, and 6 to cover different building heights, exterior wall orientations (including with and without exterior shade), and occupants (Table 1).

Table 1. Summary of locations and items of monitoring.⁵

Level	Suite	Suite type	Sensor location	Orientation	Plywood, RH/T/MC	Indoor, RH/T	Heating energy
1	110	1 Bed A - Type 1	Bedroom	South		1	1
			Living room	South		1	1
	112	3 Bed - Type 1	Bedroom 1	Southwest		1	
			Bedroom 2	South		1	
			Bedroom 3	South		1	
			Living room	-		1	
	113	3 Bed - Type 2	Bedroom 1	Northwest		1	
			Bedroom 2	North		1	
			Bedroom 3	North		1	
			Living room	-		1	
	116	Studio	Studio	North	1		1
3	301	Studio	Studio	West		1	1
	303	1 Bedroom A - Type 2	Bedroom	Southwest	1		1
			Living room	South	1		1
	304	1 Bedroom - Type	Bedroom	Southeast		1	1
			Living room	South		1	1
	306	Studio	Studio	East	1		1
	313	Studio	Studio	North	1		1
	316	3 Bedroom - Type 2	Bedroom 1	Northwest		1	
			Bedroom 2	North		1	
			Bedroom 3	North		1	
			Living room	-		1	
	317	3 Bed - Type 1	Bedroom 1	Southwest		1	
			Bedroom 2	South		1	

⁵ Suites and numbers in red indicate a good amount of data have been collected from sensors for performance assessment.



Level	Suite	Suite type	Sensor location	Orientation	Plywood, RH/T/MC	Indoor, RH/T	Heating energy
6			Bedroom 3	South		1	
			Living room	-		1	
	601	Studio	Studio	West		1	1
	603	1 Bedroom A - Type	Bedroom	Southwest	1		1
			Living room	South	1		1
	60	1 Bedroom - Type 5	Bedroom	Southeast		1	1
			Living room	South		1	1
	60	Studi	Studio	East			1
			Roof		1		
	61	Studi	Studio	North			1
			Roof		1		
	616	3 Bedroom - Type 2	Bedroom 1	Northwest		1	
			Bedroom 2	North		1	
			Bedroom 3	North		1	
			Living room	-		1	
	617	3 Bed - Type 1	Bedroom 1	Southwest		1	
			Bedroom 2	South		1	
			Bedroom 3	South		1	
			Living room	-		1	
Sum	18		43		9	32	17

As there was already confidence in the split-insulated wall assemblies with performance data also being generated from other studies (Wang and Ngo 2021; Wang 2021), only seven locations from the exterior walls of five suites (i.e., 116, 303, 306, 313, 603) were selected for installing sensors to measure temperature (T), relative humidity (RH), and wood moisture content (MC) from the interior surface of the plywood sheathing. The stainless moisture pins were inserted into the plywood in a depth of about 6 mm, with MC readings based on Douglas fir⁶ and calibrated with the measured temperature. Two locations in the roof assembly (i.e., suites 606 and 613, respectively) were similarly instrumented to assess hygrothermal performance of the roof. To assess indoor thermal comfort, RH/T sensors were installed on interior walls of the selected 11 suites including 32 living spaces (i.e., studios, bedrooms, living rooms) in total, to measure indoor temperature and RH. In addition, a type of energy submeter was used to measure electrical consumption of the baseboard heaters inside the selected 12 suites including 17 living spaces in total. These suites are studio and one-bedroom suites, assumed to be smaller households. Installation of

⁶ The resistance-based moisture content measurement method may overestimate the moisture content of plywood due to the effect of the glue lines on electrical resistance, especially for damp plywood. The glue is typically based on phenolic formaldehyde, coupled with sodium hydroxide for accelerating curing of the adhesive (Wang and Thomas 2018).



the submeters were subcontracted to the project electrician to meet the building safety requirements. FPInnovations did not independently verify the installation, or readings from the sensors. The hardware used for monitoring is shown in Appendix I.



Figure 2. An RH/T/MC sensor with probes installed on interior surface of plywood wall sheathing.



Figure 3. An RH/T/MC sensors with probes installed inside roof.



To collect data from the sensors, three gateways were installed on levels 1 (Janitor Room), 3 (M & E closet), and 6 (M & E closet), respectively, to wirelessly connect the sensors installed throughout the building. A Telus hub was installed in the M & E closet on level 3 to provide internet connection for the three gateways. Data collection started in February 2021 when the building was near completion, with the wireless sensors reporting readings every five minutes to the data loggers.

Data loss unfortunately started not long after activation of the monitoring system and became increasingly severe. Dr. Neal Holcroft of FPInnovations checked the monitoring system on site in April 2022 and identified the issue was caused by sensors, not gateways or internet connections. The sensors must have failed due to failure of their batteries, which are expected to last 10-15 years under normal indoor conditions (i.e., warm, dry). However, they may have shortened service life under adverse conditions (e.g., cold/damp conditions), which could have occurred during on-site storage. For convenience, all sensors were shipped to the site in early 2020, given the distance from FPInnovations' Vancouver office to the site. Installation of most sensors, however, were delayed, partially due to delays in the construction and various constraints for travel related to the COVID-19 pandemic. The uninstalled sensors were stored inside a container on the site before they were finally installed in the building in early 2021. A proposal was made by FPInnovations in 2022 to repair and replace damaged sensors and to survey occupants for building performance. However, permission for building access was not provided following the ethics reviews required by BC Housing. The reviewers had concerns about potential effects of the study on privacy and health of the occupants.

This report aims to provide the collected data to show building performance. About one third of the sensors, as shown in red in Table 1, have reported data continuously since 2021 for at least a year. The data are shown in the following section for discussions. Other data are listed in Appendix II as additional information.

5 RESULTS AND DISCUSSION

5.1 Hygrothermal Performance of Envelope Assemblies

Hourly data collected from February 2021 are used to show moisture conditions of the plywood sheathing from the construction stage into service. The prefabricated panels were installed about one year earlier; however, no data were collected earlier to specifically show construction wetting since it was not convenient to set up the monitoring system in early stages of the construction. Monitoring hygrothermal performance of a building assembly primarily aims to provide insight about its long-term durability performance.

For wood, the amount of moisture it contains is one of the most important factors influencing its properties and building-related performances including strength, stiffness, swelling/shrinkage, mould growth, and decay. The “S-Dry” lumber commonly used in wood framing is kiln-dried to a MC of 19% or lower. Composites, such as plywood usually have a MC below 12% at manufacture. But dry wood can absorb moisture from humid air and liquid water sources. Related to durability, mould needs a minimum



surface RH of around 80%⁷ to grow on wood at a temperature of 20-25°C (Nielsen *et al.* 2004). Compared with mould growth, decay can cause weight loss and significant strength reductions and is the largest wetting-related durability concern for structural wood. For most wood products, such as kiln-dried dimension lumber and engineered wood products used in construction, their MC typically needs to rise to approximately 26% (the low end of fibre saturation point) for decay to initiate at around 20°C (Wang *et al.* 2010). It may take months for detectable structural damage to occur under marginal conditions. However, for damp wood (i.e., with a MC of 40-80%) in a warm environment (e.g., at a temperature of 20-30°C), decay and the consequent strength loss can occur quickly, within weeks in susceptible wood.

All the hygrothermal measurements from the sensors installed in the exterior wall and the roof assemblies indicate the service environment for the plywood sheathing has been dry since completion of the construction, and the wall/roof sheathing has been well protected against water penetration in service. Taking the measurements from a wall location on level 1 (north-facing suite 116, Figure 4) as an example, the measured temperature remains similar before and after occupancy, assuming occupancy started in September 2021, with the temperature largely staying above 10°C in the winter. The RH measured from the interior surface of the sheathing has remained about 50%, indicating a dry and consistent service condition for the wood. The MC measured from the plywood sheathing has remained slightly below 10% in service. The higher initial MC in the chart indicates the wood had been slightly damper in the construction. The measurements from the roof locations (Figure 5) inside the building are slightly warmer and drier, compared to those from the exterior wall assemblies. Looking at both exterior wall and the roof assemblies, the thick insulation installed exterior to the plywood sheathing has kept the wood warm and in low humidity throughout the year. For the wall, the vapour-permeable exterior insulation and sheathing membrane will also allow drying towards the exterior following wetting incidents, for example, that could occur during construction. Such field results are consistent with those of similar wall assemblies tested at FPInnovations' Test Hut in Vancouver (Wang 2021; 2023; 2025a). To conclude, the exterior sheathing in the building envelope has remained dry at all measurement locations, without sign of wetting. The good practices implemented including the use of split insulated assemblies with thick exterior insulation and using prefabricated, well protected wall panels/assemblies during the construction help ensure long-term durability of the building envelope.

⁷ The equilibrium moisture content of solid wood is approximately 16% in an environment with a relative humidity of 80% and a temperature of 20°C, and about 9% when the relative humidity drops to 50%.

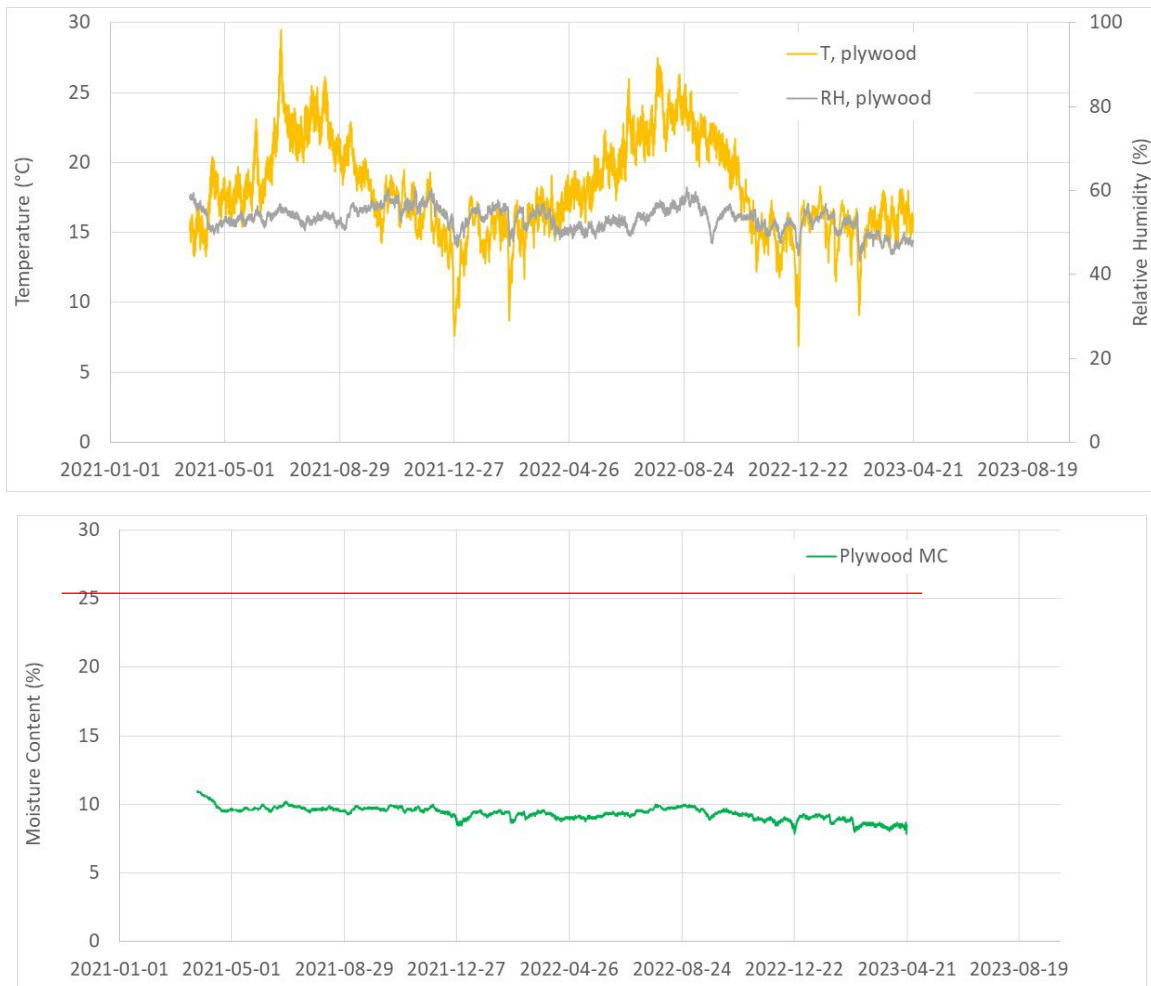
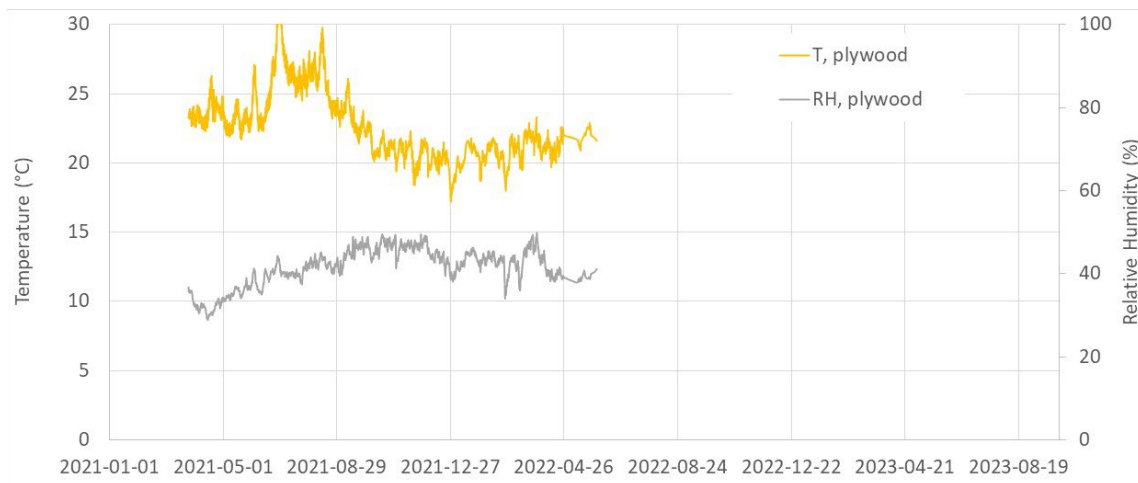


