

Investigating the effects of intermittent indoor temperature control on hygrothermal risks in energy-efficient homes^{*}

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ABSTRACT

The building sector is increasingly prioritising reduced operational energy demand to mitigate climate change. In Australia, the National Construction Code 2022 mandates a minimum 7-Star energy rating for new residential. While current energy performance certificates (EPCs) successfully incentivise energy efficiency, growing evidence suggests they may overlook critical indoor environmental quality risks, particularly indoor moisture and mould growth in highly insulated and airtight dwellings. Internationally, moisture risk assessment commonly references ASHRAE 160; however, the standard assumes continuous conditioning, whereas residential buildings are typically intermittently conditioned. This discrepancy raises questions about the adequacy of EPC assessment assumptions in predicting real-world performance. This study investigates indoor temperature profiles in intermittently conditioned homes in south-eastern Australia, focusing on two external wall systems: brick veneer and compressed fibre cement sheet construction. Two scenarios were evaluated: (1) continuously controlled indoor temperature and relative humidity, consistent with ASHRAE 160, (2) intermittently controlled indoor temperature with regulated relative humidity. The performance of mitigation strategies, including ventilated wall cavities and vapour control layers, was assessed under both scenarios across multiple climate zones. Results reveal frequent exceedances of the 21.1 °C threshold, particularly in kitchen-living and bedrooms, leading to spatially and climatically variable mould risk profiles. Importantly, mitigation measures demonstrated context-dependent performance, in several cases, the inclusion of an interior vapour control layer increased mould risk under intermittent conditioning, contrary to its effectiveness under continuous conditioning. These findings highlight the need for next-generation EPCs to integrate dynamic conditioning patterns and occupant behaviour alongside energy metrics to ensure healthy buildings.

1. Introduction

The international movement toward energy-efficient buildings began in earnest in the 1970s, triggered largely by the global oil crises of 1973 and 1979. Energy-efficient building design has emerged as a crucial strategy to cope with climate change, driven by the recognition that buildings contribute approximately one-third of global energy-

related carbon emissions [1,2]. International commitments, such as the Paris Agreement, have catalysed a rapid expansion of building codes and energy performance certificates (EPCs), now adopted by around 80 countries, reflecting a 30% increase since 2015 [3]. Energy-efficient building design is now widely supported by regulatory frameworks and mandatory EPCs in many countries [4–6]. Policymakers increasingly enforce more stringent regulations because advanced energy codes

Abbreviations: ASHRAE, American Society for Heating, Refrigeration and Air-conditioning engineers; CSIRO, Commonwealth Scientific and Industrial Research Organisation; CZ, Climate Zone; DCV, Demand-Controlled Ventilation; EPCs, Energy Efficient Certificates; IEA, International Energy Agency; IEQ, Indoor Environmental Quality; IQR, Interquartile Range (Statistics); MPC, Model Predictive Control; MI, Mould-growth Index; NatHERS, National House Energy Rating Scheme; NCC, National Construction Code; RBC, Rule-Based Control; RH, Relative Humidity; RMY, Reference Meteorological Year; R-value, Thermal Resistance (m²·K/W); SHGC, Solar Heat Gain Coefficient; U-value, Thermal Transmittance (W/m²·K); WHO, World Health Organization; WUFI, Wärme Und Feuchte Instationär (Heat and Moisture Transiency).

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can reduce building energy consumption by up to 70%, delivering substantial cost savings, enhanced energy security, and long-term decarbonization benefits [7–9]. Australia has aligned with this global direction and recent updates to the National Construction Code (NCC) have included the move from 6-Star to a more stringent 7-Star house energy rating requirement for new residential buildings in 2023, with plans to extend similar standards to existing building by 2030 [10,11].

While improvements in building envelope thermal performance have been shown to reduce operational energy use, researchers and building occupants have identified potential unintended consequences, namely a greater presence of indoor moisture accumulation and interstitial mould growth. Airtight construction significantly limits natural infiltration, which can lead to interstitial moisture entrapment and elevated interior relative humidity inside buildings. Unless ventilation, (often mechanical), is carefully integrated and appropriate material choices for building envelope components are made, ideal conditions can be created for surface and interstitial mould growth and moisture accumulation. Empirical data suggest mould damage affects homes in Australia, Europe, UK, U.S., and Canada [12,13]. Indoor dampness is strongly linked to respiratory symptoms, asthma, allergies, poorer overall well-being and even premature death in extreme case [14–16].

Exposure to indoor dampness and mould presents significant health and economic challenges internationally. In the United States, research attributes approximately 21% of asthma cases and 8–20% of respiratory infections to such exposure, resulting in annual healthcare costs of US \$1–3.5 billion, with broader societal costs exceeding US \$3.5 billion [17]. More recent estimates indicate that mould-related infections alone cost US \$5.6 billion annually, in addition to US \$16.8 billion in asthma-related healthcare expenditures [18]. Similarly, in the United Kingdom, the total cost of mould-related respiratory diseases is estimated at up to £15.4 billion annually [19]. In New Zealand, the cumulative cost of mould-related issues has been estimated at NZD 52.3 billion since the 1990s [20].

In Australia, the national asthma burden may be attributable to exposure to damp and mould, with significant implications for public health spending, especially in low-income housing. Additionally, of the 2,178 Victorian residential insurance claims analysed in 2023, 92% (1,995 claims) had at least one water-related defect [21]. Excessive interstitial moisture within building envelopes has contributed to degraded indoor air quality and costly remediation efforts for over a decade [22–24].

Buildings designed to meet high EPCs through increased airtightness and insulation may inadvertently create indoor environmental conditions that promote mould growth [12,22,25–27]. Mould presence can adversely affect indoor air quality and occupant health and contribute to long-term economic burdens through increased healthcare costs, building damage, and remediation efforts [28,29]. To address these risks, Australia has adopted AIRAH technical document DA07 (an Australian version of ASHRAE Standard 160); an internationally recognised criteria for moisture control in buildings [4]. Despite the adoption of AIRAH DA 07, the recommended thresholds, always maintaining indoor temperatures between 21.1 °C and 23.9 °C and relative humidity no greater than 70%, are rarely achieved in Australian residential environments. This is due to a significant misalignment between the requirements of ASHRAE160 and the thermostat and conditioning requirements prescribed by the National Construction Code (NCC) and Nationwide House Energy Rating Scheme (NatHERS).

In Australia, the NatHERS is used to assess whether new residential building designs comply with mandated EPC requirements. Recognising Australia's predominantly temperate climates, the NCC (in conjunction with NatHERS) prescribe an intermittent conditioning schedule based on typical occupant activity patterns [30]. These guidelines, combined with Australia's predominantly temperate climate and common energy-saving practices, contribute to the widespread intermittent operation of conditioning (heating and cooling) systems in residential buildings [31]. This conditioning pattern leads to fluctuating indoor temperatures and

RH conditions, both of which influence the directional flows of moisture and indoor mould growth. Indoor temperature always plays a critical contributing role as one of the primary parameters in hygrothermal and bio-hygrothermal assessments [32]. Understanding the impact of intermittent conditioning induced temperature variability, particularly in scenarios where RH is regulated but temperature is not, can provide additional insights into the possible exacerbation of indoor surface and interstitial growth mould risks.

There is currently a lack of robust studies comparing indoor temperature profiles under unrestricted and intermittent residential building operation with those maintained through continuous temperature control. In Australia, where regulated indoor temperatures are not mandated and households predominantly rely on intermittent conditioning, limited evidence exists regarding the health relevance of internationally adopted indoor temperature benchmarks under local climatic conditions, such as the World Health Organization (WHO) recommended range of 18–21.1 °C and the thresholds prescribed in AIRAH DA07 and ASHRAE 160 [33,34]. This discrepancy raises critical questions regarding the validity of current EPCs, that are predominantly energy-driven and rely on standardized indoor climate assumptions. Consequently, EPC-based assessments risk obscuring the complexities of everyday building use, further widening the well-documented 'performance gap' between predicted ratings and actual energy and hygrothermal outcomes [35–38]. To ensure that indoor thermal benchmarks remain a viable proxy for public health, particularly in contexts characterized by intermittent residential building interior conditioning, it is essential to evaluate their translation into real-world residential performance. Understanding these dynamics is critical, as transient thermal environments may trigger moisture-related health risks that static benchmarks fail to capture.

This study examines the extent to which computer-based simulations of select NatHERS 7-Star typical residential external wall systems, located in south-eastern Australia exceed the AIRAH DA07 (and ASHRAE 160) prescribed Mould-growth Index (MI) benchmarks under the two studied conditioning scenarios. It examines the potential for mould growth under two conditions: continuously controlled, and intermittently controlled indoor air temperatures while maintaining RH limits. Building on this comparison, the study further evaluates the effectiveness of mitigation strategies, specifically, the inclusion of ventilated wall cavities and vapour control layers, and their combinations. This approach allows for an assessment of whether these typically adopted interventions provide consistent performance across different operational patterns. The findings aim to inform building design and construction practices that integrate new EPCs with indoor environmental quality, particularly in regions exhibiting similar climate profiles and intermittent conditioning behaviours, supporting the development of energy-efficient housing that also ensures healthy indoor environments.

