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HOLISTIC HYGROTHERMAL PERFORMANCE ASSESSMENT OF EMERGING TIMBER ENVELOPES: FIELD TESTING AND TRANSIENT BUILDING SIMULATIONS.

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ABSTRACT: The use of timber in construction brings multiple benefits, such as reducing the environmental impacts of buildings, as it often presents a lower embodied carbon alternative. However, given the material's hygroscopic nature, when timber-based construction systems are not designed correctly, they can present a high risk of mould growth, compromising building performance and occupant health. This study investigates resilience to moisture and mould growth of Australian emerging mass-timber and timber-based envelopes under real climatic conditions. Field testing is conducted on different wall and roof configurations, varying insulation types, weather membranes, and timber boards. Findings from field testing are used to validate assumptions from transient hygrothermal performance simulations performed with WUFI software. The use of photovoltaic cladding is also investigated in simulations.

KEYWORDS: timber construction, high-performance envelopes, hygrothermal, mould growth

1 – INTRODUCTION

Timber is gaining significant attention as a building material from both industry professionals and academic researchers. This growing interest is driven by the numerous potential benefits timber offers, including sustainability aspects and contribution to carbon offsets in construction [1]. Additionally, timber's aesthetic appeal and versatility in construction make it an attractive option for modern architectural designs. However, when not designed correctly, it can present a high mould risk, compromising structural performance, occupant health, and materials' functionality and durability [1–3].

This research investigates the risk of mould growth associated with emerging timber envelopes in Australia, including mass-timber and timber-framed typologies. The hygrothermal performance of 12 different external wall configurations is tested in real climatic conditions. Each configuration's transient hygrothermal behaviour is also assessed with WUFI simulation software [4], and validated against field testing results. The use of building-integrated photovoltaics (BIPV) is also investigated through simulations, given the increasing adoption of such technologies on the Australian building market.

2 – BACKGROUND

2.1 MOISTURE MANAGEMENT IN THE AUSTRALIAN CONTEXT

One in three Australian homes suffers from excessive dampness and mould proliferation [5], which is exacerbated by inadequate architectural strategies, poor construction practices and bad maintenance [6], resulting from a lack of awareness and knowledge in the construction sector about the topic.

Indoor mould is correlated to severe adverse health symptoms, such as severe allergic asthma, hypersensitivity pneumonitis and allergic alveolitis, allergic rhinitis and sinusitis [7,8]. The Healthy Housing CRE [9] has established that, over the next 20 years, it will cost AUD 1.9B to treat health conditions caused by mould exposure in homes and AUD 2.4B in lost productivity in household income.

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Furthermore, mould is responsible for early biodeterioration of building materials, requiring anticipated renovation works. A recent estimate indicates that around AUD$300M is spent every year on mould remediation works [10,11]. These estimates underscore the profound social and economic impact of mould in Australia.

Mould thrives in humid environments and is commonly found in areas with poor ventilation, such as bathrooms, basements, and kitchens. Further, mould can develop due to the excessive presence of moisture within building components, often resulting from extreme events such as flooding or from condensation issues [6]. The latter is frequently attributed to inadequate consideration of moisture control during the design phase [12].

In Australia, moisture management in buildings has been neglected in design and construction practices until very recently, and was only formally introduced in the context of the National Construction Code (NCC) of Australia in 2019 [6]. This is further evidenced by the increasing number of complaints about water damages filed to the VBA[8], the Victorian Managed Insurance Agency (VMIA) and Domestic Building Dispute Resolution Victoria [13] . On the other side, progressively higher energy efficiency requirements and tighter fireproof provisions over recent years are significantly changing the hygrothermal performance of buildings [6]. Indeed, stricter energy-efficient provisions rely on building envelope airtightness as a measure to decrease uncontrolled thermal exchanges between the indoor and outdoor environments. However, when not accompanied by updated ventilation strategies, an increase in airtightness can lead to under-ventilated interiors that are unable to dissipate additional moisture, which favours condensation and mould growth within building structures [6]. This issue is further exacerbated in building envelopes when thermal bridging is present.

2.2 Moisture Management in Timber Buildings

Another factor that influences mould growth is the availability of nutrients and the medium on which biogermination happens [3]. The higher the content of organic carbon available, the easier it is for mould to grow and expand [6,14].

Timber-based construction materials are particularly vulnerable to mould growth for two key reasons. Firstly, as an organic material, timber provides ample nutrients that support mould development. Secondly, its hygroscopic nature enables it to absorb and retain moisture, creating ideal environmental conditions for mould to thrive [15]. However, there are numerous examples of timber-based buildings around the world, across very diverse climatic conditions, that have lasted for centuries. Historic structures, such as traditional wooden temples in Japan and Scandinavian stave churches, demonstrate that when timber is properly selected, treated, maintained and repaired, it can remain durable and resistant to mould growth for generations. Designing for a specific climate and other factors, such as adequate ventilation, controlled indoor humidity, and protective coatings, contributes to the longevity of timber buildings and structures.

2.3 Moisture Management and BIPV

As Australia moves toward decarbonization and a more sustainable energy system, the solar technologies market's potential continues to grow. Building-integrated photovoltaics (BIPV) in Australia can play a pivotal role in the building sector transition to net zero, given the country's high level of solar radiation, sufficient to meet its energy needs [16]. Australia has one of the highest rates of rooftop solar panels globally, especially in residential installations [17]. Integrated façade solutions are less common but are emerging as a viable alternative when roof surfaces are limited, such as in the case of multi-story buildings.