Figure 4. Measured temperature (T) and relative humidity (RH) (top), and wood moisture content (MC) (bottom) from north-facing wall in studio suite 116.



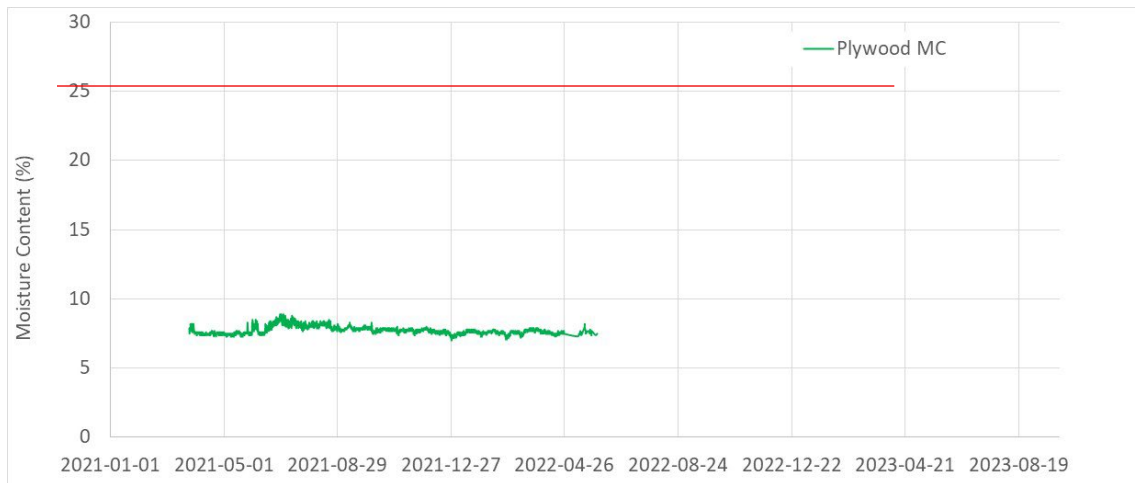


Figure 5. Measured temperature (T) and relative humidity (RH) (top), and wood moisture content (MC) (bottom) from roof in suite 613.

5.2 Indoor Thermal Comfort

The measurements from several suites for three or four years, started from January 2022 in early occupancy, are used here to show seasonal changes in the indoor environment in operation. The indoor environment (temperature, humidity etc.) is an important design consideration as it affects occupant thermal comfort. Indoor temperature is a key parameter for thermal comfort. It depends on many factors, such as thermostat setting, exterior environmental conditions, building envelope performance (i.e., airtightness, thermal insulation), solar heat gains (orientation of exterior walls, windows), air exchange rates between indoor and outdoor, occupants and their behaviour (appliances, cooking, showering, opening windows), and so on. To respect privacy, no information about occupants or occupant behaviour (e.g., frequency of opening windows, use of portable air conditioners) is collected in this study.

The charts from Figure 6 to Figure 10 show the hourly temperature and RH measured from suites 110, 113, 301, 317, and 601, respectively. The monitored living spaces include bedrooms, living rooms, and studios, with orientations covering east, west, north, and northwest. The temperature largely ranges from about 15°C to 30°C and varies greatly among suites/spaces. For example, the temperature in the south-facing suite 110 and the west-facing studio suites 301 and 601 occasionally drops to 15°C and remains largely below 20°C, indicating the occupants are probably tolerant of a cooler indoor space in the winter, which could reduce space heating energy consumption (see section 5.4 for discussion). The two suites (south-facing 110, north-facing 113) on the first floor appear to be relatively cooler throughout the years; but the effect of building height is not clear given the limited data available. In terms of orientation, two west-facing studio suites (301, 601) appear to be the warmest, with indoor temperature frequently exceeding 28°C in the summer. The warmest time with temperature exceeding 25°C in these suites all occur in the summer (June-August).

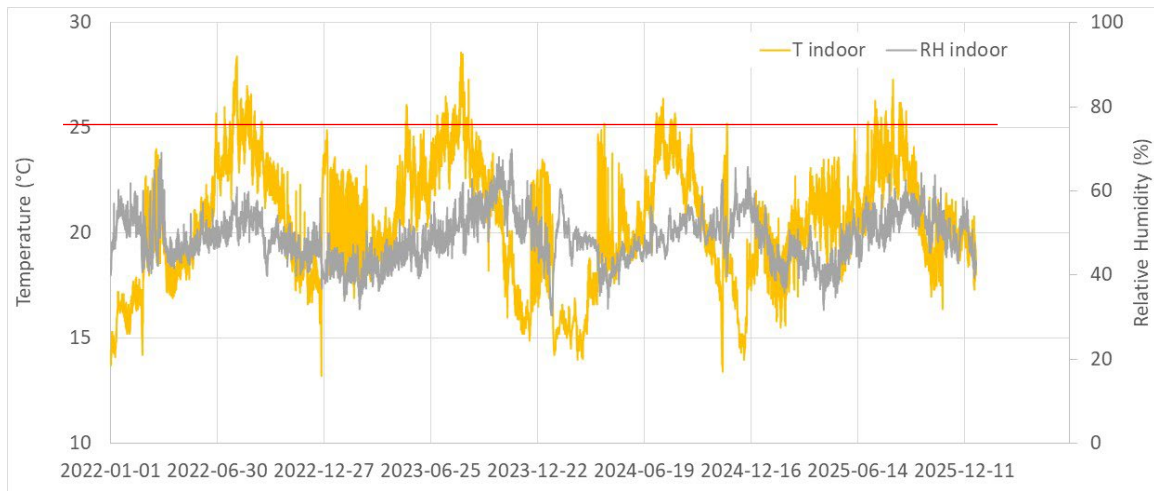
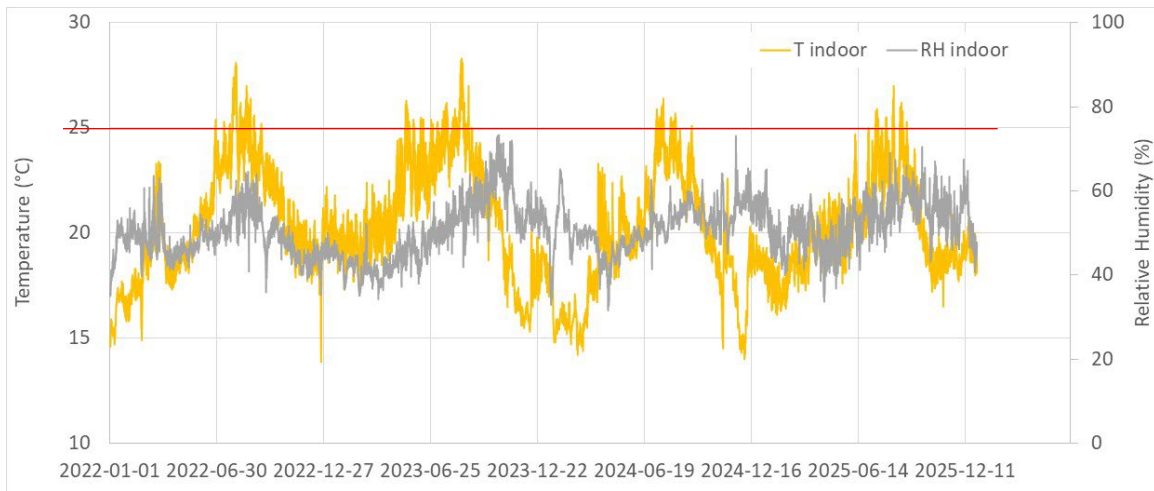
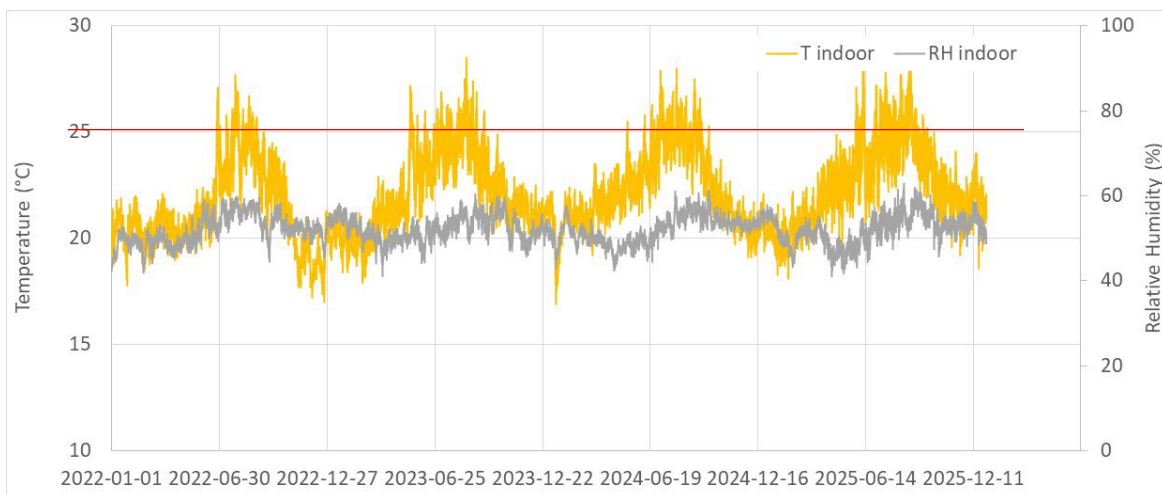


Figure 6. Measured indoor temperature (T) and relative humidity (RH) from one-bedroom south-facing suite 110: bedroom (top) and living room (bottom).