2. Methods

This study adopts a two-step approach that integrates energy performance simulations, like EPC assessments, and hygrothermal simulation to assess the impact of residential interior intermittent air and moisture conditioning on simulation-based external wall hygrothermal performance.

Step 1: Calculation of Indoor Climate Profiles.

In the first step, the Accurate building energy rating software, developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), is used to apply the 7-Star NatHERS requirements. Applying climate data files for southeastern Australia, this process generates hourly indoor temperature and relative humidity conditions within a low-rise detached house design whilst intermittently occupied and conditioned. NatHERS accredited software underpins the performance targets set within the National Construction Code (NCC) and have been instrumental tools in reducing the simulation-based heating and cooling energy demand linked to greenhouse gas emission

from Australian homes [39–41]. The house plan adopted for this research is shown in Fig. 1. Each thermal zone, which defines the intermittent conditioning regime is colour-coded differently. This figure shows a four-bedroom home with a floor area of 152.5 m² and an interior volume of 366 m³. The 7-Star energy rating was achieved through adjustments to the glazing system and external wall insulation properties, in accordance with the requirements of NCC 2022, as detailed in Table 1. NatHERS assigns distinct thermal energy load limits to Climate Zone (CZ) 21 (Melbourne), CZ 66 (Ballarat), and CZ 64 (Cape Otway) to reflect their unique meteorological profiles and varying climate-based heating/cooling demands. These individualized benchmarks ensure that building performance is evaluated against localized environmental stressors, maintaining a consistent 7-star stringency across diverse geographical regions.

The AccuRate simulation incorporates intermittent conditioning schedules, that reflect realistic Australian occupant behaviour as prescribed by EPC and NCC 2022 [42]. This phase produced hourly indoor air temperature profiles for different intermittently conditioned zones including living rooms, bedrooms, kitchens, and bathrooms, within corresponding wall orientations and climate zones.

Step 2: Hygrothermal and Bio-hygrothermal Simulations.

In the second step, the indoor climate profiles calculated from AccuRate are used as critical input for WUFI ©Pro 6 and VTT [43,44], for assessing heat and moisture transport through building envelopes of the following two conditioning scenarios:

- Scenario A: Continuous conditioning as prescribed by AIRAH DA07, (ASHRAE Standard 160), where indoor temperature is maintained within controlled limits (temperature between 21.1 °C and 23.9 °C), and RH regulated ≤ 70% of all time.
- Scenario B: Intermittent controlled temperature conditioning, based on the profiles derived from AccuRate results, reflecting temperature fluctuations, whilst RH levels (≤ 70%) are maintained.

These simulations are conducted on timber-framed brick veneer and compressed fibre cement sheet (CFCS) clad external wall systems, which represent 54.2% and 20.3% of new 2024 NatHERS 7-Star dwellings in Victoria, respectively [45]. These two wall types are the most used external wall assemblies in newly constructed NatHERS 7-Star detached residential buildings across Victoria and are also the most prevalent wall systems in new housing developments nationwide. Their widespread adoption makes this research critical to understanding the moisture performance of typical Australian building envelopes under the current EPCs [45,46]. The study primarily examines moisture behaviour and interstitial mould growth risks in these widely used wall systems.

2.1. Climate zones

Accurate representation of outdoor climate is essential for reliable building energy rating, hygrothermal and bio-hygrothermal simulation outcomes, as external conditions significantly influence the heat and moisture dynamics of building envelopes [47,48]. In this study, a comprehensive dataset reflecting typical annual weather conditions was used, incorporating hourly data on temperature, humidity, solar, wind speed, and precipitation.

The NCC climate zones divide Australia into eight broad regions based on temperature and humidity patterns to guide regulatory requirements for construction material choices. In contrast, the NatHERS, defines 69 more granular climate zones derived from localised weather data used specifically for energy performance [49], Fig. 2. While both systems aim to address climatic variability, the NCC zones are used for compliance with construction regulations, whereas NatHERS zones are applied in EPC assessments. This study references NCC climate zones to align with regulatory construction requirements but also considers the thermal diversity captured by NatHERS zones to ensure comprehensive performance evaluation.

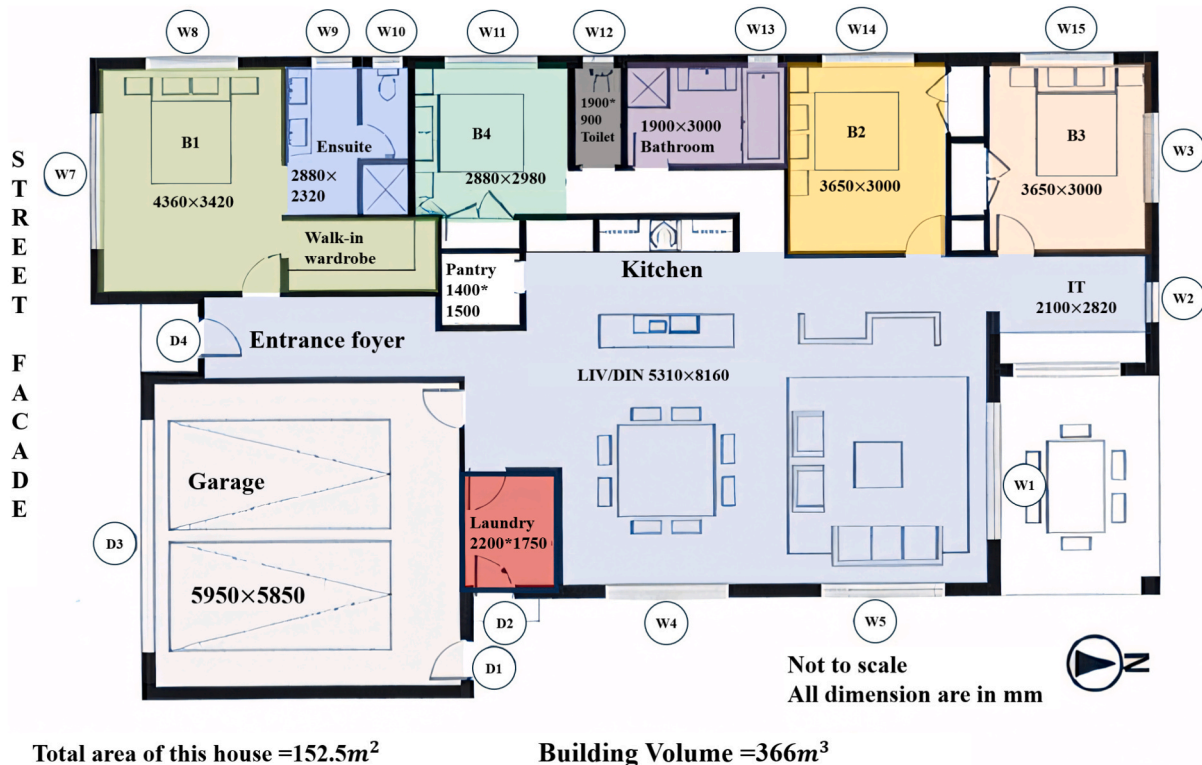


Fig. 1. The floor plan of a typical residential dwelling (Not to scale).

Table 1
AccuRate Simulation Details for the Glazing System of a Timber-Frame 7-Star House (NatHERS 2023).