Combining BIPV systems with timber walls could provide great advantages in reducing buildings' carbon footprint; however, it may also bring along hygrothermal challenges. Timber components are sensitive to moisture, and PV modules' high operating temperature can cause microclimate changes and negatively affect heat and moisture transfer through external walls [18] by raising the temperature of nearby surfaces creating additional thermal gradients [19] . To mitigate these issues in roof installations, a wide ventilated air gap is commonly employed behind PV modules. However, ventilation cavities in external walls are generally limited and do not offer the same design and space flexibility.

Despite the challenges, BIPV in facades has been adopted successfully across several projects worldwide . This study aims to provide insights regarding the opportunity for integration of PV cladding on timber-based envelopes in Australia.

3 – PROJECT DESCRIPTION

This research project tackles the holistic hygrothermal performance assessment of emerging timber envelopes through empirical field testing and transient building simulation.

Empirical studies are carried out at the University of Sydney. PHEBE (Prototype of Highly Efficient Building Envelopes) is a modular testing facility hosted by the Sydney School of Architecture, Design and Planning, designed ad-hoc to test the resilience of different timber-based construction systems (wall and roof, see Figure 1) to moisture stresses, condensation and mould growth risks. This study focuses on external wall technologies only, while roof systems will be investigated in future studies.

Empirical monitoring was carried out for 11 months, and the collected data was used to compare outcomes and validate assumptions.

3.1 Experimental Setup

In this study, 12 distinct wall configurations were tested, as illustrated in Figure 1. Each configuration was designed to isolate a single variable, ensuring that only one factor

[8] VBA refers to the Victorian Building Authority

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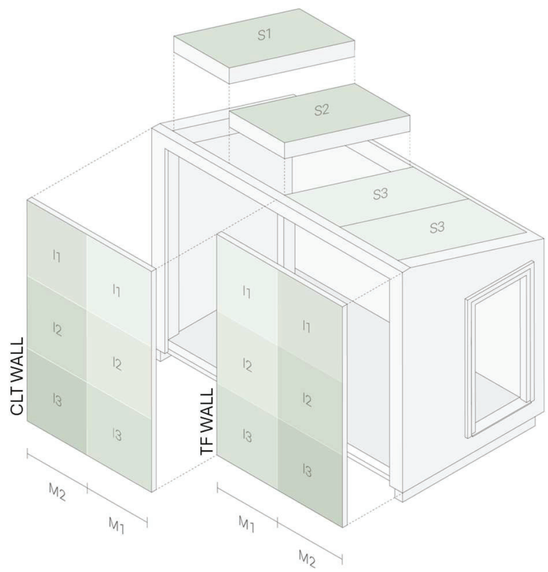
was altered between any two modules for controlled comparisons. Configuration variables included:

- Two structural types – timber-framed (TF) and cross-laminated timber (CLT)
- Three insulation products – mineral (I1, rockwool), natural (I2, woodfiber) and synthetic (I3, PIR)
- Two weather membranes – class 3 (M1) and class 4 (M2) vapour permeabilities.

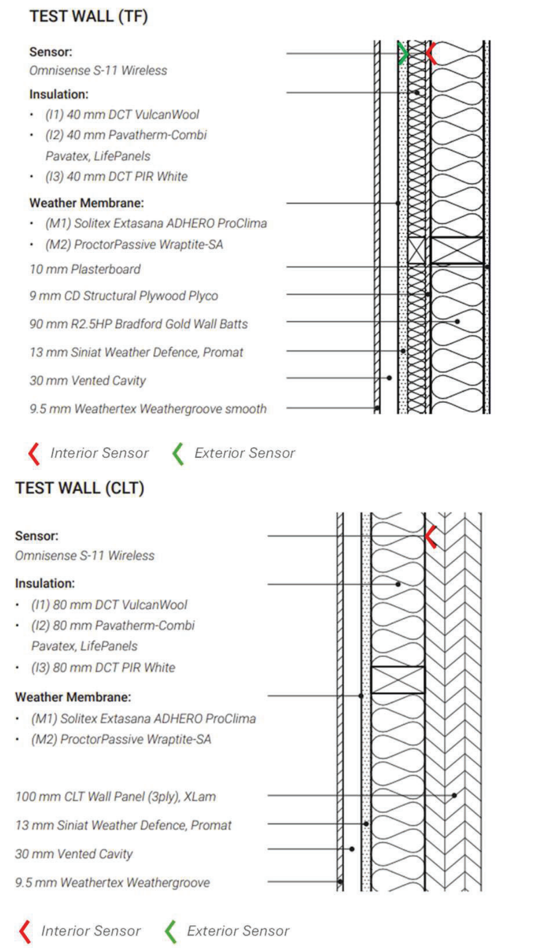
Figure 1: PHEBE Wall Configuration



S-11 wireless sensors within wall modules are used to monitor moisture content in wood (%WMC), temperature (T) and relative humidity (RH), with an accuracy of ±0.4°C/±3.5%RH. CLT test walls are equipped with 6 sensors, one per configuration, at the interface between CLT and insulation. TF test walls are equipped with 12 sensors, two per configuration, at either interface of the external insulation with the plywood bracing board and at the fire-rated gypsum board. The sensors' location within the walls is illustrated in Figure 2.

Rainscreen cavity ventilation rate was measured via anemometer, to be used as input data in WUFI transient simulations. Sensors data have been collected continuously for 11 months, from April 2024 until March 2025. This configuration enabled a full characterisation of the hygrothermal performance of the test modules.