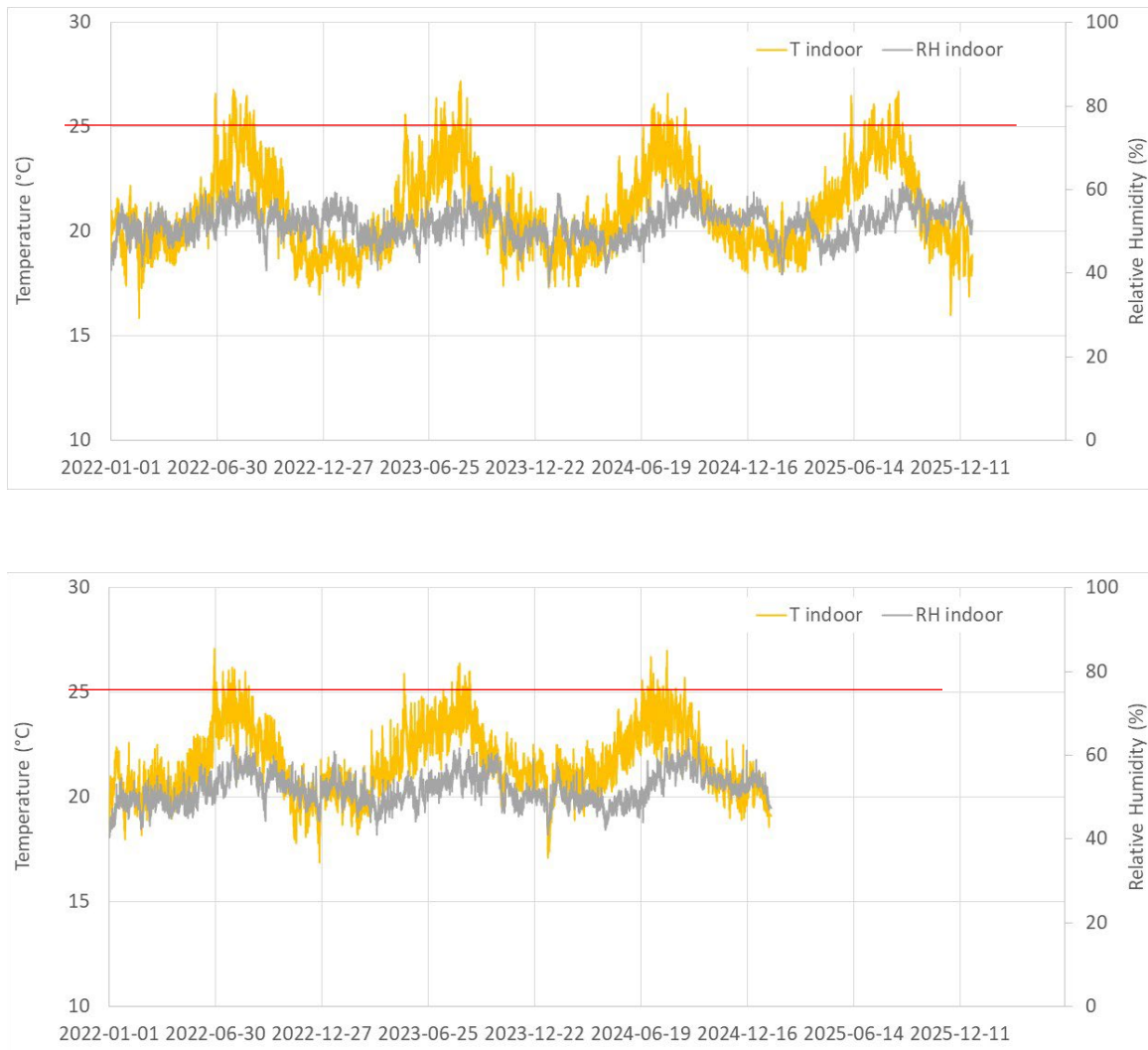


Figure 7. Measured indoor temperature (T) and relative humidity (RH) from three-bedroom suite 113: two of the north-facing bedrooms (top, middle) and living room (bottom).

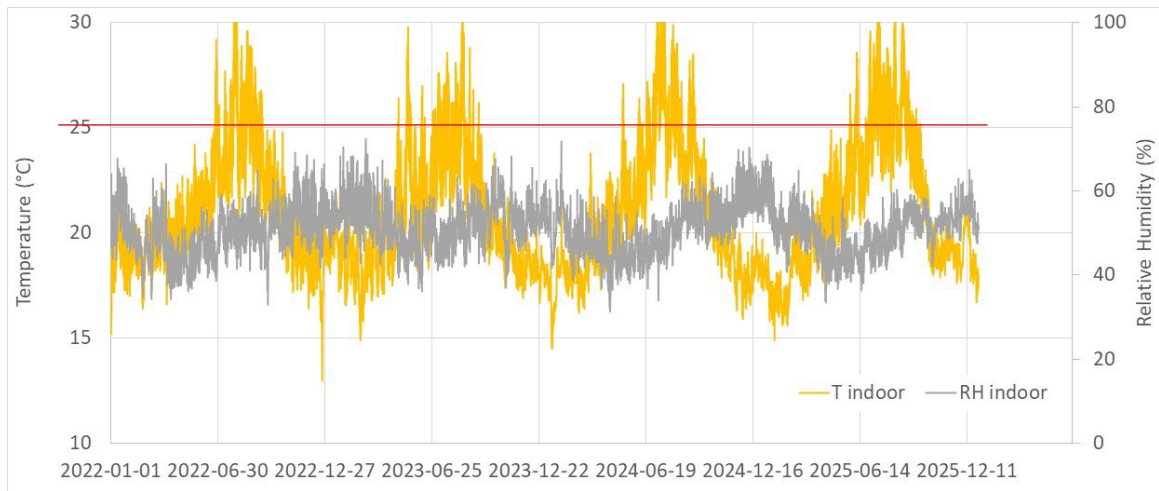
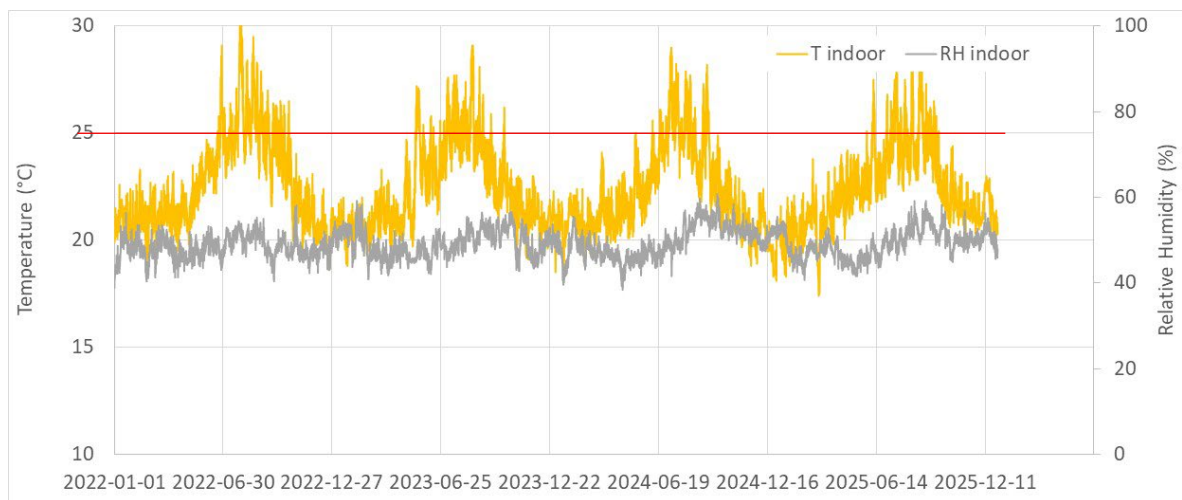
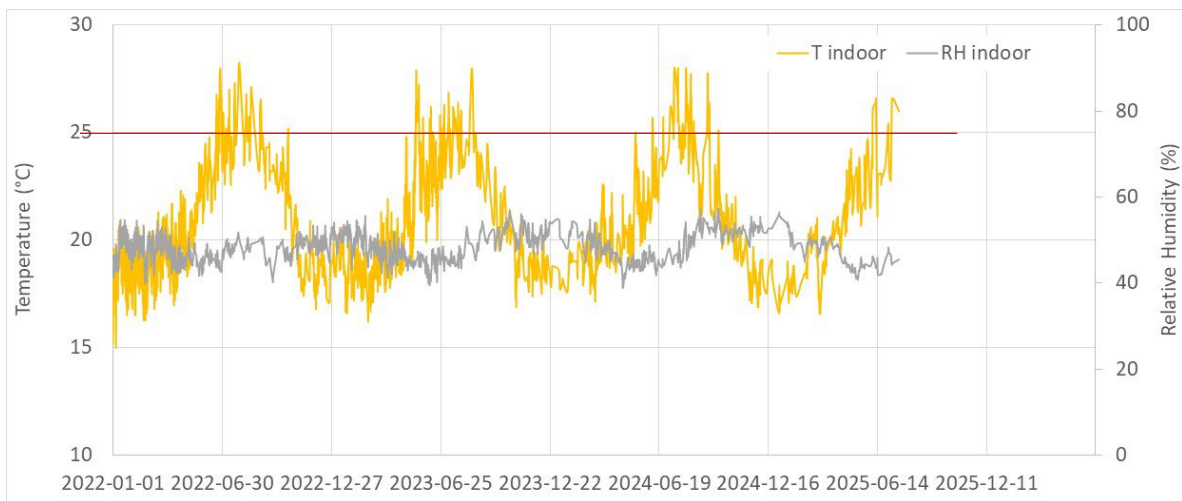


Figure 8. Measured indoor temperature (T) and relative humidity (RH) from west-facing studio suite 301.



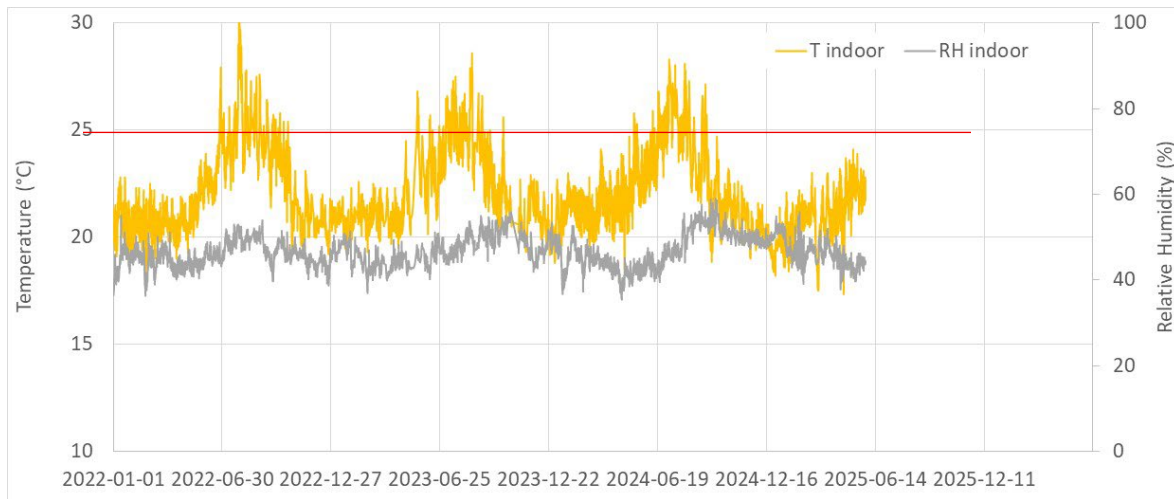


Figure 9. Measured indoor temperature (T) and relative humidity (RH) from three-bedroom suite 317: southwest-facing bedroom (top); south-facing bedrooms (middle); and living room (bottom).

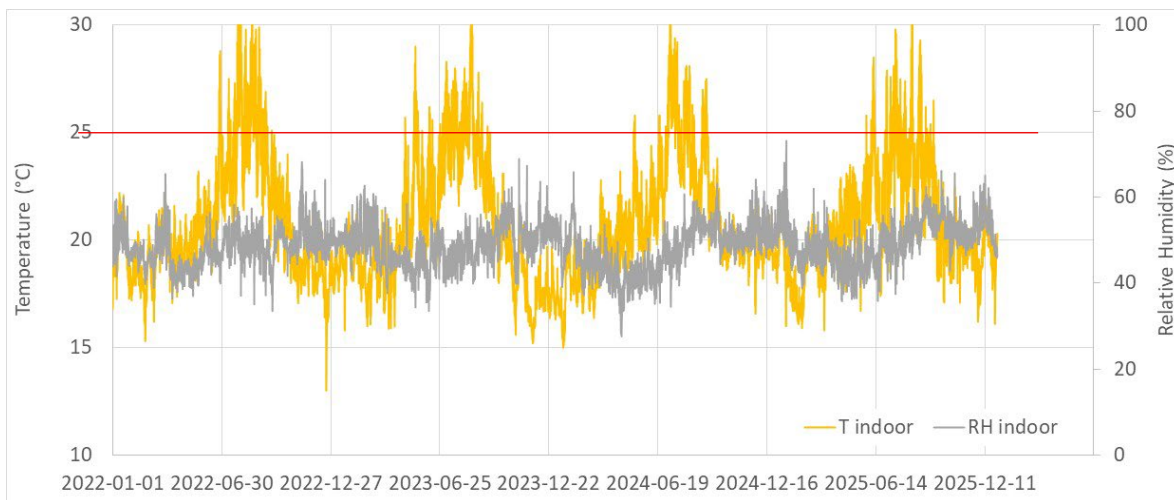


Figure 10. Measured indoor temperature (T) and relative humidity (RH) from west-facing studio suite 601.