Climates	NatHERS CZ 21 (NCC CZ 6–7)	NatHERS CZ 64 (NCC CZ 6–7)	NatHERS CZ 66 (NCC CZ 4)	NatHERS CZ 66 (NCC CZ 6–7)
7 Star	R-2.7 wall batts	R-2.7 wall batts	R-2.5 wall batts	R-2.5 wall batts
21%	R-6.0 Ceiling batt	R-6.0 Ceiling batt	R-6.0 Ceiling batt	R-6.0 Ceiling batt
Glass to floor area	R-2.7 Insul Partition	R-2.7 Insul Partition	R-2.5 Insul Partition	R-2.5 Insul Partition
	Garage/ Living	Garage/ Living	Garage/ Living	Garage/ Living
	Laundry/ Living	Laundry/ Living	Laundry/ Living	Laundry/ Living
	Living, Dining, Kitchen	Living, Dining, Kitchen	Living, Dining, Kitchen	Living, Dining, Kitchen
	TND-002–017	TND-002–017	TND-002–015	TND-002–017
	Aluminium A DG 4Clr/ 10Ar/4EA: U = 3.5: SHGC = 0.53	Aluminium A DG 4Clr/ 10Ar/4EA: U = 3.5: SHGC = 0.53	Aluminium A DG 4Clr/ 10Ar/4Clr: U = 4.1: SHGC = 0.57	Aluminium A DG 4Clr/ 10Ar/4EA: U = 3.5: SHGC = 0.53
	Bed 1, Bed 2, Bed 3, Bed 4	Bed 1, Bed 2, Bed 3, Bed 4	Bed 1, Bed 2, Bed 3, Bed 4	Bed 1, Bed 2, Bed 3, Bed 4
	TND-002–015	TND-002–017	TND-002–015	TND-002–015
	Aluminium A DG 4Clr/ 10Ar/4Clr: U = 4.1: SHGC = 0.57	Aluminium A DG 4Clr/ 10Ar/4EA: U = 3.5: SHGC = 0.53	Aluminium A DG 4Clr/ 10Ar/4Clr: U = 4.1: SHGC = 0.57	Aluminium A DG 4Clr/ 10Ar/4Clr: U = 4.1: SHGC = 0.57
	Non- habitable	Non- habitable	Non- habitable	Non- habitable
	TND-002–001	TND-002–001	TND-002–001	TND-002–001
	Aluminium A SG 3Clr: U = 6.5: SHGC = 0.66	Aluminium A SG 3Clr: U = 6.5: SHGC = 0.66	Aluminium A SG 3Clr: U = 6.5: SHGC = 0.66	Aluminium A SG 3Clr: U = 6.5: SHGC = 0.66
MJ/m2. annum	62	88	161	161
Simulation result (MJ/m2. annum)	Orientation 1: 60.2 Orientation 2: 58.6 Orientation 3: 55.4 Orientation 4: 53.9	Orientation 1: 86.5 Orientation 2: 83.4 Orientation 3: 79.6 Orientation 4: 83.4	Orientation 1: 168.4 Orientation 2: 161.4 Orientation 3: 154.0 Orientation 4: 159.6	Orientation 1: 168.4 Orientation 2: 161.4 Orientation 3: 154.0 Orientation 4: 159.6

2.1.1. The NatHERS climate zone

The selected of NatHERS CZ 21, CZ 64 (+CZ 62) and CZ 66 represent three distinct thermal zones within south-eastern Australia. CZ 21 represents Melbourne, the second most populated city in Australia, whilst the inclusion of CZ 64 and CZ 66 represent the top two jurisdictions for new housing approvals, accounting for the highest volume of residential development in the studied area, see Table 2.

2.1.2. The NCC climate zone

Since the construction requirements are based on NCC climate zones, the external wall system construction typologies for simulations were structured to align with the NCC requirements. This alignment ensures that the simulation results are directly applicable to the current regulatory framework in Australia. The base case design incorporates construction details specified by current regulations, utilizing an external pliable membrane that meets the water vapour diffusion requirements mandated by the AS4200.1, see Table 3 [11,50]. This approach strengthens the relevance and practical application of the findings within the context of real-world performance.

2.1.3. Studied wall systems

This study analysed simulation-based risks from the two most common low-rise timber-framed residential external wall systems in south-eastern Australia. The construction requirements for a code compliant Compressed Fibre Cement Sheet (CFCS) external wall system are shown in Fig. 3. The CFCS exterior wall system does not require a cavity. Fig. 4 shows the same information for the clay masonry veneer (brick veneer)

Table 2
New house approval in NatHERS and NCC climate zones.

NatHERS	NCC	Location of weather station	New Houses approval by 2024 (%)
21	6	Melbourne	6%
22	6	East Sale	12%
27	4 and 6	Mildura	9%
60	6	Tullamarine	12%
61	4 and 6	Mt Gambier	2%
63	6	Warrnambool	4%
64 (+62)	6	Cape Otway (+Moorabbin)	25%
66	4 and 6	Ballarat	30%
TOTAL			100%

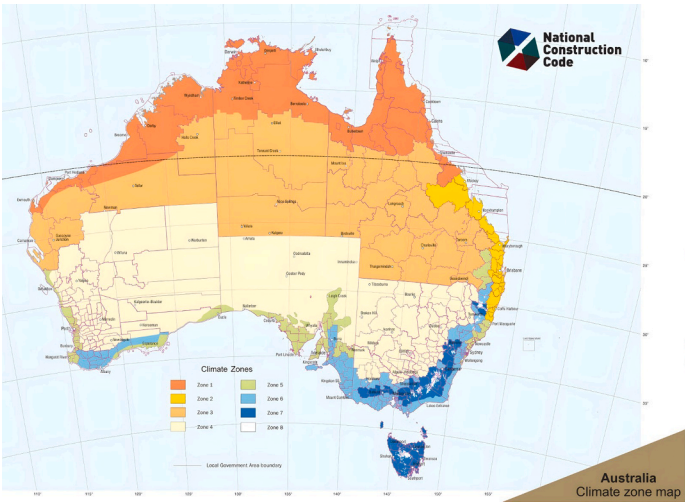


Fig. 2. The NCC climate zone map (left), the NatHERS climate zones map (right).

Table 3

7-Star EPC regulatory water vapour diffusion requirements of exterior membranes, NCC 2022.

NCC Climate Zone	Exterior membranes	Vapour permeances		Corresponding Water Vapour Diffusion Resistance Factor
		Min $\geq$ ($\mu\text{g}/\text{N.s}$)	Max $<$ ($\mu\text{g}/\text{N.s}$)	
CZ 4-5	Min Class 3	0.1429	1.1403	≥ 175.4078 to < 1399.5801
CZ 6-8	Min Class 4	1.1403	No Max	< 175.4078

exterior wall system, but this wall type is required to include a ventilated and drained cavity between the clay brick and the timber or steel framed structure. The ventilated and drained cavity (also named as an air space or air gap), is typically at least 40 mm to ensure moisture transport is minimised.

2.2. Indoor climate profiles

Indoor climate data is critical for evaluating how different conditioning regimes influence hygrothermal and bio-hygrothermal performance within residential environments. While ASHRAE 160 standard is commonly used worldwide, it does not fully capture the unique characteristics that exist in Australia and many countries that include intermittent conditioning regimes. Specifically, the absence of defined continuous numerical thresholds for indoor air temperature often results in Australian homes experiencing thermal environments that are less than or may exceed recommended indoor air temperatures.

To accurately reflect local Australian intermittently uncontrolled temperature conditioning, the NatHERS intermittent conditioning schedule was applied, as shown in Table 4. Occupant-generated moisture was incorporated into the AccuRate simulations as well as latent heat, with moisture and latent heat loads calculated based on the floor area of each zone (living areas, kitchen, and bedrooms) and national benchmarks for occupancy and internal loads [51]. At present, latent heat and moisture contributions from bathrooms are not included in the

model.

AccuRate calculates hourly indoor temperature profiles for individual rooms by accounting for factors like plan and wall orientations, intended function, and estimated occupancy [52]. The interior vapour generation was modelled, assuming continuous moisture production, see Table 5 below, the highlighted row is applied in this study. This approach captures the dynamic behaviour of indoor humidity under typical Australian usage pattern.

Table 4

Heating and cooling schedules, NCC2022, column2, summary of table H6V2a.

Hour ending at	Duration	Habitable rooms other than bedrooms	Bedrooms
1:00–6:00	6H	OFF	ON
7:00–9:00	3H	ON	ON
10:00–18:00	9H	ON	OFF
19:00–23:00	5H	ON	ON
0:00	1H	OFF	ON
Summary	24Hrs	On 16Hrs, 66.7% of a day	On 14hrs, 58.3% of a day

Table 5

Residential design moisture generation rates form ASHRAE160, 2016.

Number of bedrooms	Number of occupants	Moisture generation rate		
1 bedroom	2	7 L/day	$0.8 \times 10^{-4} \text{kg/s}$	0.64b/h
2 bedrooms	3	9 L/day	$1.0 \times 10^{-4} \text{kg/s}$	0.83b/h
3 bedrooms	4	10 L/day	$1.2 \times 10^{-4} \text{kg/s}$	0.92b/h
4 bedrooms	5	11 L/day	$1.3 \times 10^{-4} \text{kg/s}$	1.01b/h
Additional bedrooms	+1 per bedroom	+1L/day	$+0.1 \times 10^{-4} \text{kg/s}$	+0.11b/h

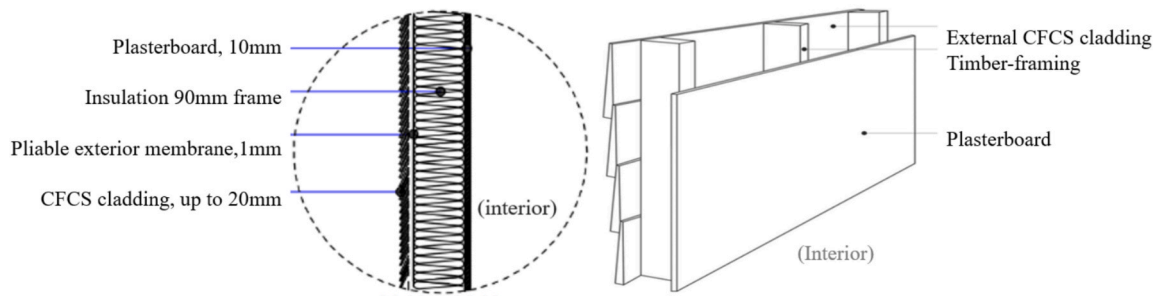


Fig. 3. Lightweight clad external wall system section detail (left) and diagram (right).