Figure 2: PHEBE's timber-framed (TF) and cross-laminated timber (CLT) wall assemblies



3.2 VIRTUAL SIMULATIONS

Hygrothermal simulations are performed with WUFI Pro version 7.1 [4], developed by Fraunhofer Institute for Building Physics. This software enables transient analysis of heat and moisture transfer through building assemblies, accounting for vapor diffusion and liquid transport within materials. The risk of mould growth is subsequently evaluated using the WUFI-VTT post-processor. The accuracy of virtual simulations heavily relies on the underlying calculation assumptions. In this study, simulation parameters are taken from the ASHRAE 160 [20], considered one of the most sophisticated framework for hygrothermal risk assessment [1].

Outdoor climate: hygrothermal modelling requires main climatic parameters, such as temperature, relative humidity, solar radiation, hourly rainfall, wind speed and direction. Usually, this information is collected into the Moisture Reference Year (MRY) file [21].

Indoor climate: hourly indoor temperature (Table 1) and relative humidity (Table 2) is modelled according to the simplified method reported by the ASHRAE 160.

Table 1: Hourly indoor design temperature

24-hour outdoor running mean temperature [$T_{o,24}$]	Indoor design temperature [^oC]
$T_{o,24} < 18.3^0C$	21.1
$18.3^0C < T_{o,24} < 21.1^0C$	$T_{o,24} + 2.8$
$T_{o,24} > 21.1^0C$	$T_{o,24} + 2.8$

Table 2: Hourly indoor design relative humidity

Daily average outdoor temperature [^oC]	Indoor design RH [%]
$T_{o,day} < 10^0C$	40
$10^0C < T_{o,day} < 20^0C$	$40 + (T_{o,day} + 10)\%$
$T_{o,day} > 20^0C$	70

Construction assemblies: construction assemblies are based on PHEBE's tested configurations. As WUFI requires specific moisture-dependent material properties that are not always available for all commercially available products, a material mapping process was carried out to match the real-world products with the relevant properties from the WUFI database. When certain properties were missing, the closest match was selected from WUFI's extensive in-built database to ensure a comprehensive and accurate material specification, following the methodology of previous studies [22]. Material properties are presented in Table 3.

The rainscreen cavity ventilation rate was measured in PHEBE field testing. An additional configuration was assessed via simulations, substituting the modules' Weathertex cladding with Photovoltaic (PV) cladding. Rainscreen cavity and PV properties are presented in Table 4.

Table 3: Materials Properties

Material	Thick-ness *(meters)*	Conducti-vity *(W/m.K)*	Density *(kg/m3)*	WVD R[9]
Cladding[10] [14]	0.01	0.22	1000	200
CLT[11]	0.1	0.104	399	79
Fire-rated gypsum board. [12]	0.013	0.25	870	10.4
Class 3 membrane (M1)[13]	0.001	2.40	244	410
Class 4 membrane (M2)[14]	0.001	2.30	290	41
Mineral insulation (I1)[15]	0.08	0.034	80	1.3
Natural insulation (I2)[16]	0.04	0.041	145	3
Synthetic insulation (I3)[17]	0.04	0.027	32.5	72
Plywood	0.009	0.10	500	700
Glasswool	0.09	0.036	26.20	1.2

Table 4: Rainscreen Cavity and PV Properties

Rain screen properties	
Air Velocity (m/s) (measured)	0.4[18]
PV panel properties	
Thickness (meters)	0.012 [19]
Conductivity (W/m.K)	60
Density (kg/m3)	2256 [23]
Emissivity (ε)	0.89 [24]
Reflectivity (r)	0.056 [25]
Absorptivity (α)	0.944 [20]

Surface and boundary conditions: boundary conditions are summarised in Table 5. Except for the rain factors, all values were sourced from the WUFI database, ensuring consistency with established hygrothermal modelling parameters. The rain factors were determined using the wind-driven rain model outlined in the ASHRAE 160 standard, allowing for a more accurate representation of moisture exposure due to precipitation.

Table 5: Surface and Boundary Conditions

Exterior Boundary Conditions	
Orientation	South [21]
Rain load	Calculation method [22]
Exterior surface air film resistance	Weatherboard: 0.3 PV (perTable 4)
Short-wave radiation value	Weatherboard: DIN4108 medium (0.6) PV (perTable 4)
Ground reflectivity	0.2 (standard value)
Rain adhering factor	0.7

[9] WVDR: Refers to water vapour diffusion resistance
[10] Weathertex Weathergroove
[11] Xlam - 3 Ply CLT
[12] Siniat Weather Defence
[13] Solitex Extasana Adhero Proclima
[14] Proctor Passive Wraptite-SA
[15] DCT VulcanWool Insulation (rock fibre stonewool)
[16] Pavatherm-Combi Pavaflex Life Panels
[17] DCT PIR White
[18] 0.4 m/s measured, converted to ACH 4.01 for intput in WUFI.