To assess overheating potential and severity, this study uses the criterion of the Passive House standard, with a threshold of 25°C to calculate the yearly overheating hours in the monitored suites to be consistent with the previous studies (Wang 2019; Wang and Ngo 2021; Wang 2025b). The standard has an upper limit of 10% (i.e., 876 hrs) for the yearly maximum number of hours with indoor temperature exceeding 25°C to prevent indoor overheating (Passive House Institute 2026). It has recently added a new provision to target less than 5% (i.e., 438 hrs) to achieve a more comfortable indoor environment.

The total hours in a year, with the average hourly indoor temperature exceeding 25°C are calculated for suites 110, 113, 301, 317, and 601, respectively, with 10 indoor spaces in total, based on the indoor temperature measured from January 1, 2022, to December 31, 2024 or 2025, depending on the suite (i.e.,



the data available) (Table 2). The data from these suites indicate overheating is overall not severe in this building. Only one suite, west-facing studio 601 shows severe overheating, with 15.7% of the hours from 2022 to 2025 having indoor temperature exceeding 25°C. The other west-facing suite 301 follows with 9.7%, based on four years' measurements. The overheating must have been mostly contributed by solar heat gains when the exterior temperature peaks during later summer afternoons. The exterior shade probably does not function well enough to block such solar heat. By comparison, the four south-facing living spaces have overheating hours ranging from 6.1% to 9.1%, meeting the Passive House requirement. The exterior shading installed at their windows appears to be effective at least for the south-facing suites. The two north-facing spaces inside suite 113 also have a considerable number of overheating hours, with 8.2% and 2.8% of yearly hours exceeding 25°C, respectively; although the north, compared to the other orientations, receives the smallest amount of solar energy. The two interior living rooms (without exterior windows) inside suites 113 and 317, have overheating hours of 1.3% and 4.1%, respectively; their cooler environment must have been contributed by a lack of direct sun exposure. Solar heat is one of the major sources of indoor heat; in addition, the temperature inside a living space is affected by other factors, such as appliances (e.g., fridge), occupants (e.g., occupant density, age) and their behaviour (e.g., cooking etc.), and ventilation rates. Related to this study, previous monitoring of seven suites in a similar six-storey wood-frame residential building (with smaller exterior shades) in Vancouver showed south- and west-facing suites had more severe overheating than the other orientations (Wang 2019).

Table 2. Summary of overheating hours with measured indoor temperature exceeding 25°C.

Suite	Measurement location	Major orientation	Average yearly hours with measured indoor temperature exceeding 25°C (hr)	Percentages ⁸ of overheating, yearly (%)
110, one-bedroom	Living room	South	669 (2676 hrs in 4 years)	7.6
	Bedroom	South	567 (2264 hrs in 4 years)	6.5
113, three-bedroom	Living room		112 (335 hrs in 3 years)	1.3
	Bedroom 2	North	718 (2873 hrs in 4 years)	8.2
	Bedroom 3	North	242 (968 hrs in 4 years)	2.8
301, studio	Studio	West	851 (3404 hrs in 4 years)	9.7
317, three-bedroom	Living room		356 (1069 hrs in 3 years)	4.1
	Bedroom 2	South	794 (3177 hrs in 4 years)	9.1
	Bedroom 3	South	536 (1609 hrs in 3 years)	6.1
601	Studio	West	1379 (5514 hrs in 4 years)	15.7

⁸ The number in red indicates the overheating percentage exceeds the 10% limit and those in orange indicate exceeding the 5% limit.



The effect of window orientation is further assessed. Figure 11 shows the changes in the hourly indoor temperature in three living spaces facing different orientations during a warm week in August 2022, together with the exterior temperature reported by Environment Canada for the location of Victoria International Airport. It appears the indoor temperature in both the south- and north-facing suites/living spaces is more consistent throughout the day and less affected by the large fluctuations in the exterior temperature. The north-facing location is slightly cooler than the south-facing location based on the measurements from these two suites. In the south orientation, the exterior shading installed at the window must have reduced solar heat gains to a great degree. By comparison, the west-facing living space shows the largest effect of window orientation, with the largest fluctuations in indoor temperature among the suites monitored. The indoor temperature in the west-facing suite/space tends to rise later in the day, typically after 4:00 pm, compared to that in the south orientation. It often becomes cooler in the early morning (e.g., 6:00 am) than the south-facing suite/living space. However, when it is hot outside, for example, with the exterior temperature above 25°C, the late solar heat gains probably become too large for the indoor space to cool down overnight; as a result, the west-facing suite/living space is warmer than the south-facing suite/living space in the early morning.

For the suites experiencing severe overheating, measures, such as providing more efficient and orientation-specific exterior shading, increasing mechanical/natural (cross) ventilation, and providing cooling (e.g., use of a portable cooler) in a warm season should reduce the time and intensity of overheating. Use of mechanical cooling is the most effective way to prevent indoor overheating, as confirmed with similar performance monitoring of an energy efficient, six-storey wood-frame residential building in a northern BC climate (Wang and Ngo 2021).

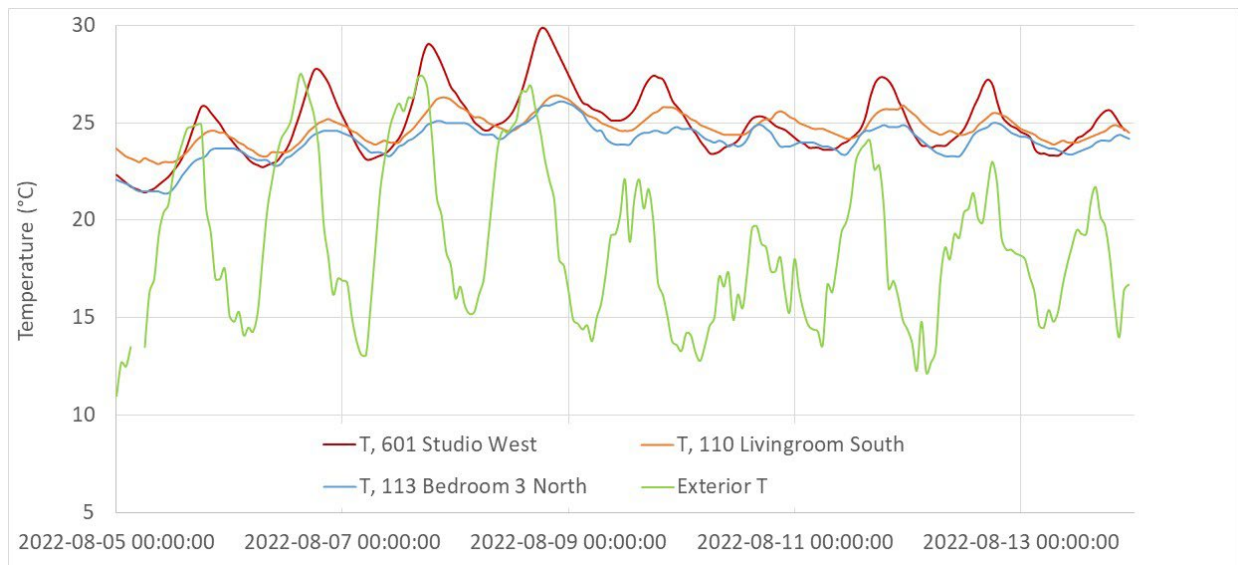


Figure 11. Measured indoor temperature (T) of three living spaces in different orientations together with exterior temperature from August 5 to 13, 2022.



5.3 Indoor Humidity

Compared to temperature, indoor humidity often has a smaller effect on indoor comfort for most occupants. However, prolonged high humidity (e.g., above 80%) will accelerate metal corrosion and microbial growth, which may adversely affect indoor environment and even structural durability (ASHRAE 2016). On the other hand, persistently dry air, e.g., with the RH below 20%, tends to cause occupant discomfort and exacerbate respiratory problems and allergies. This commonly occurs in heating seasons in a cold and dry climate. Health Canada recommended an indoor RH between 35% and 50% for healthy conditions (Health Canada 2016). The ASHRAE standard on indoor thermal comfort allows a wider range of RH related to indoor thermal comfort, depending on temperature, air speed, and personal factors, such as clothing insulation and activity level (ANSI/ASHRAE 2017).

In the context of energy efficient buildings, the indoor humidity can be specifically influenced by the design measures to achieving high energy efficiency. For example, with HRVs in operation, the airtight building envelope may increase the humidity level when there is a large indoor moisture load. For this building, the RH measured from suites 110, 113, 301, 317, and 601 show the indoor RH has largely remained around 50%, a comfortable and healthy level of humidity for occupants.

5.4 Heating Energy Consumption

The measurements of space heating electricity consumption are shown in the following charts (Figure 12- Figure 16), based on readings from the submeters used. Only six meters installed in five suites provided continuous readings for four years (suites 110, 116, 306, and 601) or two years (suite 313). The charts indicate most of the energy consumption has occurred only in the winter, with almost horizontal lines (i.e., negligible electricity use) over the other seasons. This is reasonable for a building located in a heating-dominated climate. It also reflects the overall good energy performance of the building, as space heating is typically needed in shoulder seasons (i.e., spring and fall) in most conventional (i.e., less energy efficient) buildings. However, the energy consumption varies greatly among the suites/occupants, ranging from 23.0 to 0.1 kWh/m²/yr, as shown in the charts and in Table 3. Both one-bedroom suite 110 and studio suite 313 have space heating energy consumption exceeding the energy step code requirement of 15 kWh/m²/yr. The other three suites monitored (116, 306, 601) show much smaller amounts of space energy use, far below the code requirement. Suites 116 and 601 show almost a negligible amount of energy use, indicating the baseboard heaters inside the suites have barely been turned on over the years monitored. Note no utility bills are collected to verify the energy consumption measurements in the study. The data indicate occupant behaviour including their tolerance for a cooler environment in the winter and a warmer environment in the summer is critically important to achieve building energy efficiency. They also reflect the high energy efficiency and climate resiliency of the building. Such performance has become critically important at a time, when climate change with extreme weather events has become increasingly severe.

Taking into consideration overheating, west-facing suite 601 has the most severe overheating in the summer but consumes the least amount of space heating energy in the winter among the suites monitored. On the other hand, south-facing suite 110 has a moderate level of overheating in the summer but consumes the largest amount of space heating energy in the winter. Relevant to this study, it was



reported the total energy use in a similar energy efficient six-storey residential building in Vancouver ranged from 15.3 to 135.6 kWh/m²/y, varying greatly among suites/occupants (Wang 2019, data from the project architect). It again indicates the large impact of occupant behaviour on building energy efficiency.