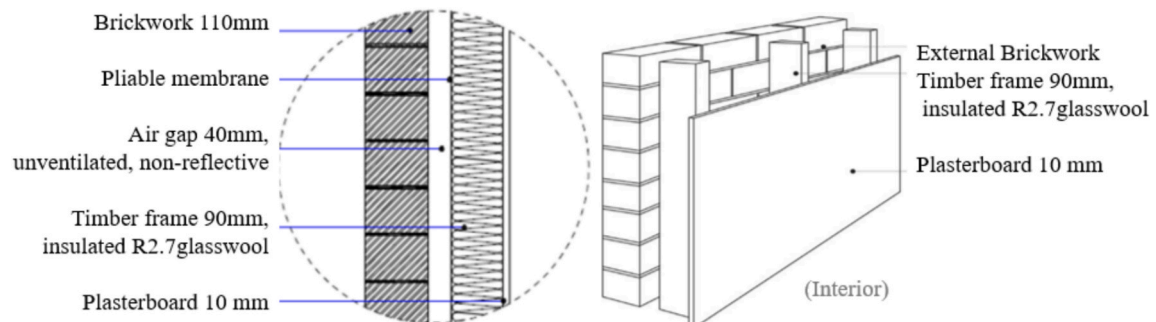


Fig. 4. Brick veneer external wall section detail (left) and diagram (right).

2.3. Simulation parameters

In this study, a series of strategically positioned monitoring points were implemented to evaluate the influence of both indoor and outdoor environmental conditions on the thermal and moisture dynamics within the wall assembly. A default air exchange rate for the indoor environment of 0.2 air changes per hour was applied to reflect typical Australian 7-Star energy efficient residential ventilation scenarios [53]. Each individual layer of the wall assembly was analysed over a ten-year period for its thermal behaviour, the start and end water content to indicate moisture accumulation and predicted interstitial mould growth risks. Detailed material properties associated with each layer are presented in Table 6 below. Material properties including vapour permeability, thermal conductivity, and moisture storage are assigned based on manufacturer data and standard material libraries.

This study employs hygrothermal simulation to evaluate the risk of interstitial and interior surface mould growth within the two selected timber framed external wall systems. The assessment utilizes the Mould-growth Index (MI), a quantitative metric that predicts mould proliferation based on environmental and material parameters. Key inputs for the simulation include climatic data, material properties, ventilation rates, and strategically placed monitoring points within the wall assemblies. Based on collaborative advice from Fraunhofer IBP, the mould-growth sensitivity class for pine sapwood (classified as very sensitive) is selected.

Additionally, to investigate mitigation strategies, the study explores the application of a ventilated cavity and vapour controlling interior and exterior membranes, both individually and in combination, under intermittent conditioning patterns. Fig. 5 illustrates the comprehensive layering applied to each wall system. Their influence on internal moisture buffering, temperature moderation, and MI values is compared to evaluating their suitability for high-performance building envelopes exposed to intermittent uncontrolled temperature operation.

Eight monitoring points were systematically positioned across four critical layers within each wall assembly to assess bio-hygrothermal performance. These points are listed below; this configuration enables a detailed analysis of moisture dynamics and potential mould growth across different material interfaces within the building envelope.

- The interior and exterior surfaces of the plasterboard.
- The interior and exterior surfaces of the glass-wool batt insulation.
- The interior and exterior surfaces of the pliable membranes.
- The interior and exterior surfaces of the cladding.

In NCC 2022 vol Two, the condensation verification approach mandates that the MI must not exceed 3.0 at either of the following locations:

- (a) the interior surface of the water control layer; or.
- (b) any surfaces of building fabric components located interior to the water control layer.

Given the significance of moisture-related challenges in timber-framed construction and the growing interest in this area, this study focuses on the timber located directly adjacent to the interior surface of the water control layer. This location also exhibited the highest MI among all monitoring points examined.

The analysis utilised the Sedlbauer/VTT MI model, which predicts the risk of mould formation over time on a scale from 0 (no growth) to 3 (visual results of mould on surface) and 6 (very high and tight colonization of mould growth on the surface). This empirical model accounts for variations in substrate material, surface temperature, and RH to predict mould growth and decline across hourly timesteps. The study examines both short-term (seasonal) and long-term (annual) accumulation of mould risk, offering a comprehensive evaluation of cyclic and sustained hygrothermal exposure on material surfaces.

3. Results

In accordance with general solar design principles that prioritize access to natural daylight in habitable rooms, particularly living and kitchen shared spaces, this study adopts floorplans with north and east orientations scenarios. These orientations were chosen to maximize solar exposure to primary occupied zones like living areas during daytime hours, especially in winter, to support thermal comfort and reduce reliance on heating. This approach emphasizes the temperate climate approach of providing sunlight to habitable rooms to minimize energy needs.

3.1. Analysis of outdoor climates

To characterise seasonal variations across the three NatHERS climate zones investigated, this study first calculated daily averages from hourly Reference Meteorological Year (RMV) climate profiles [49], and corresponding hourly rainfall profiles. From these daily values, the monthly maximum, minimum, and median are then derived. These statistical measures provide the basis for understanding seasonal patterns and for informing the subsequent 10-year hygrothermal and bio-hygrothermal simulations.

Fig. 6 below shows the data within 1.5 times the interquartile range (IQR) of outdoor monthly temperature and RH of CZ21. Panel (a) presents maximum, median, and minimum monthly temperatures (°C) alongside total monthly solar radiation (Wh/m²). Maximum temperatures ranged from 15 °C in July to 39 °C in January, while minimum temperatures varied between 2.3 °C in May and 11.1 °C in February. Median temperatures followed a seasonal pattern, peaking in summer (December–February) and reaching their lowest values in winter (June–August). Solar radiation was highest in January (204,601 Wh/m²) and December (204,473 Wh/m²), and lowest in June (56,705 Wh/m²).

Panel (b) displays maximum, median, and minimum relative humidity (RH, %) together with total monthly rainfall (mm). Median RH remained relatively stable, ranging between 58.5% and 76% throughout

Table 6
Applied Material properties in the simulation parameter.

Material	Layer Thickness (m)	Bulk density (kg/m ³)	Porosity (m ³ /m ³)	Spec. Heat Capacity (J/kgK)	Thermal Conductivity (W/mK)	Water Vapour diffusion resistance factor
Fiber Cement Sheathing Board	0.006	1380	0.479	840	0.5	127.7
Extruded Clay Brick	0.11	1820	0.41	959	0.6	9.5
External Membrane	0.001	130	0.001	2300	2.3	175.4
Glass-wool Batted Insulation	0.09	26.2	0.978	1650	0.036	1.8
Interior Membrane	0.001	85	0.086	2500	2.4	34,000
Paper-faced Gypsum Plaster Board	0.010	880	0.65	1050	0.163	6

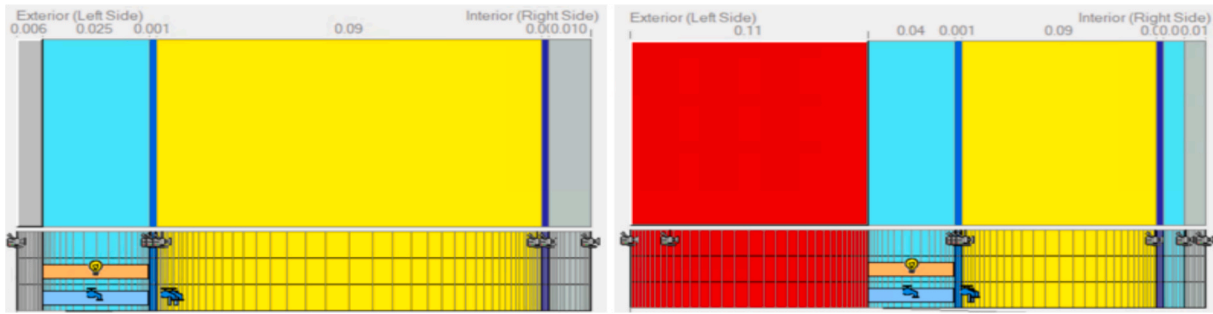


Fig. 5. The WUFI setting with the case applied all layers, CFCS (left) and brick veneer (right) systems.