[19] Based on standard stack configuration: Assumed stack: 5mm front glass + 2mm encapsulant and cells + 5mm rear glass.
[20] Absorptivity of module in the visible spectrum, assuming transmittance, t=0 ($\alpha + r + t = 1$)
[21] South orientation selected as the worst case scenario for Sydney climate.
[22] *ASHRAE Standard 160, 4.6 Design Rain Loads on Walls B-15.*

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Exterior surface air film resistance	0.04
Initial material conditions	Moisture and temperature (constant) Initial RH (80%) T^0 (20^0C)
Exterior Climate	17 NSW Sydney Observatory Hill (NatHERS)
Interior Boundary Conditions	
Interior surface air film resistance	0.13
Interior surface Sd value	No coating assumed.
Interior Climate	Heating only and floating temperature (20^0C and 24^0C)
Building Data	Air exchange rate (10 ACH) Building volume 11.15 m^3
General Parameters	
Calculation period (Sensors comparison) and standard hygrothermal performance assessment	30/04/2024 to 20/03/2025 and 30/04/2024 to 30/04/2034

Assessment Criteria: The hygrothermal performance assessment of the different configurations follows the VTT mould growth model [26], integrated within the WUFI Pro software platform**.**

Table 6 : VTT Moulg growth model assessment criteria

Code	Mould risk level	Mould growth index (MI)
Green	Acceptable	MI < 1
Yellow	Further assessment needed	1< MI < 3
Red	Not acceptable	MI > 3

4 – RESULTS

Results are organised in three sections. Section 4.1 reports on field testing measurements in real climatic conditions (Sydney) for TF and CLT external wall assemblies, with six different configurations for each structural type. Sensors' data is compared with WUFI simulations outcomes (over 11 months). Section 4.2 reports on WUFI hygrothermal simulations over 10 years to assess mold growth risk in all wall configurations. Section 4.3 presents simulation results for PV-integrated rainscreen over 10 years for selected TF and CLT wall configurations.

4.1 Field Testing vs Simulation Data

Monitored data from field testing is presented in Graph 1 for CLT walls (Interior sensor) and Graphs 2 and 3 for TF walls, respectively, Interior and Exterior sensors. Results are reported for six different wall configurations per structural type (TF and CLT), varying insulation products (I1, I2, I3) across columns and membrane types (M1, M2) per row. Data from sensors is compared with WUFI hygrothermal simulation data, extracted over a period of 11 months, from March to April of the third simulated year. Graphs report on both tested and simulated daily average temperature (°C) and relative humidity (%RH) for each wall configuration.

Sensors in CLT wall assemblies (see Graph 1) do not show significant temperature fluctuations overall when compared to the simulated data, with some discrepancies in the cooler months of the year, between May and September. The measured data indicates lower temperatures than the simulated for all configurations, with an mean absolute error ranging from 0.62 °C to 1.18 °C. In terms of relative humidity, results vary across configurations, with an mean absolute error ranging from 3.84 %RH for mineral insulation (I1) to 0.92 %RH for synthetic insulation (I3), where tested and simulated results are well aligned. It is interesting to note that while sensors data do not show any significant difference across configurations with different insulations or membranes, simulated data seem to show lower average humidity in cooler months in assemblies with mineral and natural insulation.

Sensors placed on the internal side of the plywood in timber-framed assemblies (see Graph 2) show minimal temperature fluctuations compared to the simulated data, with an mean absolute error ranging from 0.32°C to 1.29°C. In terms of relative humidity, conversely to what is observed in CLT wall assemblies, simulated data appears to be higher than measured data across all assemblies, with an absolute error range of about 3.7 %RH for walls with natural insulation and higher than 11 %RH for walls with syntethic insulation. While measured data shows great consistency across assemblies with different insulation types, the change of membranes appears to affect performance to a greater extent, with class 3 membrane maintaining lower level of RH within both mineral and natural insulation-based assemblies.

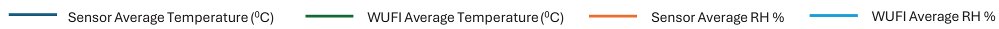
Exterior sensors data in timber-framed walls (see Graph 3), placed on the fire-rated gypsum board, show minimal temperature fluctuations between measured and simulated data across all configurations, with an absolute error ranging from 0.10°C to 0.65°C. However, relative humidity fluctuations between sensors and simulated data are more pronounced. In configurations with mineral insulation (I1), the simulated data is higher than the measured values consistently across the year, with an mean absolute error ranging from 7.33 %RH (M2) to 10.18 %RH (M1). In contrast, configurations with natural (I2) and synthetic (I3) insulation show higher measured relative humidity compared to the simulated data in cooler months, with an absolute error ranging from 1.04 %RH to 4.79 %RH.

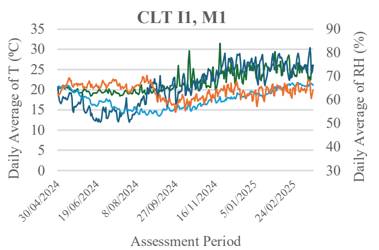
Walls with class 4 membrane seem to maintain lower level of RH in simulated data, especially in mineral insulation-based walls. This trend is not observed in sensor data which report similar results between membranes, with class 3 membrane instead showing slighly lower RH consistently across all insulation configurations. Overall, exterior sensors measured RH shows much higher fluctuations compared to data from interior sensors.

Discrepancies between sensor readings and simulated data in timber frame structures can be attributed to several factors, including variations in material properties, the presence of thermal bridges leading to increased temperature and humidity fluctuations not represented in 1D cross-sectional analysis, and especially differences in boundary conditions between real-environmental changes in testing set-up and the climate file used for simulations.

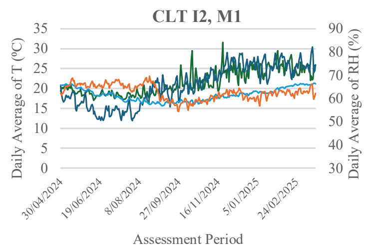
Overall, the inherent hygroscopic nature of CLT panels and their structural continuity that minimizes thermal bridging, enhance their ability to maintain consistent thermal and moisture conditions, providing a more reliable and predictable environment compared to timber-framed assemblies.