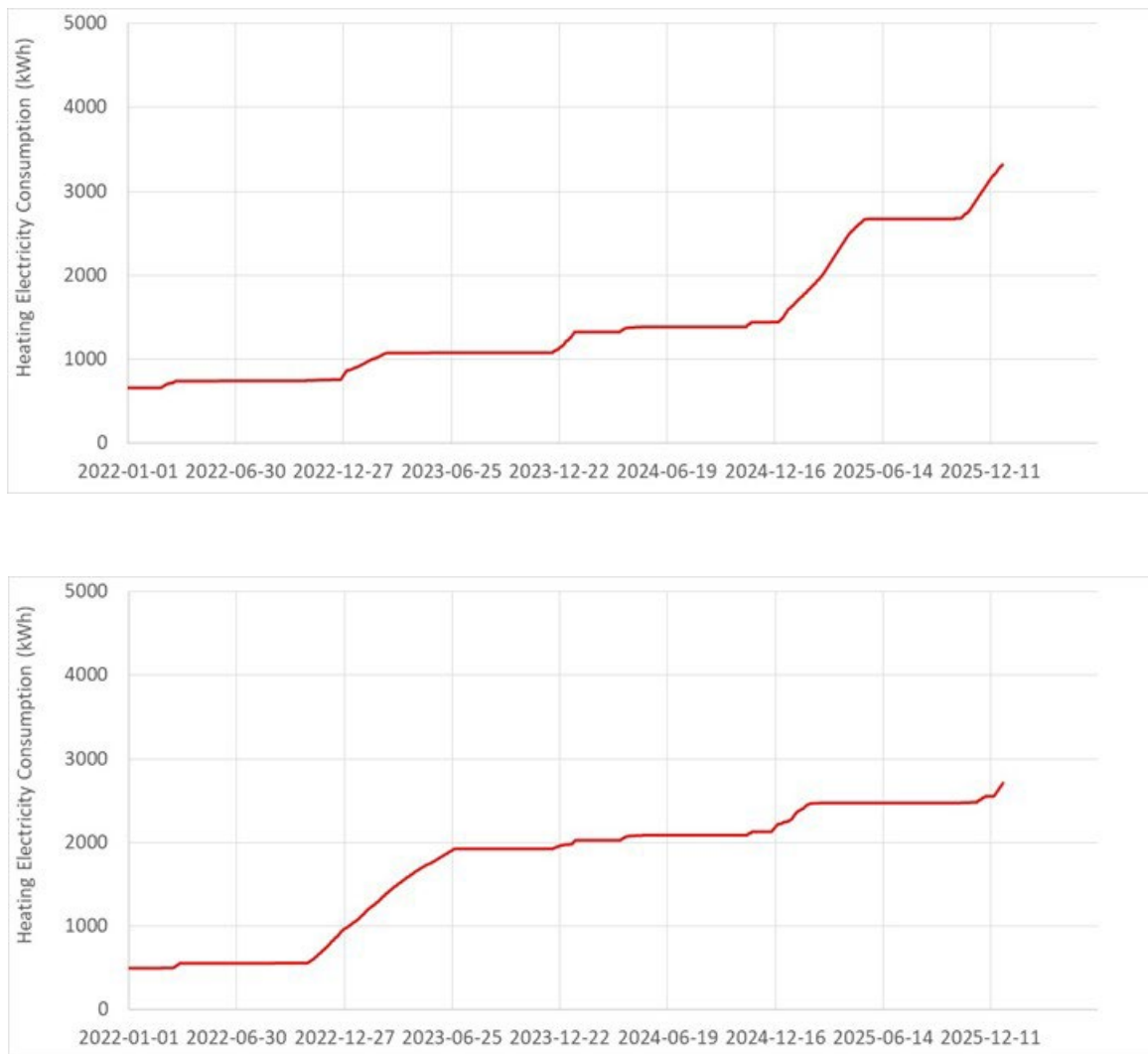


Figure 12. Measured space heating electricity consumption from south-facing one-bedroom suite 110: living room (top); bedroom (bottom).

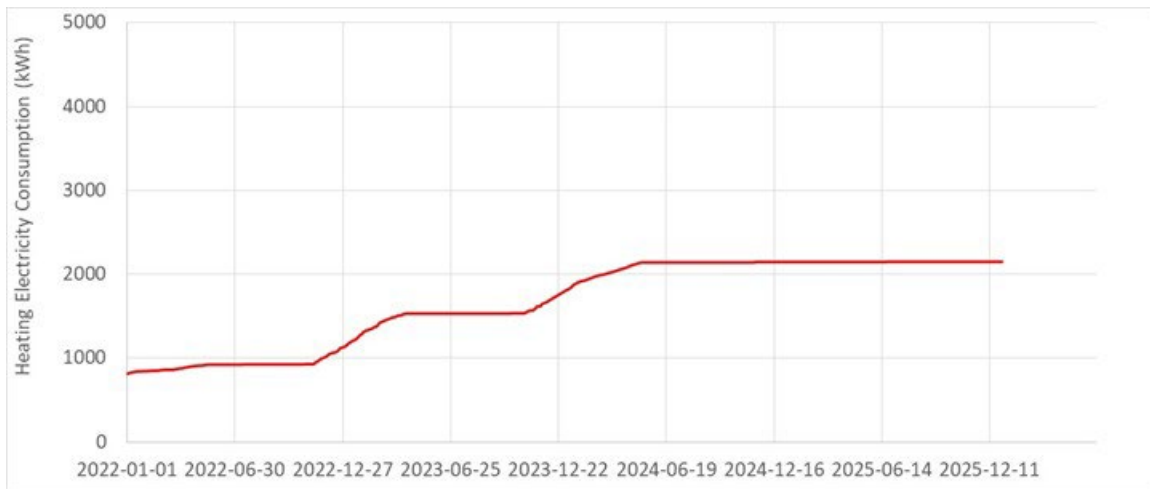


Figure 13. Measured space heating electricity consumption from north-facing studio suite 313.

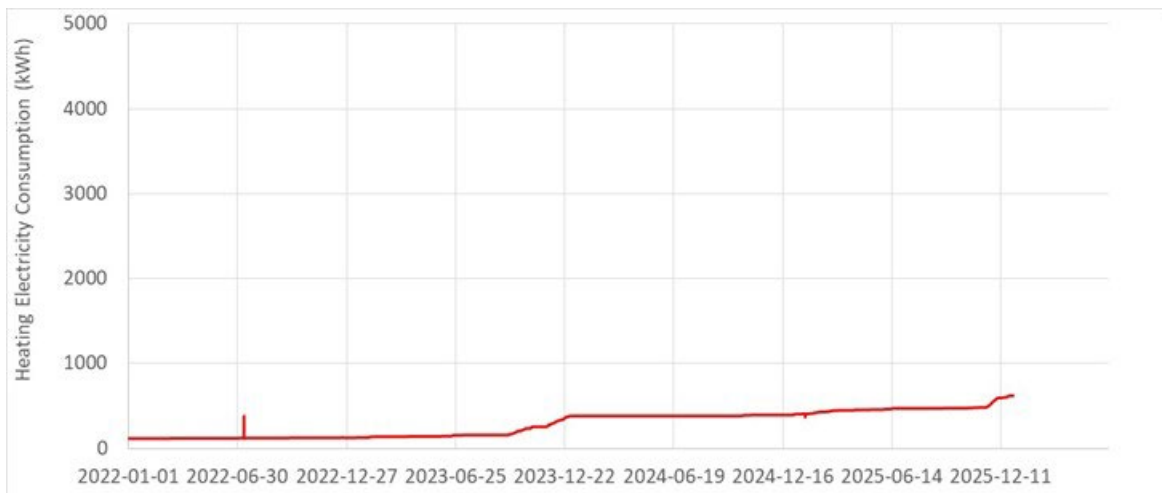


Figure 14. Measured space heating electricity consumption from east-facing studio suite 306.

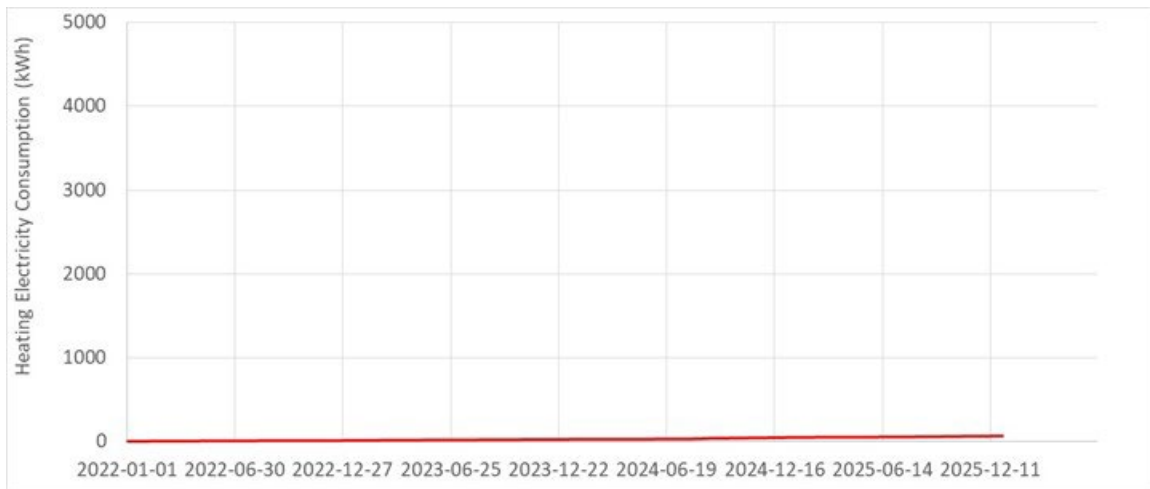


Figure 15. Measured space heating electricity consumption from north-facing studio suite 116.

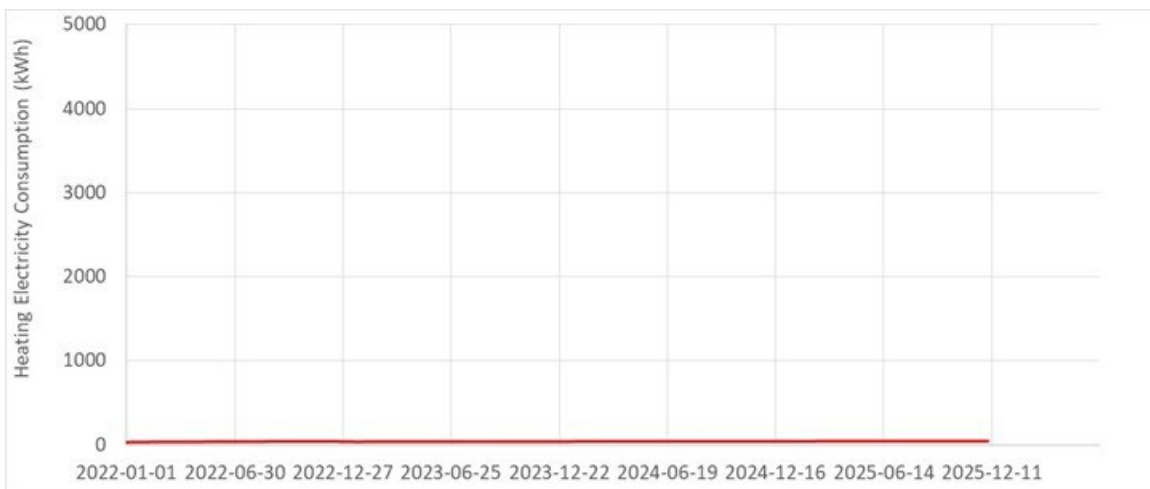


Figure 16. Measured space heating electricity consumption from west-facing studio suite 601.

Table 3. Summary of space heating electricity consumption.

Suite	Measurement space	Major orientation	Electricity consumption (kWh)	Yearly electricity consumption (kWh/yr)	Area (m ²)	Heating energy consumption (kWh/m ² /yr)
110, one-bedroom	Living room	South	2659 in 4 years	664.8	53	23.0
	Bedroom	South	2212 in 4 years	553.0		
313, studio	Studio	North	1215 in 2 years	607.5	33	18.4
306, studio	Studio	East	504 in 4 years	126.0	33	3.8
116, studio	Studio	North	63 in 4 years	15.8	33	0.5
601, studio	Studio	West	14 in 4 years	3.6	33	0.1



6 CONCLUSIONS

This report provides hygrothermal performance, indoor environment, and space heating electricity consumption for an energy efficient, six-storey, wood-frame residential building in Victoria. Major conclusions include:

- The plywood exterior sheathing has remained dry at all measurement locations based on available sensor data from walls and roofs. The split-insulated exterior wall/roof assemblies both with thick exterior insulation keep the exterior sheathing warm and thereby dry in cold weather. The use of highly vapour-permeable exterior insulation and self-adhered membrane in the exterior wall will also allow drying towards the exterior if incidental wetting occurs. These design measures contribute towards long-term durability of the exterior walls.
- The measured temperature and RH from the building indicate overall comfortable indoor space. Use of exterior shading appears to be effective to reduce solar heat gains, especially for the south-facing suites. Among the five suites with relatively complete data collected from the sensors installed, two west-facing suites have the largest hours with indoor temperature exceeding 25°C; one of the suites has 15.7% of the yearly hours with indoor temperature exceeding 25°C, not meeting the Passive House requirements.
- Electricity consumption for space heating ranges from 23.0 to 0.1 kWh/m²/yr for the five suites with data available, based on the submeters installed. Two suites have space heating energy consumption exceeding the energy step code requirement of 15 kWh/m²/yr. The other three suites monitored show much smaller amounts of space energy use, far below the code requirement. Occupant behaviour including the tolerance of the occupants for a cooler environment in the winter and a warmer environment in the summer is critically important for achieving building energy efficiency. The data also reflect the high energy efficiency and climate resiliency of the building, which have become increasingly important to battle climate change.

7 IMPLICATIONS FOR DESIGN AND CONSTRUCTION

The following information and best practices may be taken into consideration when designing and installing highly insulated, wood-frame buildings to improve their thermal performance and long-term durability, based on the monitoring results of this study.