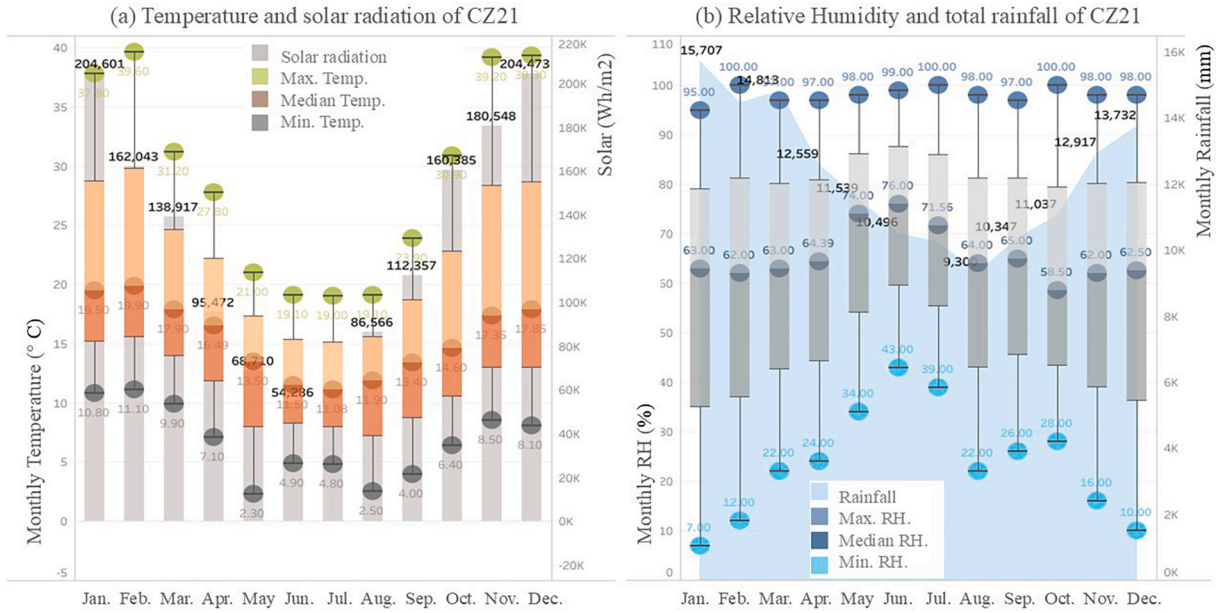


Fig. 6. Monthly 1.5 IRQ climate characteristics of CZ21 based on hourly data for a year.

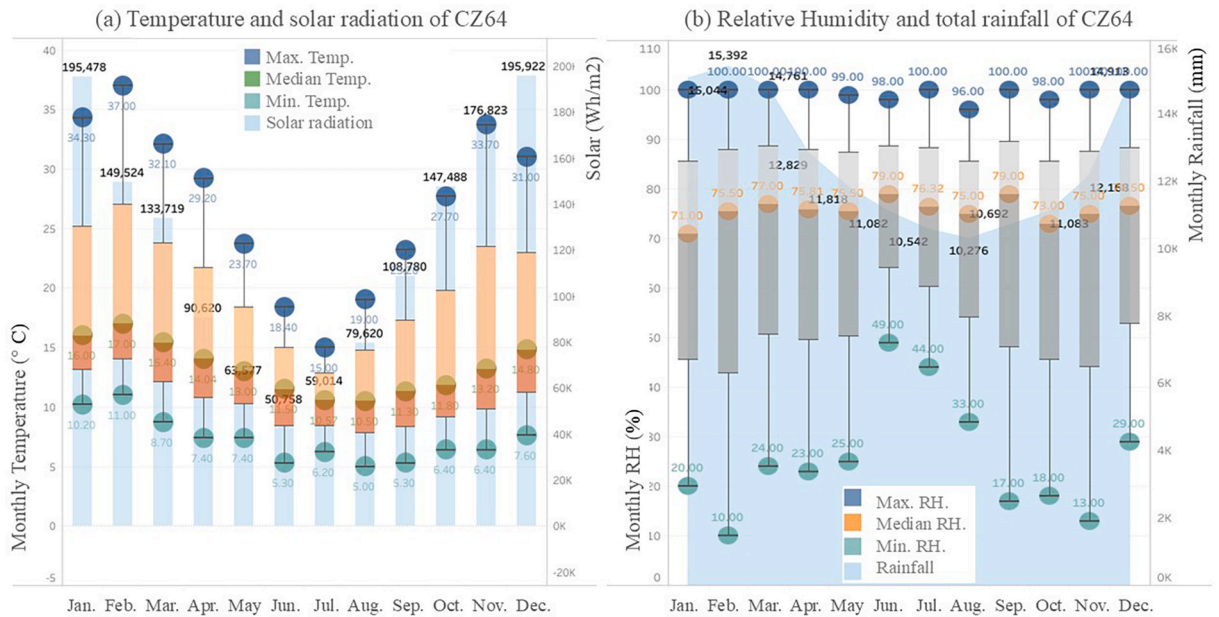


Fig. 7. Monthly 1.5 IRQ climate characteristics of CZ64 based on hourly data for a year.

the year, with maximum RH consistently near 100% and minimum RH between 7.4% in January and 43% in June. Monthly rainfall totals ranged from 9,300 mm in August to 15,707 mm in January, with higher rainfall observed during summer and early autumn months. In summary, CZ21 typically experiences cool winter, hot summer and lower median relative humidity, and reduced summer rainfall.

Fig. 7 presents the monthly climatic conditions for CZ 64 derived from hourly data. Panel (a) Temperature and solar radiation: Maximum temperatures range from 15.0 °C in July to 37.0 °C in February, while minimum temperatures range from 5.0 °C in August to 11.0 °C in February. Median temperatures follow a seasonal trend, peaking in summer (January–February) and reaching their lowest in winter (June–July). Monthly total solar radiation is highest in January (195,478 Wh/m²) and December (195,922 Wh/m²), and lowest in June (50,758 Wh/m²). On the right panel (b) Relative humidity and rainfall: Maximum relative humidity remains close to 100% year-round, while minimum values range from 18% in February to 49% in June. Median relative humidity varies between 71% and 79%. Monthly total rainfall ranges from 10,276 mm in November to 15,392 mm in February, with higher rainfall observed during summer months.

Fig. 8 presents the monthly climate characteristics of CZ 66, illustrating seasonal variability in temperature, solar radiation, relative humidity, and rainfall. The left panel (a) shows a pronounced annual temperature cycle, with peak maximum temperatures in January and February (38.5–38.7 °C) and the lowest minimum temperatures in June (−2.4 °C). Solar radiation follows a similar seasonal trend, reaching the highest value in January (222,792 Wh/m²) and the lowest in June (58,668 Wh/m²). The right panel (b) reveals consistently high maximum relative humidity of 100% all year-round, with median values ranging from 57% in January to 95% in June. Rainfall peaks in February (12,633 mm) and March (12,665 mm), with the driest month being July (9,118 mm).

The climate of CZ 66 is temperate with distinct seasonal variations, characterised by warm summers, cool winters, moderate solar radiation seasonality, high humidity, and substantial year-round rainfall. Summer is warm but not excessively hot, with median temperatures, while winter is cold. The consistently high maximum relative humidity, combined with precipitation in all months, indicates a moist climate. When compared to CZ 21, CZ 66 is cooler in summer and winter, receives slightly lower annual solar radiation, and experiences consistently higher relative humidity. Both CZ 66 and CZ 21 typically have a more

pronounced summer peak in solar exposure, but CZ 21 has a longer dry season. In comparison with CZ 64, CZ66 is generally cooler, particularly in summer maximum temperatures, and CZ64 slightly lower solar radiation levels than CZ 66 and CZ 21.

Synthesising these observations above CZ 66, CZ 21, and CZ 64 represent distinct climatic gradients. This combined profile highlights the climatic diversity across the three zones: CZ 21's warm-dry seasonality, CZ 64 mild-humid year-round conditions, and CZ 66 cool-humid, high-rainfall regime with strong seasonal temperature contrast.

3.2. Indoor temperature results of each room

One of the key objectives of this research is to identify which rooms are most susceptible to moisture accumulation and mould growth under intermittently uncontrolled temperature conditioning, and to examine how variations in room temperature arise from the combined effects of plan layout, orientation, and the primary activities conducted within each space. Currently, the shower moisture and latent heat are not included in the AccuRate simulation.

A comparison of differences in room temperature patterns between an intermittent conditioning scenario and the DA07-prescribed continuous conditioning of CZ21 is shown in Fig. 9. The red dotted line indicates 21.1 °C threshold, which serves as the prescribed lower limit under ASHRAE 160 methodology.

Subplots (a) through (c) display hourly temperature variations over a representative week (the first week of January). Subplots (d) through (f) illustrated the monthly temperature distribution for January based on NCC CZ21 results. Finally, subplots (g) through (i) present the annual temperature profile, highlighting the seasonal influence on the simulation results. The darker line represents temperature fluctuations under intermittent conditioning, while the lighter line illustrates results for the continuous conditioning. In the latter case, the temperature is consistently maintained at a maximum threshold of 21.1 °C. Based on the results across these varying temporal scales, the bedrooms and kitchen/living zones typically show the highest calculated RH conditions. Interestingly, the calculated RH values are very similar to in-house measurements obtained between 2013 and 2015 from new and existing housing in Tasmania [54,55]. Using the Kitchen and Living zones as a representative example, the following analysis examines variations across different climate zones to illustrate the impact of conditioning patterns on indoor environmental conditions.