Graph 1: CLT Wall Configurations – Sensor data vs Simulation data.

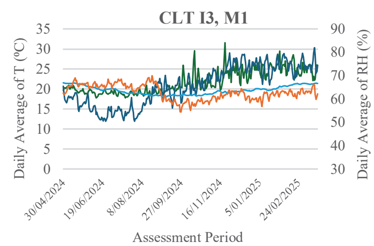




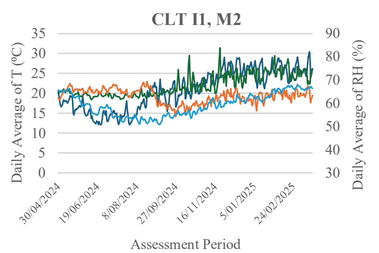
Absolute error (mean): 1.18 ^{0}C, 3.73 % RH
Standard deviation (diff.): 2.19 ^{0}C, -0.11 % RH



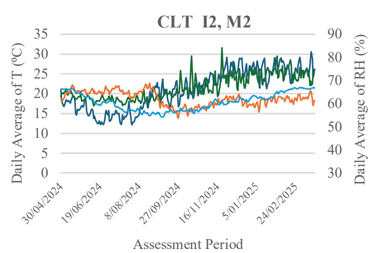
Absolute error (mean): 0.79 ^{0}C , 1.14 % RH
Standard deviation (diff.): 1.80 ^{0}C , 0.70 % RH



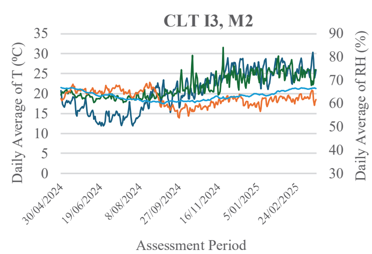
Absolute error (mean): 1.04 ^{0}C, 0.92 % RH
Standard deviation (diff.): 1.98 ^{0}C , 1.72 % RH



Absolute error (mean): 1.10 ^{0}C, 3.84 % RH
Standard deviation (diff.): -2.18 ^{0}C, 1.17 % RH

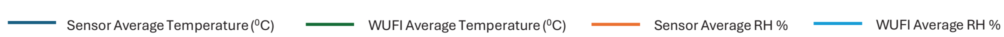


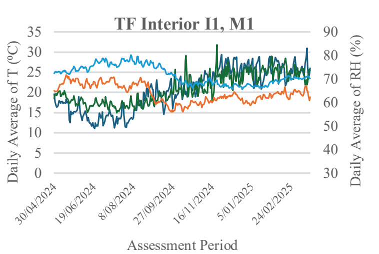
Absolute error (mean): 0.62 ^{0}C, 1.43 % RH
Standard deviation (diff.): -1.80 ^{0}C, 0.34 % RH



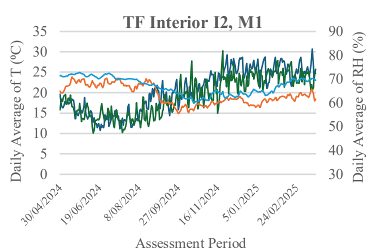
Absolute error (mean): 1.02 ^{0}C, 1.00 % RH
Standard deviation (diff.): -2.00 ^{0}C, -1.37 % RH

Graph 2: TF Wall Configurations – Sensor data (Interior) vs Simulation data.

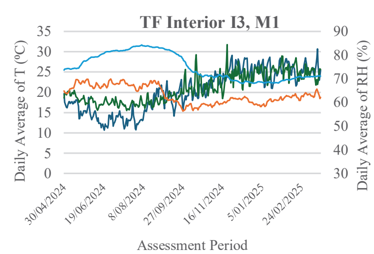




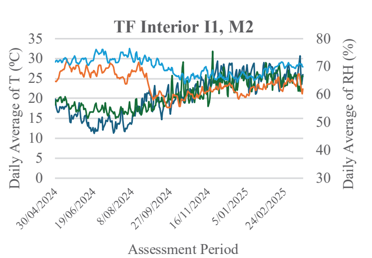
Absolute error (mean): 0.43 ^{0}C, 7.82 % RH
Standard deviation (diff.): -1.42 ^{0}C, 0.22% RH



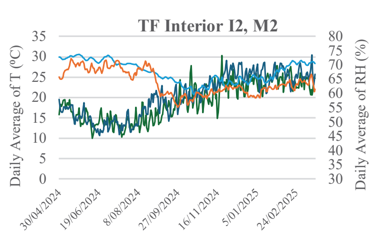
Absolute error (mean): 1.29 ^{0}C, 3.73 % RH
Standard deviation (diff.): -0.46 ^{0}C, -0.48 % RH



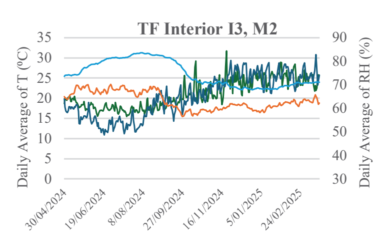
Absolute error (mean): 0.81 ^{0}C, 11.17 % RH
Standard deviation (diff.): -1.50 ^{0}C, 1.92 % RH