- Using prefabricated panels can speed up construction and thereby reduce the time of exposure during construction. It helps prevent construction wetting to improve long-term durability.
- For building envelope design, whenever possible, specify a high level of exterior insulation to keep the wood warmer and drier in service.
- Vapour-permeable exterior membrane and exterior insulation facilitate the drying of the wood towards the exterior in a heating climate and help ensure long-term durability.



- If overheating occurs, measures, such as providing shading at windows, increasing ventilation by adjusting ventilators or opening windows when it is cooler outside, and providing cooling (e.g., by using portable air conditioners) in a warm season may become necessary to improve indoor thermal comfort.

8 LESSONS LEARNED ABOUT INSTRUMENTATION

Severe data loss unfortunately occurred in this study due to issues with the monitoring system. The following lessons are learned to improve instrumentation of similar monitoring studies in the future.

- Hardware including sensors and gateways should not be stored on site for long to reduce the time of possible exposure to adverse conditions, such as damp and cold environments.
- Hardware must be installed by knowledgeable and experienced professionals.
- Select instrumentation locations that will be suitable for monitoring building performance and relatively safe from potential damage.
- Sensors should not be installed until the selected assemblies are completely sheltered from exposure (e.g., rain). They are ideally installed right before building enclosure to minimize the chance of potential damage caused by adjacent construction work (e.g., plumbing, electrical work).
- Provide a good margin of safety when deciding the maximum distance between the wireless sensors and the gateways to ensure good connections for smooth data collection.
- Provide replication and redundancy in the number of monitoring locations and sensors/gateways used to improve resiliency of the monitoring system.
- The locations of installed hardware (e.g., sensors, gateways) in the building should ideally remain accessible after building completion and occupancy to make it convenient for possible future accesses for repair and replacement.

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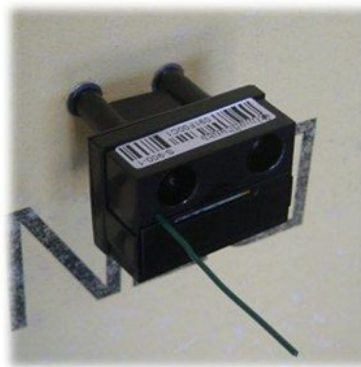
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APPENDIX I: INSTRUMENTATION



1. A sensor for measuring temperature, relative humidity, and wood moisture content



2. A sensor with three ports for measuring temperature, relative humidity, and wood moisture content (left), and probe (right)



3. A submeter for measuring electricity consumption



4. Gateway

Figure 17. Hardware used in this monitoring study.



APPENDIX II

EXTRA MONITORING RESULTS

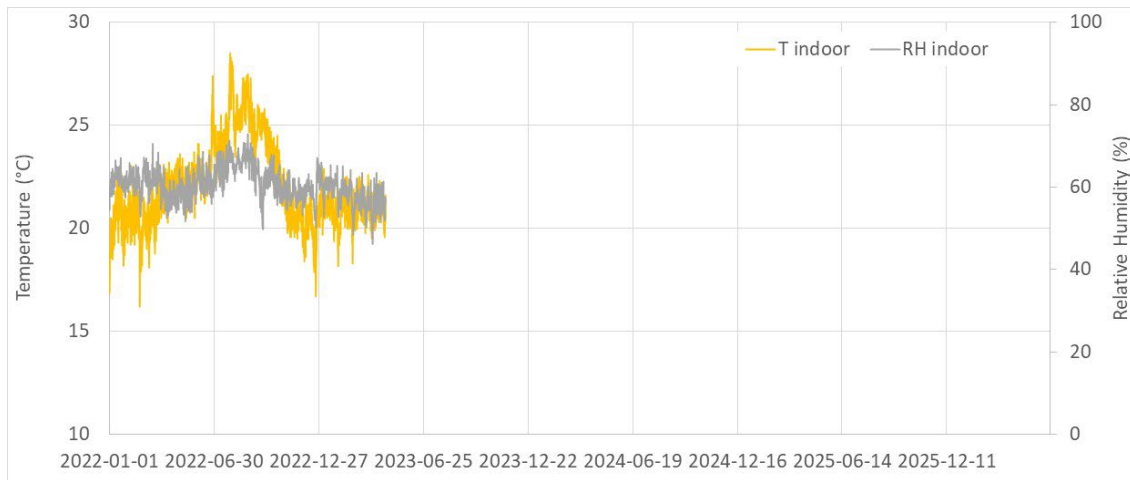


Figure 18. Measured indoor temperature (T) and relative humidity (RH) from north-facing studio suite 116.

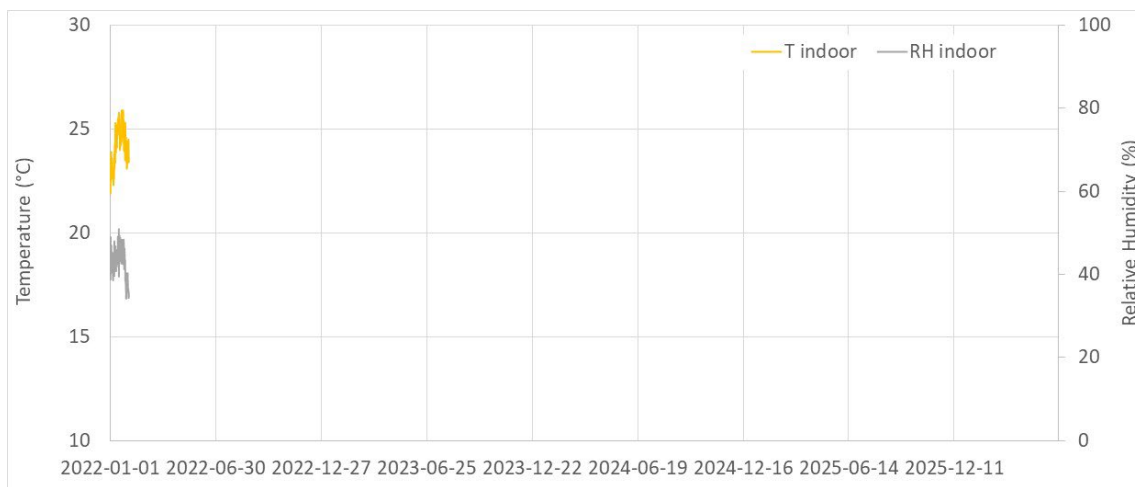


Figure 19. Measured indoor temperature (T) and relative humidity (RH) from south-facing living room of suite 303.

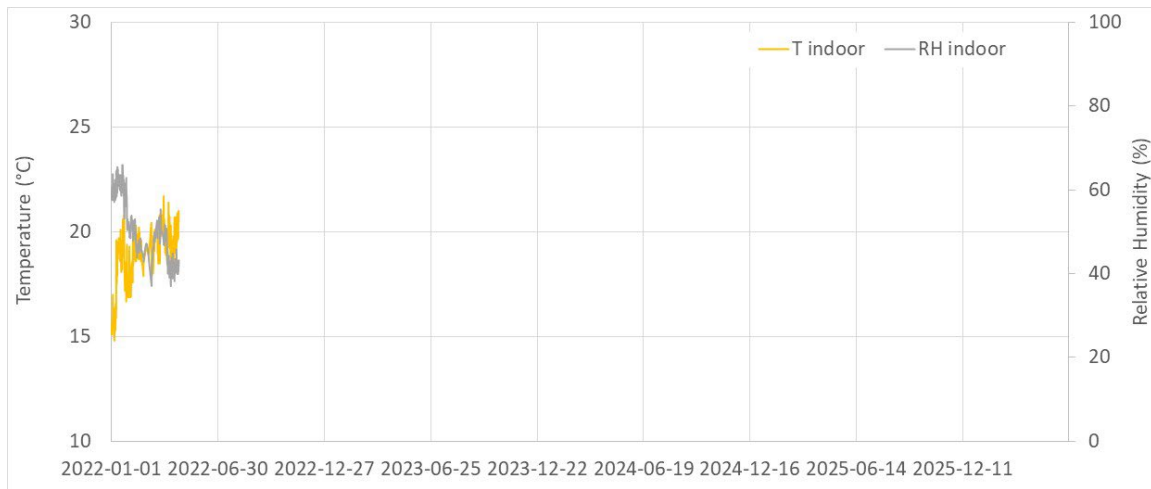


Figure 20. Measured indoor temperature (T) and relative humidity (RH) from south-facing living room of suite 304.

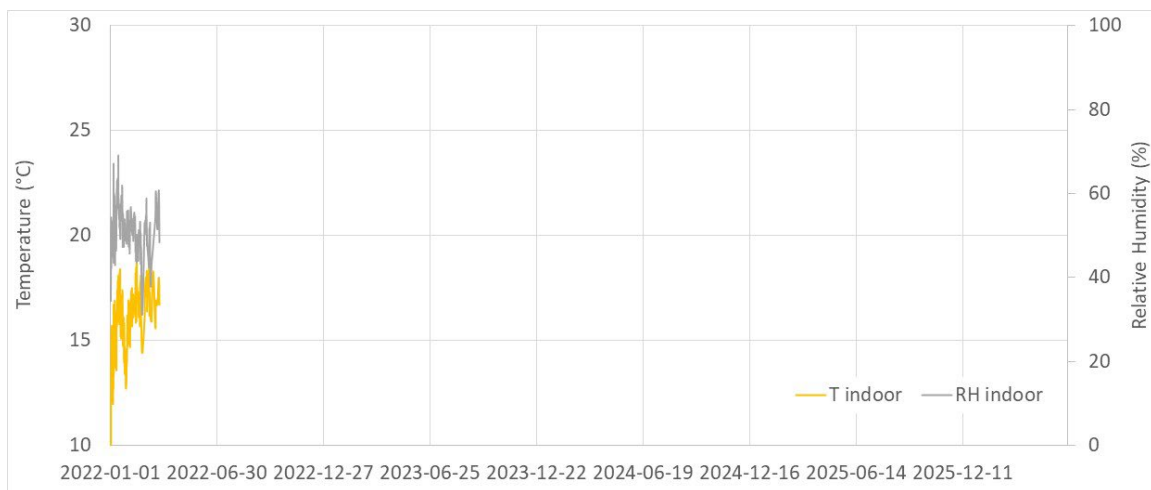


Figure 21. Measured indoor temperature (T) and relative humidity (RH) from east-facing studio suite 306.