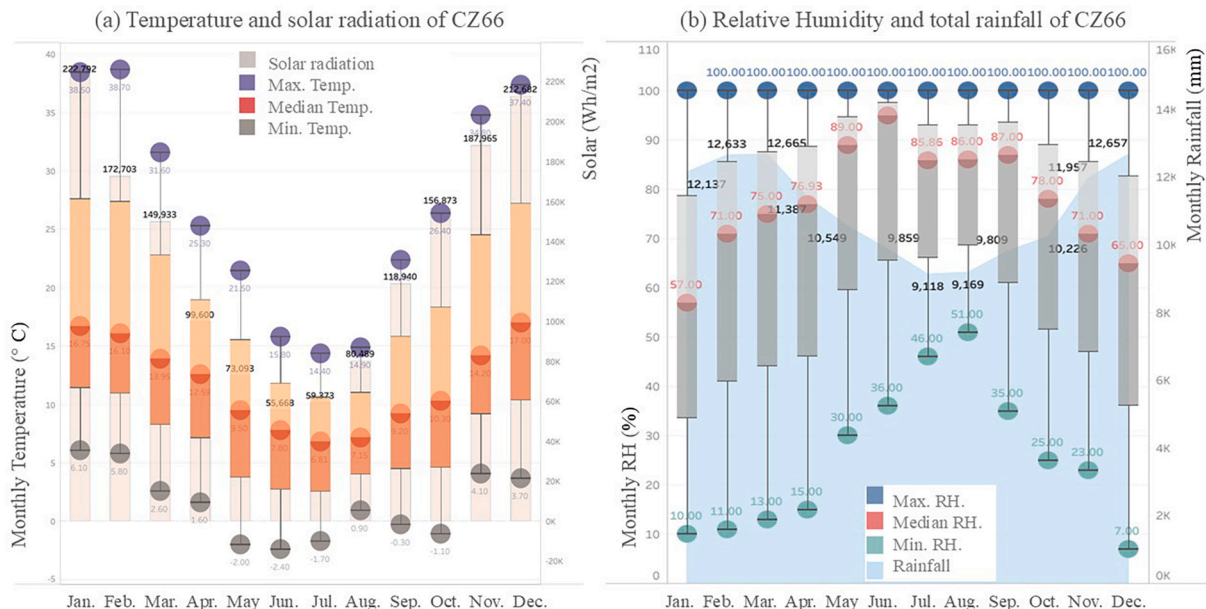


Fig. 8. Monthly 1.5 IRQ climate characteristics of CZ66 based on hourly data for a year.

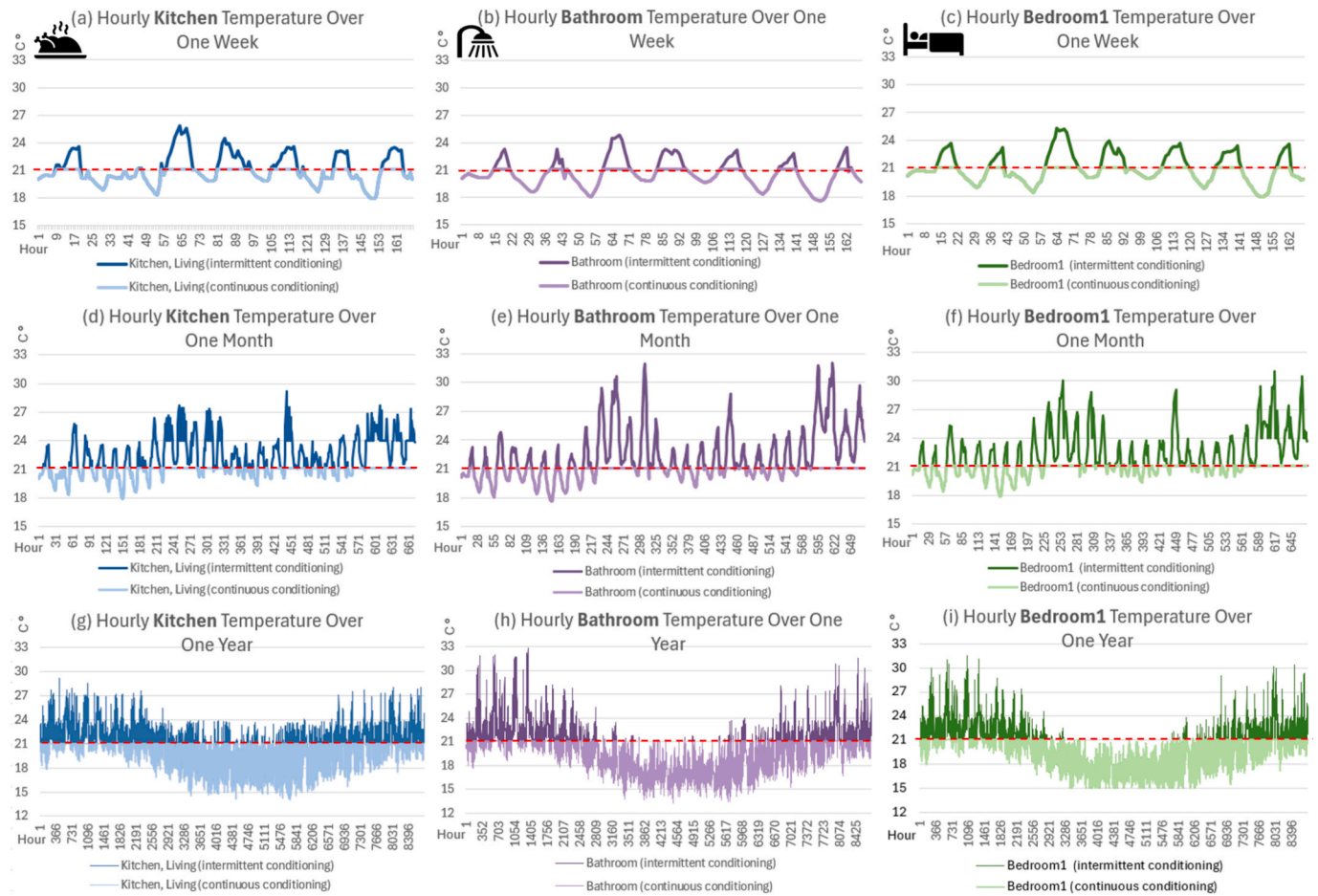


Fig. 9. Comparison of indoor temperatures for the two studied conditioning scenarios for the north-oriented house in CZ21.

3.2.1. NatHERS CZ 21

Table 7 presents calculated indoor temperature profiles for different rooms in two plan orientations of CZ 21. For each room, maximum, minimum, and average temperatures are listed alongside the percentage of percentages $>21.1^{\circ}\text{C}$ and below $<18^{\circ}\text{C}$, thresholds typically associated with thermal comfort limits in residential buildings.

Across both orientations, these CZ 21 results of indoor temperatures exhibit reduced diurnal fluctuations compared to the outdoors

(maximums $\leq 36.3^{\circ}\text{C}$ vs. 39.6°C outdoors; minimums $\geq 11.9^{\circ}\text{C}$ vs. 2.3°C outdoors), indicating that the building envelope and internal thermal mass moderate extremes. The average indoor temperatures for most spaces range narrowly between 19.0°C and 20.8°C . Living areas and bedrooms maintain indoor temperatures above 21°C for 29–41%, with only 11–16% of hours below 18°C . In contrast, service areas such as laundries and bathrooms show greater deviations: laundries record the highest proportion of hours below 18°C (up to 39.9%), while

Table 7

Calculated indoor temperatures under intermittent conditioning in NatHERS CZ21, NCC CZ6.

Plan Orientation	Zone/Room	Wall Ori.	Max. $^{\circ}\text{C}$	Min. $^{\circ}\text{C}$	Avg. $^{\circ}\text{C}$	$>21^{\circ}\text{C}$ (%)	$<18^{\circ}\text{C}$ (%)
	Outdoor		39.6	2.3	15.8	+14.1	71.1
	Kitchen, living	N, S, E	29.2	14.0	20.1	+40.7	11.1
	Bathroom	W	32.8	13.6	19.7	+28.3	30.6
	Bed 1	W, S	31.5	15.0	20.1	+29.6	15.5
	Bed 2	W	34.1	15.0	20.5	+36.2	12.6
	Bed 3	N, W	33.7	15.0	20.6	+36.8	12.9
	Bed 4	W	36.3	15.0	20.4	+34.9	13.7
	Laundry	E	31.8	11.9	19.3	+24.8	35.7
	En-suite	W	32.0	15.0	19.8	+28.1	20.0
	Toilet	W	35.8	13.6	20.1	+33.5	27.0
	Kitchen, living	S, E, W	28.3	14.0	20.8	+38.4	11.1
	Bathroom	N	31.2	13.4	19.9	+30.4	25.5
	Bed 1	W, N	34.5	15.0	20.4	+34.6	13.7
	Bed 2	N	31.5	13.4	19.9	+34.4	11.9
	Bed 3	N, E	34.2	15.0	20.6	+38.5	12.6
	Bed 4	N	31.9	14.3	20.6	+38.1	12.4
	Laundry	S	31.4	11.9	19.0	+22.6	39.9
	En-suite	N	33.1	15	19.9	+29.5	15.7
	Toilet	N	32.4	13.8	20.4	+38.3	20.8

bathrooms in both orientations have elevated percentages of hours above 21 °C (28–30%) coupled with higher sub-18 °C exposure (25–35%).