Absolute error (mean): 0.32 ^{0}C, 5.96 % RH
Standard deviation (diff.): -1.32 ^{0}C, -0.95 % RH



Absolute error (mean): 1.23 ^{0}C, 3.76 % RH
Standard deviation (diff.): 0.45 ^{0}C, 0.61 % RH



Absolute error (mean): 0.59 ^{0}C, 11.42 % RH
Standard deviation (diff.): 1.53 ^{0}C, -1.70 % RH

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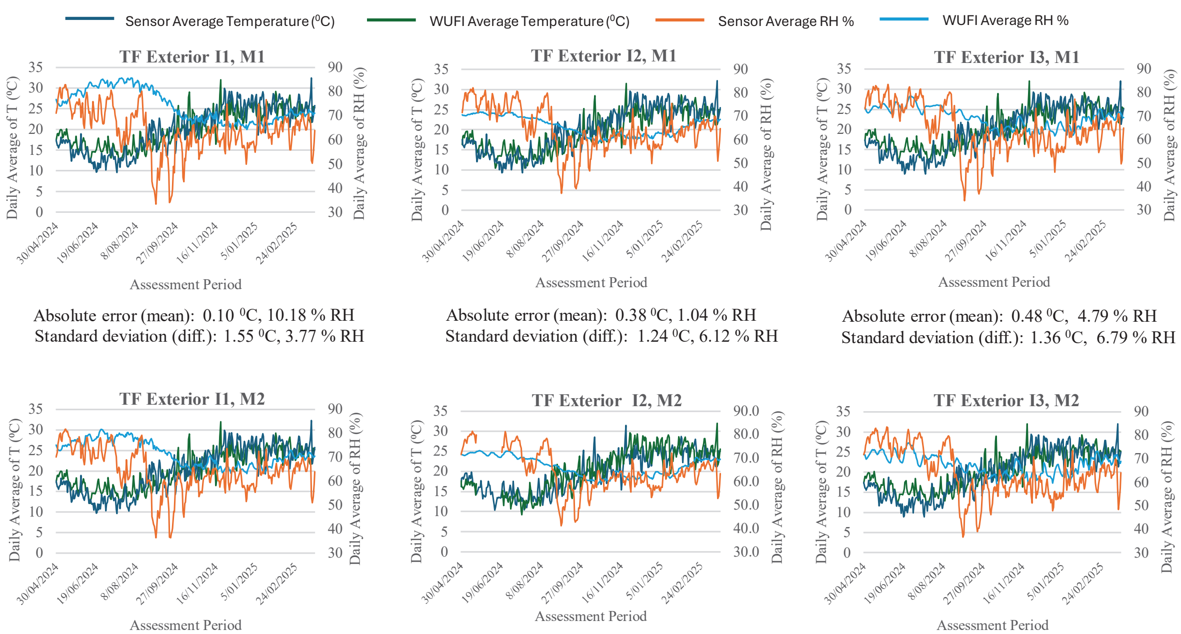
Graph 3: TF Wall Configurations – Sensor data (Exterior) vs Simulation data.



TF Exterior I1, M1 — Absolute error (mean): 0.10 ⁰C, 10.18 % RH; Standard deviation (diff.): 1.55 ⁰C, 3.77 % RH

TF Exterior I2, M1 — Absolute error (mean): 0.38 ⁰C, 1.04 % RH; Standard deviation (diff.): 1.24 ⁰C, 6.12 % RH

TF Exterior I3, M1 — Absolute error (mean): 0.48 ⁰C, 4.79 % RH; Standard deviation (diff.): 1.36 ⁰C, 6.79 % RH

TF Exterior I1, M2 — Absolute error (mean): 0.11 ⁰C, 7.33 % RH; Standard deviation (diff.): 1.51 ⁰C, 4.41 % RH

TF Exterior I2, M2 — Absolute error (mean): 0.64 ⁰C, 1.74 % RH; Standard deviation (diff.): 0.96 ⁰C, 4.72 % RH

TF Exterior I3, M2 — Absolute error (mean): 0.44 ⁰C, 3.56 % RH; Standard deviation(diff.): 1.40 ⁰C, 6.70 % RH

4.2 Mould Growth Risk

The hygrothermal performance simulation results show no risk of mould growth for CLT wall assemblies, over a projected 10-year period, demonstrating their resilience to moisture under standard conditions across any given configuration. Results are summarized in Table 7. Predictions appear to be consistent with measured data.

Timber-framed assemblies results indicate a low risk of mould growth overall, except for synthetic insulation-based walls (I3, iterations #9 and #12) exhibiting medium risk of muld growth over 10 years, as detailed in Table 8. These predictions are not substantiated by field testing, where RH sensor data appears overall lower in synthetic insulation-based walls than in mineral or natural configurations.

Empirical studies on rigid polyisocyanurate (PIR) insulation on different wall systems have concluded that the hygrothermal performance of PIR can vary depending on the panel thickness. Thicker insulation provides better moisture control; however, special consideration must be given to the facer material, as it also affects the performance [27].