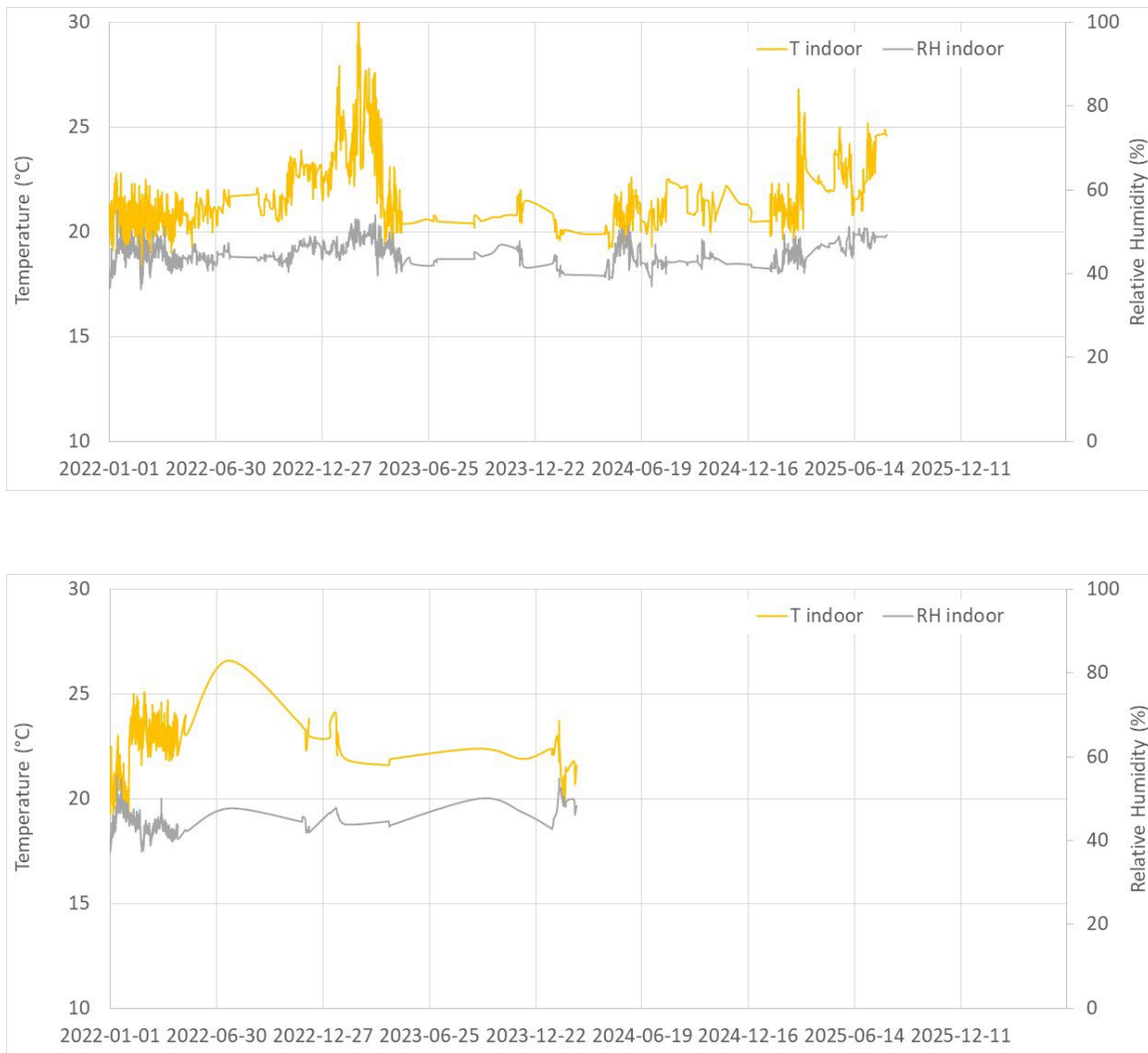


Figure 22. Measured indoor temperature (T) and relative humidity (RH) from three-bedroom suite 316: north-facing bedroom (top); living room (bottom).

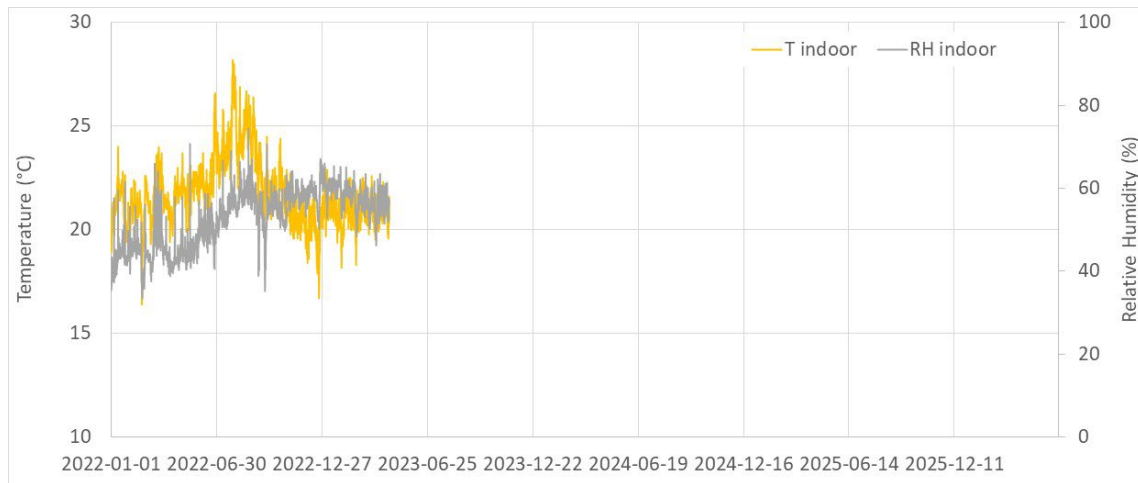


Figure 23. Measured indoor temperature (T) and relative humidity (RH) from north-facing studio suite 313.

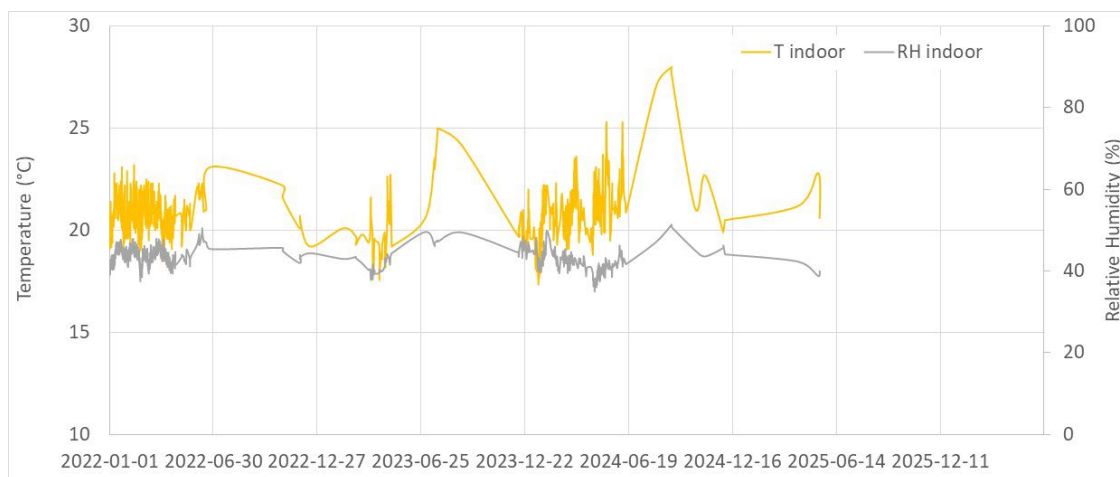


Figure 24. Measured indoor temperature (T) and relative humidity (RH) from south-facing room of three bedroom-suite 617.

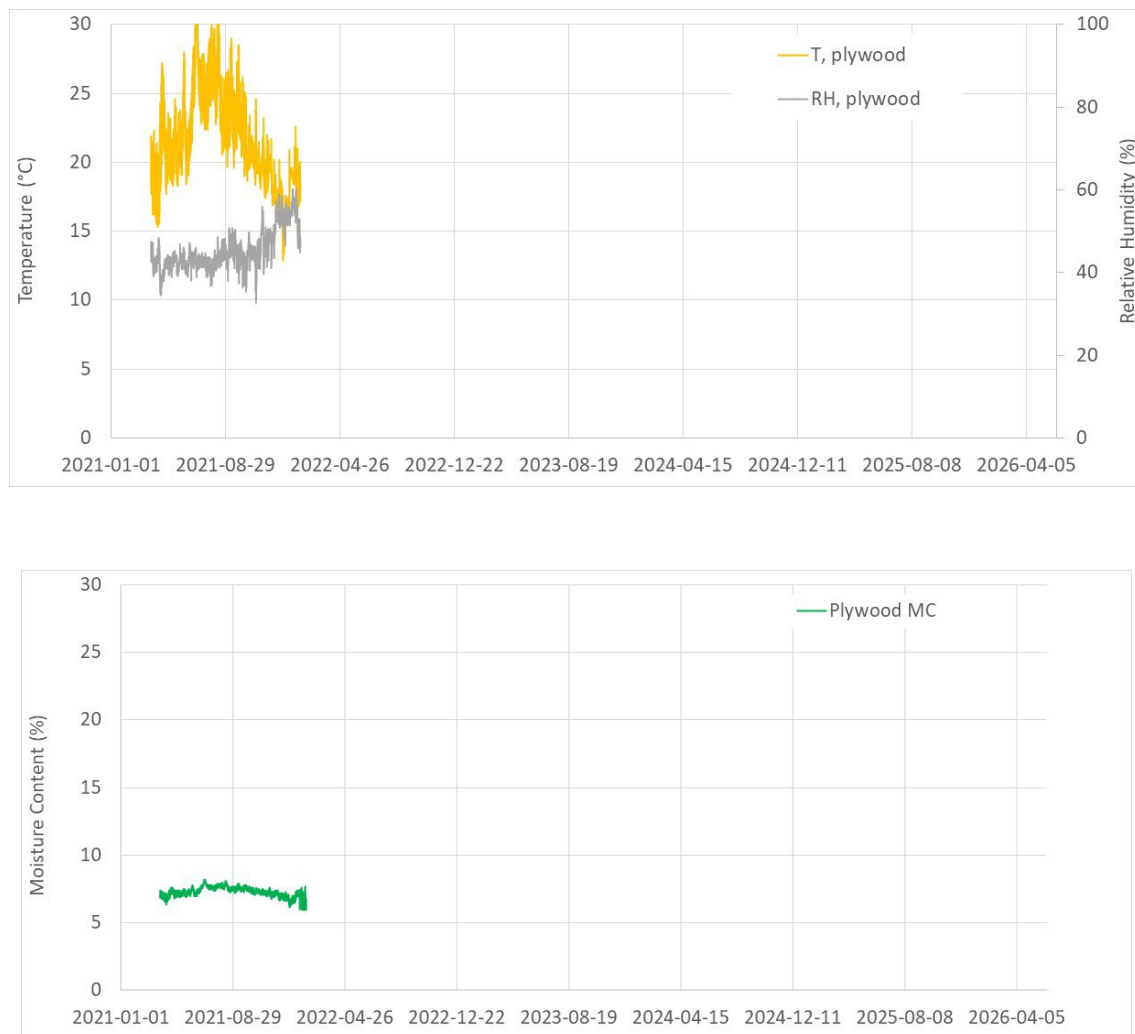


Figure 25. Measured temperature (T) and relative humidity (RH) (top), and wood moisture content (MC) (bottom) from south-facing wall of living room of suite 303.

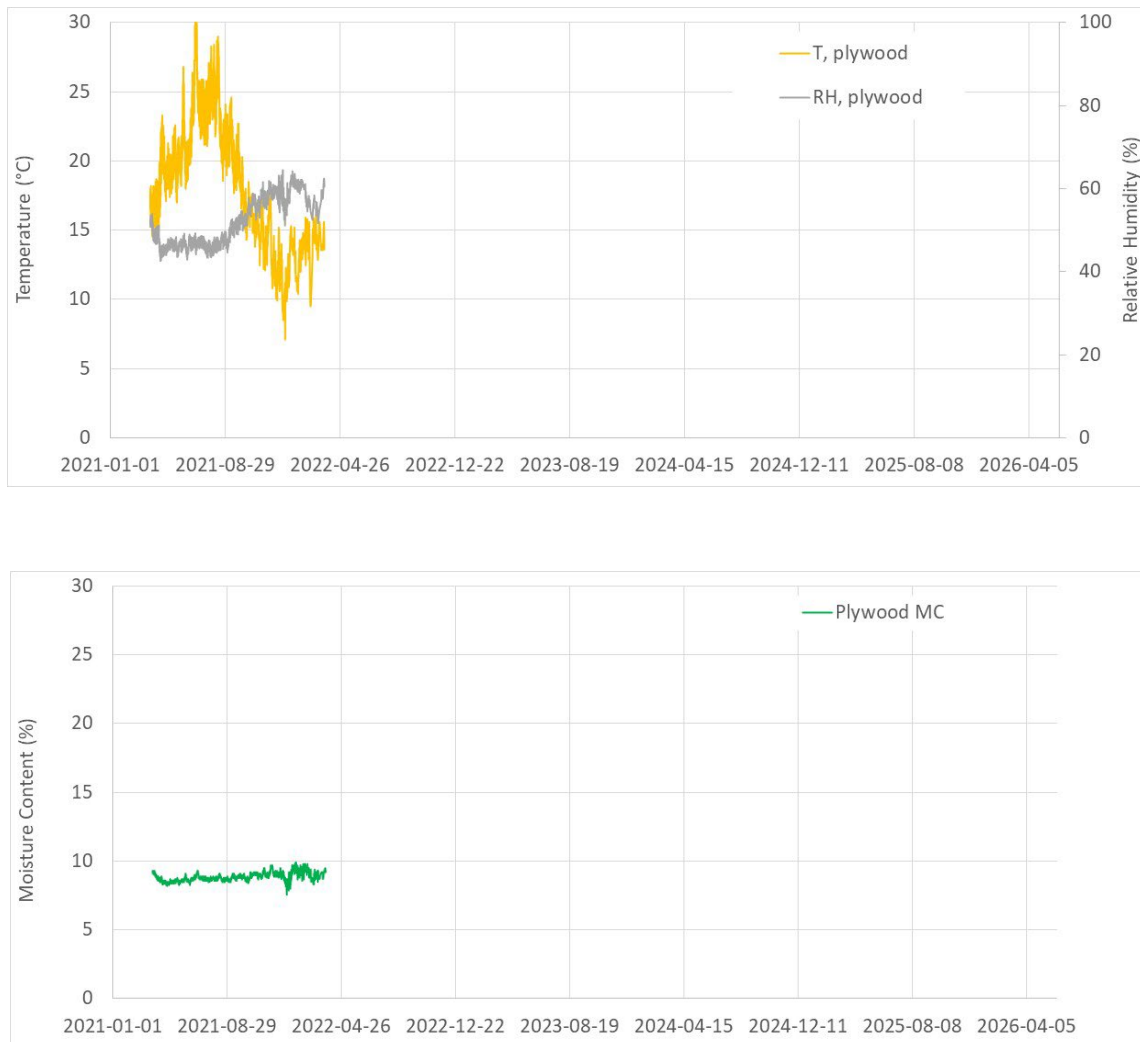


Figure 26. Measured temperature (T) and relative humidity (RH) (top), and wood moisture content (MC) (bottom) from east-facing wall of studio suite 306.