3.2.2. NatHERS CZ 64

Table 8 presents the key statistical measures in CZ 64. The simulated metrics include the key statical measure same as Fig. 7, as well as the percentage of exceeding 21 °C and falling below 18 °C. Outdoor temperature data are provided as a reference baseline.

For both orientations, the indoor thermal environment remains notably more stable than outdoor conditions, with indoor maximum temperatures ranging from approximately 27.7 °C to 32.7 °C, compared to outdoor peaks of 37.0 °C. Similarly, indoor minimum temperatures are substantially higher than the outdoor minimum of 5.0 °C, indicating the building envelope's moderating effect on thermal extremes.

However, substantial intra-room variability is observed. Living areas maintain average temperatures close to 19.8 °C for both orientations, with around 18–20% of hours exceeding 21 °C, suggesting intermittent periods of mild overheating. In contrast, service spaces such as bathrooms, laundries, and toilets show lower average temperatures (17.4–18.7 °C) and a higher proportion of hours below 18 °C, particularly in laundries, where cold conditions occur for 60–65% of the monitored period.

Bedrooms exhibit intermediate thermal performance, with average temperatures between 18.3 °C and 19.2 °C and cooler-hour proportions ranging from approximately 19% to 26%. The frequency of bedroom temperatures exceeding 21 °C (9.3–17.1%) indicates a negligible overheating risk but also suggest that occupants may experience prolonged periods at or below the thermal comfort threshold during winter.

3.2.3. NatHERS CZ 66

The data in Table 9 presents the maximum, minimum, and average indoor temperatures, along with the percentage of time above 21 °C and below 18 °C in CZ 66. The outdoor climate shows a maximum of 38.7 °C, a minimum of −2.4 °C, and an average of 12.3 °C, with temperatures exceeding 21 °C for 10.6% of the year and falling below 18 °C for 82.5% of the year.

For the North plan orientation, the kitchen/living area (N, S, E walls) exhibits relatively stable conditions, with an average temperature of 19.8 °C, maintaining temperatures above 21 °C for 23.3% of the time and below 18 °C for 21.5%. Bedrooms 2–4 generally record average temperatures between 18.9 °C and 19.0 °C, with notable differences in thermal stability depending on wall orientation. For instance, Bed 3 (N, W) has the highest maximum temperature (35.0 °C) and spends 26.0% of the time above 21 °C, indicating greater solar heat gain. Wet areas,

such as bathrooms and laundries, tend to have lower average temperatures (16.9 °C–17.5 °C) and higher percentages of time below 18 °C (61.2%–66.1%), suggesting increased susceptibility to thermal discomfort and potential condensation risks in winter.

For the East plan orientation, the thermal performance is broadly similar, though some rooms display marginally different thermal profiles due to altered solar exposure. The kitchen/living area (S, E, W walls) records an average temperature of 19.7 °C, slightly lower than the North plan but with a similar distribution of time above and below the comfort thresholds (21.2% above 21 °C and 22.2% below 18 °C). Bedrooms facing north or east (e.g., Bed 3, N, E) show increased time above 21 °C (21.2%–31.8%), reflecting enhanced solar gains. Conversely, bathrooms and laundries continue to register the lowest average temperatures (17.0 °C–17.1 °C) and the highest percentages below 18 °C (63.9%–66.4%), reinforcing the pattern observed in the North plan orientation.

3.3. Results under intermittently controlled temperature conditioning

To analyse the deleterious effects of moisture and mould growth on timber-framed construction, this study narrows its focus to the single most critical point of hygrothermal analysis: the timber material directly adjacent to the interior surface of the water control layer, where the risk of moisture accumulation is the highest.

3.3.1. Hygrothermal results

Table 10 presents the calculated moisture content accumulation of NatHERS CZ 21, CZ 64, and CZ 66 for clay brick veneer walls under intermittent temperature-based conditioning. The horizontal columns represent climate zones and apply interventions, while the rows indicate floor plan and wall orientation as well as room names.

The results show water accumulation levels in kg/m². The legend, located in the top-left corner of the table, provides a key for the color-coding, where a darker shade indicates a higher degree of moisture accumulation. The first row, as title shaded in light yellow, indicates the climate zones; the second row, with a light blue background, specifies the cavity application; the third row identifies the type of external membrane applied; and the fourth row indicates whether an internal membrane is included.

For clay brick veneer wall system, moisture accumulation is nil in CZ 21 and CZ 64 across all orientations and spaces, indicating low hygrothermal risk. In contrast, CZ 66 demonstrates substantial exterior wall system moisture build-up. Critical values are observed in exterior walls of the kitchen, living and bedrooms, with peaks exceeding 63.06 kg/m², compared to the initial water content of 1.38 kg/m². The initial water

Table 8

Key statistical measures of indoor temperatures under intermittent conditioning in CZ64, NCC CZ6.

Plan Orientation	Zone/Room	Wall Ori.	Max. °C	Min. °C	Avg. °C	>21 °C (%)	<18 °C (%)
	Outdoor		37.0	5.0	13.8	+4.90	87.2
	Kitchen, living	N, S, E	28.5	14.3	19.8	+20.0	17.5
	Bathroom	W	31.4	13.4	18.1	+8.7	52.2
	Bed 1	W, S	28.9	15.0	18.8	+11.2	26.0
	Bed 2	W	32.1	13.7	19.1	+14.9	21.1
	Bed 3	N, W	31.9	15.0	19.2	+15.9	20.6
	Bed 4	W	32.5	14.6	19.0	+14.4	22.7
	Laundry	E	30.8	12.5	17.6	+6.8	60.7
	En-suite	W	28.3	14.4	18.4	+8.1	32.4
	Toilet	W	32.4	13.8	18.5	+13.3	46.2
	Kitchen, living	S, E, W	27.7	14.3	19.8	+18.0	17.6
	Bathroom	N	30.2	13.9	18.7	+15.2	47.8
	Bed 1	W, N	32.7	15.0	19.0	+13.6	22.6
	Bed 2	N	3.07	13.5	18.3	+9.3	19.5
	Bed 3	N, E	31.4	15.0	19.2	+17.1	20.1
	Bed 4	N	30.9	13.2	19.2	+16.5	20.5
	Laundry	S	28.9	12.6	17.4	+4.9	64.5
	En-suite	N	31.3	14.6	18.6	+7.8	27.3
	Toilet	N	30.7	13.9	18.7	+15.2	40.4

Table 9

Key statistical measures of indoor temperatures under intermittent conditioning in CZ66, NCC CZ4&6.

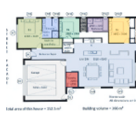
Plan Orientation	Zone/Room	Wall Ori.	Max. °C	Min. °C	Avg. °C	>21 °C (%)	<18 °C (%)
	Outdoor		38.7	-2.4	12.3	+10.6	82.5
	Kitchen, living	N, S, E	29.5	12.1	19.8	+23.3	21.5
	Bathroom	W	32.4	10.9	17.5	+13.4	61.2
	Bed 1	W, S	31.4	14.5	18.6	+14.4	34.0
	Bed 2	W	32.3	14.6	19.0	+18.2	29.0
	Bed 3	N, W	35.0	15.0	18.9	+16.3	26.0
	Bed 4	W	34.2	13.2	18.9	+17.8	30.8
	Laundry	E	30.5	9.2	16.9	+12.4	66.1
	En-suite	W	30.7	13.9	18.3	+12.9	37.7
	Toilet	W	33.7	11.7	17.9	+16.2	56.4
	Kitchen, living	S, E, W	31.4	12.2	19.7	+21.2	22.2
	Bathroom	N	29.2	10.8	17.0	+10.7	66.4
	Bed 1	W, N	32.1	14.5	18.9	+18.29	30.4
	Bed 2	N	30.2	15.0	18.7	+14.2	32.1
	Bed 3	N, E	31.4	12.2	19.7	+21.2	31.8
	Bed 4	N	29.8	15.0	18.7	+14.8	32.5
	Laundry	S	30.7	9.3	17.1	+12.1	63.9
	En-suite	N	29.5	13.9	18.2	+11.2	38.0
	Toilet	N	30.3	11.6	17.3	+12.3	63.1

Table 10

Hygrothermal performance of brick veneer wall system in assessed climate zones.