Table 7: Hygrothermal performance results for CLT walls

Iteration #	**Sensor Location**	**Case Description**		**Mould Growth risk**
		Insulation	***Membrane***	***VTT***
1	Interior	I1	M2	0.00
2	Interior	I2	M2	0.00
3	Interior	I3	M2	0.00
4	Interior	I1	M1	0.00
5	Interior	I2	M1	0.00
6	Interior	I3	M1	0.00

Table 8: Hygrothermal performance results for TF walls

Iteration #	**Sensor Location**	**Case Description**		**Mould Growt h risk**
		Insulation	***Membrane***	***VTT***
7	Interior	I1	M1	0.01
8	Interior	I2	M1	0.32
9	Interior	I3	M1	2.02
10	Interior	I1	M2	0.01
11	Interior	I2	M2	0.01
12	Interior	I3	M2	1.83
13	Exterior	Same as Iteration #7		0.01
14	Exterior	Same as Iteration #8		0.03
15	Exterior	Same as Iteration #9		0.04
16	Exterior	Same as Iteration #10		0.02
17	Exterior	Same as Iteration #11		0.00
18	Exterior	Same as Iteration #12		0.00

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4.3 MOULD GROWTH RISK AND BIPV

This section investigates the use of building-integrated photovoltaics (BIPV) as an emerging cladding technology, to understand its effects on hygrothermal performance of timber-based wall assemblies under increased temperatures contributed by the PV modules.

This time only selected configurations were chosen, including:

- TF walls (I1, I2, I3) with class 3 membrane (M1, interior and exterior) which showed higher risk of mould growth, and CLT wall;
- CLT wall (I3, M1).

Results outlined in Table 9, indicate a high risk of mould growth in timber-framed structures (interior and exterior interfaces) for configurations with mineral insulation (I1) and synthetic insulation (I3). In contrast, configurations with natural insulation (I2) show no mold growth risk over a 10-year period, highlighting the importance of the hygroscopic nature of insulation materials.

Overall, changes in microclimate caused by PV panels appear to have great effects on the hygrothermal performance of wall assemblies and need to be carefully considered in moisture safe design. Additional design considerations need to be investigated, for instance cladding rear ventilation strategies.

Table 9: Hygrothermal performance results for CLT and TF walls with BIPV cladding

Assembly	Case	Iteration Reference #	Monitor Position	Mould Growth risk
				VTT
CLT	I3, M1	6	Interior	0.00
TF	I1, M1	7	Interior	4.90
		13	Exterior	3.43
TF	I2, M1	8	Interior	0.00
		14	Exterior	0.25
TF	I3, M1	9	Interior	5.14
		15	Exterior	4.64

5 - CONCLUSIONS

This paper presented a study on the hygrothermal performance of emerging timber-based envelopes in Sydney climate, assessed both through field testing and simulations. Comparison between the two methods allowed to investigate the accuracy of the current assumptions employed for hygrothermal risk assessments, following the major hygrothermal policy framework.

Results indicate that empirical testing data does not always align with WUFI simulated data. This discrepancy underscores the importance of accurate assumptions and parameters in ensuring the reliability of simulation results. Factors such as material properties, boundary conditions, and environmental interactions must be accurately defined.

Findings shows how CLT assemblies present no risk of mould growth across all configurations, both according to tested and simulated results. These wall typologies present high resilience to moisture, opening up opportunities for integration of emerging technologies such as BIPV.

Timber-framed wall assemblies are overall more susceptible to temperature and moisture changes, and present higher risk of mould growth. When integrating PV cladding, additional design considerations are needed, including stringent insulation material selection. Enhanced cladding rear ventilation will be investigated in future studies. With appropriate design considerations, timber assemblies can provide a moisture-resilient and lower embodied carbon solution, promoting the progressive decarbonization of the construction sector.

Main study limitations and future research can be summarised as follow:

- PHEBE indoor environment is an unconditioned space (free-floating) with no active space use, leading to slow testing due to naturally occurring relative humidity loads. Future research will conduct accelerated testing by setting indoor high-humidity stress scenarios.
- WUFI model indoor and outdoor data differs from field testing data. Future studies will assess the different configurations, alligning indoor and outdoor T and RH profiles. This will enable calibration of the simulation model and results validation.

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6 - REFERENCES

[1] A. Brambilla,, E. Gasparri, Hygrothermal behaviour of emerging timber-based envelope technologies in Australia: A preliminary investigation on condensation and mould growth risk, J. Clean. Prod. 276 (2020) 124129. 10.1016/j.jclepro.2020.124129.

[2] A. Brambilla,, E. Gasparri, Mould Growth Models and Risk Assessment for Emerging Timber Envelopes in Australia: A Comparative Study, Buildings 11(6) (2021) 261. 10.3390/buildings11060261.

[3] B. Gutarowska, Metabolic Activity of Moulds as a Factor of Building Materials Biodegradation, Pol. J. Microbiol. Pol. Tow. Mikrobiol. Pol. Soc. Microbiol. 59 (2010) 119–24. 10.33073/pjm-2010-018.

 https://doi.org/10.52202/080513-0533

[4] WUFI® Pro updates | WUFI (en) (n.d.). Available at: https://wufi.de/en/software/wufi-pro/wufi-pro-updates/. Accessed March 27, 2025.

[5] L. Kempton,, G. Kokogiannakis,, P. Cooper, Mould risk evaluations in residential buildings via site audits and longitudinal monitoring, Build. Environ. 191 (2021) 107584. 10.1016/j.buildenv.2020.107584.

[6] A. Brambilla,, A. Sangiorgio, Mould growth in energy efficient buildings: Causes, health implications and strategies to mitigate the risk, Renew. Sustain. Energy Rev. 132 (2020) 110093. 10.1016/j.rser.2020.110093.

[7] A. Ghaffarianhoseini,, H. AlWaer,, H. Omrany,, A. Ghaffarianhoseini,, C. Alalouch,, D. Clements-Croome,, J. Tookey, Sick building syndrome: are we doing enough?, Archit. Sci. Rev. 61(3) (2018) 99–121. 10.1080/00038628.2018.1461060.