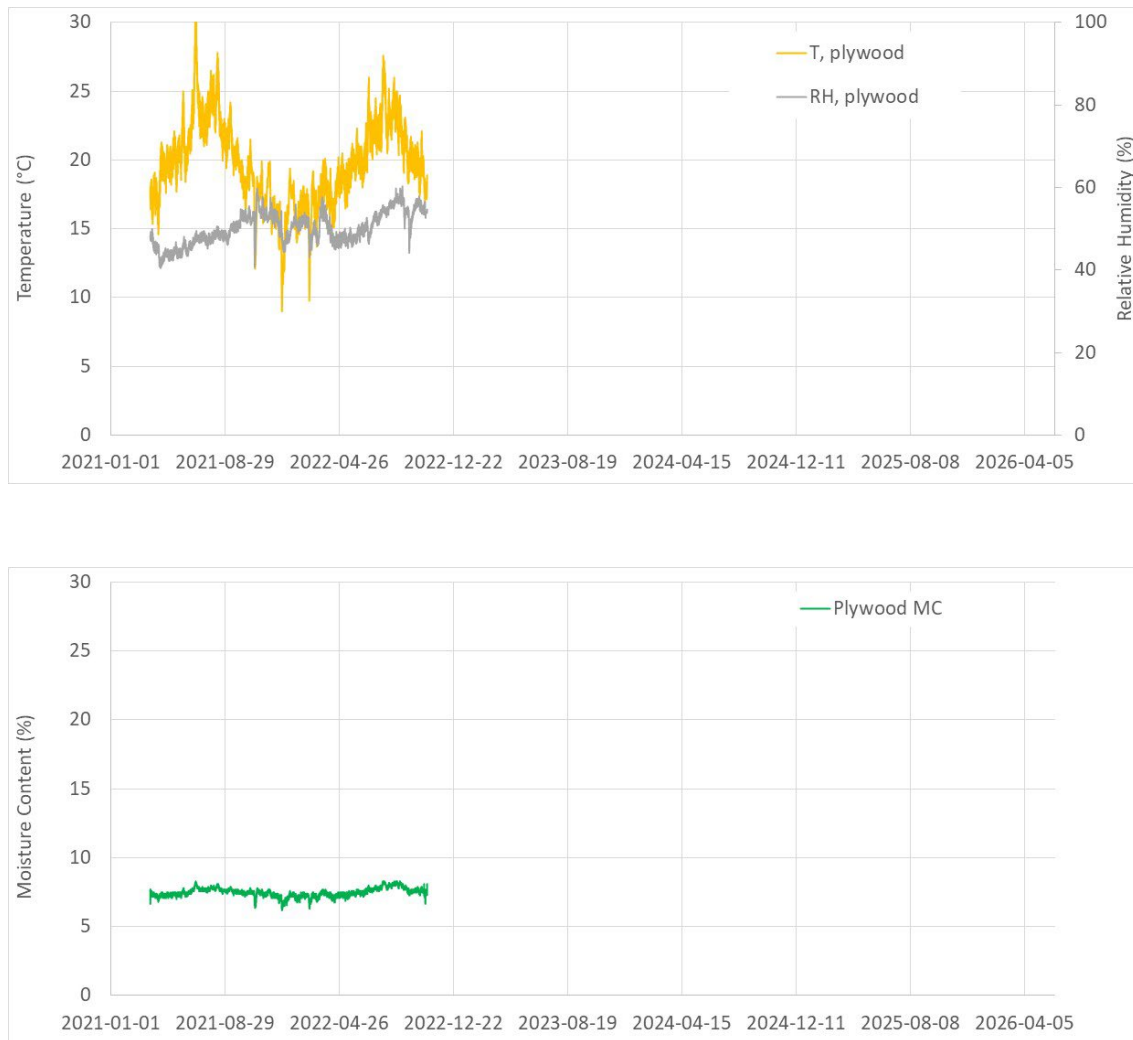


Figure 27. Measured temperature (T) and relative humidity (RH) (top), and wood moisture content (MC) (bottom) from north-facing wall of studio suite 313.

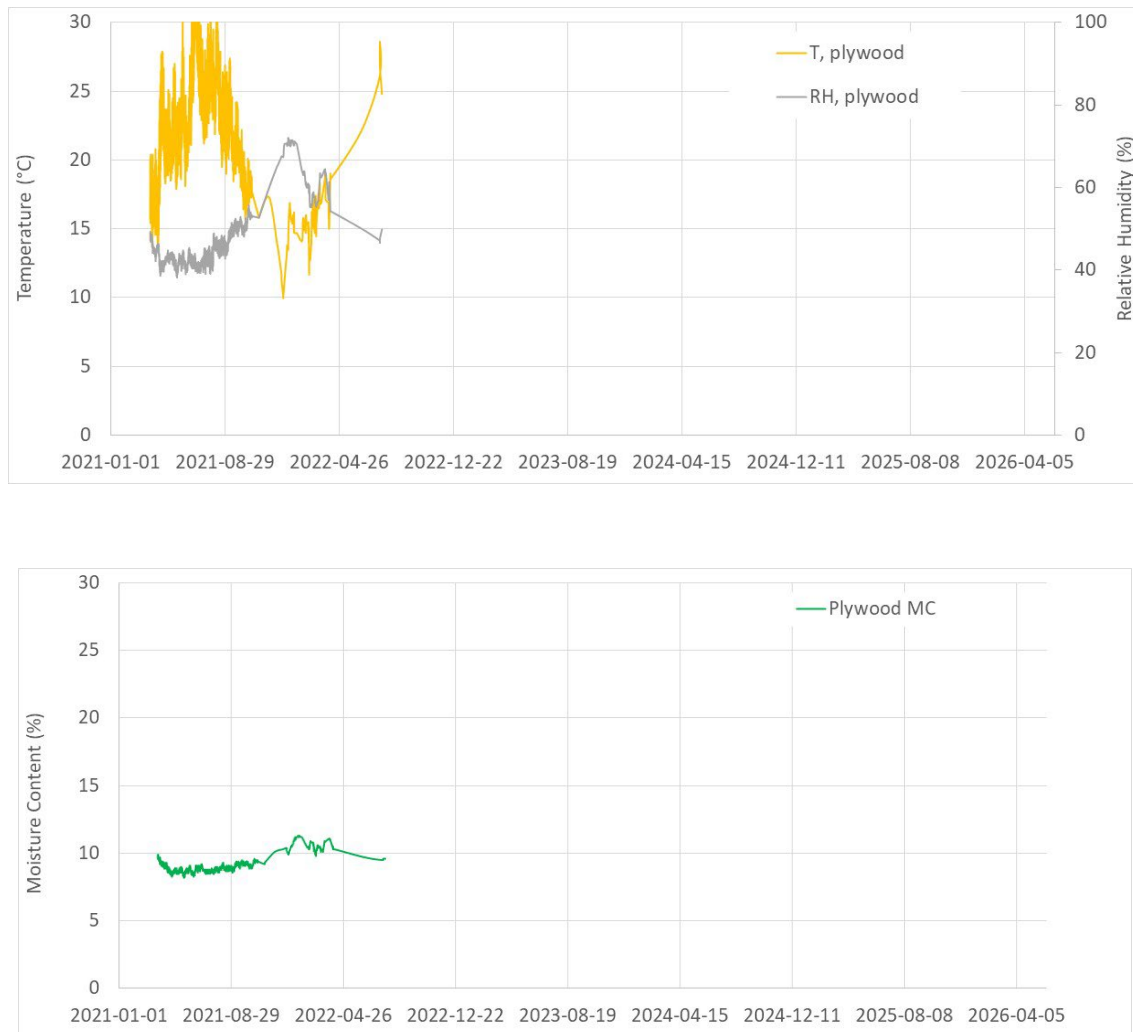


Figure 28. Measured temperature (T) and relative humidity (RH) (top), and wood moisture content (MC) (bottom) from southwest-facing wall of one-bedroom suite 603.

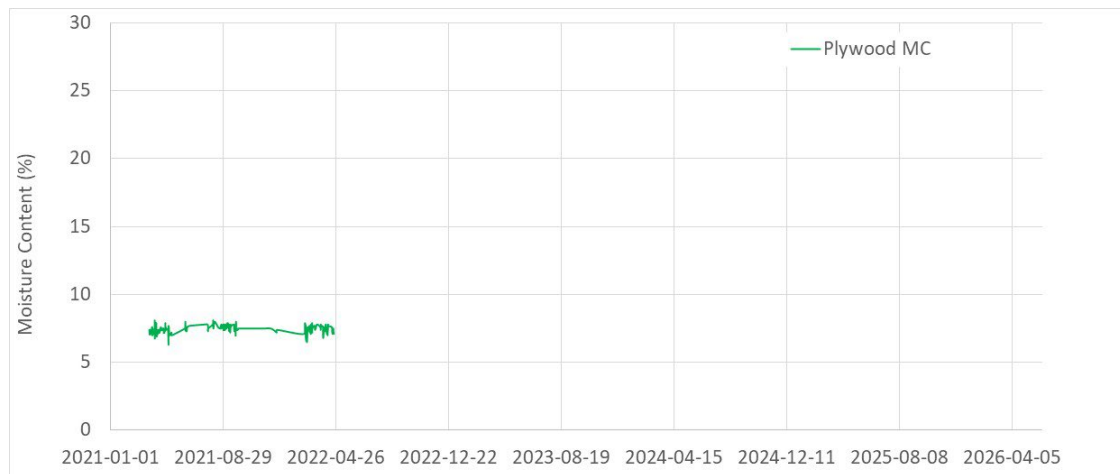
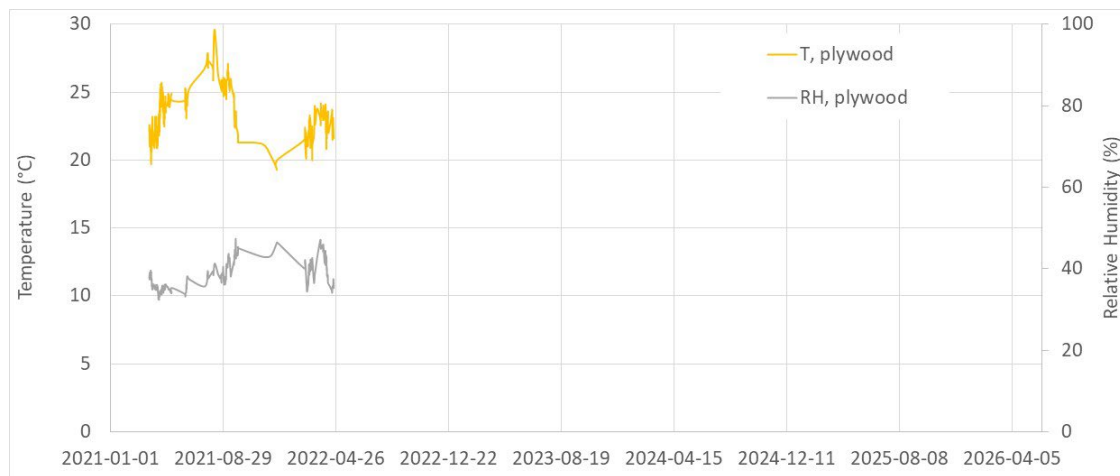


Figure 29. Measured temperature (T) and relative humidity (RH) (top), and wood moisture content (MC) (bottom) from roof of studio suite 606.

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