[8] A. Brambilla,, C. Candido,, O. Gocer, My home is making me sick! Implications of poor indoor environment quality on mould growth, in: My home is making me sick! Implications of poor indoor environment quality on mould growth, ScienceOpen, 2021, p. .

[9] Healthy Housing Centre of Research Excellence, Healthy Housing CRE reports and submissions - Submission to Parliamentary Inquiry into housing affordability and supply in Australia. Healthy Housing CRE. Available at: https://www.healthyhousing-cre.org/publications. Accessed April 9, 2025.

[10] E. Baker,, L. Daniel,, H. Pawson,, M. Baddeley,, A. Vij,, M. Stephens,, P. Phibbs,, A. Clair,, A. Beer,, E. Power,, R. Bentley,, C.T. Kulik,, R. Sinha,, W. Stone,, J. Dignam,, K. London,, S. Rowley,, K. Hulse,, C.A. Nygaard,, H. Holst,, Chris Leishman, D. Rogers,, K. Jacobs, Rental Insights: A COVID-19 Collection | AHURI, n.d.

[11] L. Coulburn,, W. Miller, Prevalence, Risk Factors and Impacts Related to Mould-Affected Housing: An Australian Integrative Review, Int. J. Environ. Res. Public. Health 19(3) (2022) 1854. 10.3390/ijerph19031854.

[12] A. Brambilla,, A. Sangiorgio, 1 - Moisture and buildings, in: A. Brambilla, A. Sangiorgio (Eds.), Moisture and Buildings, Woodhead Publishing, 2021, pp. 1–8.

[13] T. Law,, G. Sorrentino,, R. Barry,, P. Ronngard, Scoping study on the nature and extent of moisture damage in houses & apartments in Victoria, Victoria University, 2021.

[14] W. Aiduang,, K. Jatuwong,, T. Luangharn,, P. Jinanukul,, W. Thamjaree,, T. Teeraphantuvat,, T. Waroonkun,, S. Lumyong, A Review Delving into the Factors Influencing Mycelium-Based Green Composites (MBCs) Production and Their Properties for Long-Term Sustainability Targets, Biomimetics 9(6) (2024) 337. 10.3390/biomimetics9060337.

[15] C. Köse,, A.M. Taylor, Evaluation of Mold and Termite Resistance of Included Sapwood in Eastern Redcedar, Wood Fiber Sci. (2012) 319–24.

[16] RMIT University, Building Integrated Photovoltaics (BIPV) Enabler Final Report. Australian Renewable Energy Agency. Available at: https://arena.gov.au/knowledge-bank/building-integrated-photovoltaics-bipv-enabler-final-report/. Accessed April 12, 2025.

[17] Clean Energy Council, Rooftop solar generates over 10 per cent of Australia's electricity | Clean Energy Council. Available at: https://cleanenergycouncil.org.au/news-resources/rooftop-solar-generates-over-10-per-cent-of-australias-electricity. Accessed April 12, 2025.

[18] K. Ye,, H. Ge,, A. Athienitis,, X. Yang, Hygrothermal Modeling of Building Integrated Photovoltaics in Low-Rise Wood-Frame Construction, in: Proceedings of the 5th International Conference on Building Energy and Environment, Springer Nature, Singapore, 2023, pp. 1385–93.

[19] The Effect of Heat and Temperature on Photovoltaic Modules. Republic Of Solar. Available at: https://arka360.com/ros/heat-temperature-on-photovoltaic-modules/. Accessed April 14, 2025.

[20] ASHRAE ASHRAE 160 - Criteria for Moisture-Control Design Analysis in Buildings - Includes ANSI/ASHRAE addenda listed in Appendix D - Engineering Workbench, ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 2021.

[21] A. Brambilla,, H. Javed,, M. Strang, Hygrothermal climate analysis: An Australian dataset, Data Brief 42 (2022) 108291. 10.1016/j.dib.2022.108291.

[22] N. Saavedra Toro,, A. Brambilla,, A. Kuru,, E. Gasparri,, U. Berardi, Increasing the Building Envelope Resilience to Moisture and Mould Growth, in: Multiphysics and Multiscale Building Physics, Springer Nature, Singapore, 2025, pp. 241–7.

[23] A.J. Chamkha,, F. Selimefendigil, Numerical Analysis for Thermal Performance of a Photovoltaic Thermal Solar Collector with SiO2-Water Nanofluid, Appl. Sci. 8(11) (2018) 2223. 10.3390/app8112223.

[24] I. Subedi,, T.J. Silverman,, M.G. Deceglie,, N.J. Podraza, Emissivity of solar cell cover glass calculated from infrared reflectance measurements, Sol. Energy Mater. Sol. Cells 190 (2019) 98–102. 10.1016/j.solmat.2018.09.027.

[25] S. Kneipp, Reflectivity of LONGi Solar PV modules (2018).

[26] WUFI® Mould Index VTT | WUFI (en) (2017). Available at: https://wufi.de/en/2017/03/31/wufi-mould-index-vtt/. Accessed December 11, 2024.

[27] E. Iffa,, F. Tariku,, W.Y. Simpson, Highly Insulated Wall Systems with Exterior Insulation of Polyisocyanurate under Different Facer Materials: Material Characterization and Long-Term Hygrothermal Performance Assessment, Materials 13(15) (2020) 3373. 10.3390/ma13153373.