			Cavity / Climate / Exterior M. / Interior M.							
			Yes							
			CZ21		CZ64		CZ66NCC4		CZ66NCC6	
			Class 4-1 (175.4)		Class 4-1 (175.4)		Class 3-1 (1398)		Class 4-1 (175.4)	
Plan	Wall Ori.	Room	No	Yes	No	Yes	No	Yes	No	Yes
N	N	Bed3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		KL	0.00	0.00	0.00	0.00	40.45	4.21	6.49	0.00
	S	KL	0.00	0.00	0.00	0.00	2.73	9.50	48.43	0.00
		Bed1	0.00	0.00	0.00	0.00	6.33	12.97	7.33	0.00
E	N	Bathroom	0.00	0.00	0.00	0.00	22.34	2.48	63.06	0.00
		Bed1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		Bed2	0.00	0.00	0.00	0.00	43.95	19.91	0.00	0.00
		Bed3	0.00	0.00	0.00	0.00	32.71	1.52	0.00	0.00
		Bed4	0.00	0.00	0.00	0.00	0.00	4.93	0.00	0.00
		Toilet	0.00	0.00	0.00	0.00	5.75	0.00	4.16	0.00
	S	Laundry	0.00	0.00	0.00	0.00	0.00	42.85	0.00	0.00
*The start water content is 1.38kg/m².			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
			0.00	0.00	0.00	0.00	0.00	32.35	0.00	11.78
		KL	0.00	0.00	0.00	0.00	1.63	0.00	75.79	0.00

content varies among the exterior wall systems due to their different material properties.

Table 11 presents the hygrothermal performance of CFCS clad walls intermittently controlled temperature conditioning. The table structure is the same as previous one. The start water content for CFCS simulation is 1.48 kg/m². The results show no exterior wall moisture accumulation in CZ 21 and CZ 64. However, CZ 66 has several cases of calculated exterior wall moisture accumulation, especially CZ 66 (NCC 4) with Class 3–1 exterior membrane, significant accumulation is observed, mainly in the external walls of kitchens and living and bedrooms.

3.3.2. Bio-hygrothermal results

The WUFI VTT software was used for assessing mould growth potential. According to the NCC 2022, a MI value greater than 3.0 is considered unacceptable. This criterion, also defined by AIRAH DA07, is essential for meeting the NCC Performance Requirements F8P1 (Volume

One) and H4P7 (Volume Two) and is critical for minimizing the negative health effects.

Table 12 and Table 13 presents the results of the MI calculations. The legend in the top-left corner shows the MI values using two distinct colour scales, including a blue scale for MI values from 0 to < 3.0: A darker blue colour indicates a lower MI, with the colour transitioning to red Scale for MI values ≥ 3.0: A darker red colour indicates a higher MI, with the highest values being the darkest red.

For the clay brick veneer wall system, Table 12, the results for CZ 21 show that the MI remains at or below the 3.0 in blue scale. In CZ 64, several results yielded an MI of 5.0 or 6.0, which is beyond the required ≥3.0. A key finding is that the application of an interior membrane resulted in a significant increase in predicted MI, as all results fell within the red scale. In 12 out of 14 cases, the interior membrane's use appeared to increase predicted mould growth rather than mitigate it. Given that the maximum displayed MI is 6.0, it is not possible to differentiate between cases that might have produced an even higher incidence of

Table 11
Hygrothermal performance of CFCS wall system in assessed climate zones.

Moisture accumulation			Climate / Cavity / Exterior membrane / Interior membrane															
			CZ21				CZ64				CZ66NCC4				CZ66NCC6			
			No		Yes		No		Yes		No		Yes		No		Yes	
0.00	82.00	Class 4-1 (175.4)	Class 4-1 (175.4)		Class 4-1 (175.4)		Class 4-1 (175.4)		Class 3-1 (1398)		Class 3-1 (1398)		Class 4-1 (175.4)		Class 4-1 (175.4)			
Plan Ori	Wall ori	Room	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes		
N	N	KL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.67	81.53	23.95	0.00	0.00	0.00	30.59	28.55
		Bed3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.18	68.75	23.45	19.42	0.00	0.00	14.32	27.23
	S	Bed1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.81	0.00	16.24	3.06	3.80	22.97	29.78	0.00
		KL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.04	2.35	9.62	5.77	4.35	0.00	15.87	21.60
E	N	Bath	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.57	71.88	3.68	19.66	37.62	3.92		5.97
		Bed 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.69	70.24	10.89	23.52	27.17	0.00	0.00	4.52
		Bed1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.74	0.00	7.68	5.70	3.33	17.26	33.49	3.49
		Bed3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.69	72.45	0.00	8.48	0.00	0.00	23.13	0.00
	S	Bed4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.77	38.36	9.05	20.34	0.00	0.00	0.00	0.00
		ENS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	36.83	5.96	2.81	41.30	38.53	0.00	23.97	22.65
		Toilet	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.24	7.97	32.87	37.06	0.00	0.00	24.45	0.00
		Bed1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	36.83	5.96	2.81	41.30	38.53	0.00	23.97	22.65
*The start water content is 1.48kg/m².	KL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.32	67.38	13.58	0.00	4.57	0.00	36.91	21.58	
	LDY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.71	15.49	8.14	73.92	3.03	26.78	32.03	0.00	

mould. In CZ 66, an MI of 6 0.0 was frequently achieved, indicating a consistent failure to meet the ≥ 3.0 requirement. These findings suggest that further interventions are necessary to improve the system's performance in these climate zones.

The results of the CFCS external wall system presented in Table 13, show varying performance across different climate zones. In CZ 21, all cases consistently performed within the required parameters, with MI remaining at or below 3.0, in blue shading. In CZ 64, the system largely met performance requirements, with only 3 out of 44 cases exceeding an MI of ≥ 3.0 . A key finding for this climate zone is that the application of an interior membrane resulted in all cases remaining within the blue scale, indicating compliance with the performance requirement. Conversely, the system consistently failed to meet the performance requirement in CZ 66, as every case in this zone yielded an MI of 6.0. The application of a cavity or an interior membrane did not consistently serve as an effective mitigation strategy. Performance improvements, as measured by a reduction in the MI were not uniformly observed.

4. Comparison of continuously and intermittently conditioned results

Previous research indicated that no moisture accumulation was calculated at the monitoring point (adjacent to the exterior membranes of the insulation layer) in external wall systems investigated under continuous conditioning across all studied climate zones [21,24]. Although moisture accumulation was detected within the clay bricks, this does not support mould growth, as brick itself is not a suitable substrate for mould development. In contrast, under Scenario B

conditioning, moisture accumulation was predicted in both wall systems in CZ 66 (see Table 14).

Table 15 illustrates the predicted MI for south-facing brick veneer wall assemblies across multiple climate zones, room types, and the studied two conditioning regimes. Results are shown for baseline NCC-compliant construction and for enhanced assemblies incorporating interior vapour control (InM.), a ventilated cavity (C), and the combined application of both measures (InM. + C).

The predicted MI values range from <1.0 to 6.0; no values below 0.001 are reported, shown as null in the figure. Higher predicted MI values indicate greater mould growth risk. Each cell displays the predicted MI, with colour shading denoting room type and the labelled number indicating the predicted MI value. Rows represent successive construction enhancements, progressing from baseline NCC-compliant assemblies to configurations that include interior vapour control, ventilated cavities, and combined mitigation strategies for each of the studied climates respectively. This structure enables direct comparison of conditioning regime impacts as well as the relative effectiveness of individual and combined moisture-control measures. The two conditioning regimes are presented as distinct horizontal panels separated by dashed lines, enabling synthesis of hygrothermal performance trends across conditioning scenarios.

As NCC 2022 mandates the inclusion of a drained and ventilated cavity for brick veneer wall systems, interior vapour control was the only additional mitigation strategy evaluated. While the clay bricks do not support mould growth, their high moisture storage capacity allows it to absorb substantial amounts of moisture. Combined with indoor-outdoor temperature differentials, this characteristic promotes

Table 12
Bio-hygrothermal performance of brick veneer wall system in assessed climate zones.

			Climate / Cavity / Exterior membrane / Interior membrane							
			CZ21		CZ64		CZ66NCC4		CZ66NCC6	
			Yes		Yes		Yes		Yes	
			Class 4-1 (175.4)		Class 4-1 (175.4)		Class 3-1 (1398)		Class 4-1 (175.4)	
			No	Yes	No	Yes	No	Yes	No	Yes
Plan	Ori	Room								
N	N	Bed3	0.008	0.005	1.250	5.500	6.000	6.000	6.000	6.000
		KL	0.025	0.008	4.500	5.500	6.000	6.000	6.000	6.000
	S	KL	0.010	0.003	6.000	6.000	6.000	6.000	5.500	5.500
		Bed1	0.003	0.003	5.500	6.000	6.000	6.000	6.000	6.000
E	N	Bathroom	0.004	0.004	0.500	5.500	6.000	6.000	6.000	6.000
		Bed1	0.008	0.005	0.750	5.500	6.000	6.000	6.000	6.000
		Bed2	0.005	0.005	0.750	5.500	6.000	6.000	6.000	6.000
		Bed3	0.008	0.005	0.800	5.500	6.000	6.000	6.000	6.000
		Bed4	0.010	0.008	5.000	5.500	6.000	6.000	6.000	6.000
		Toilet	0.003	0.004	0.500	5.500	6.000	6.000	6.000	6.000
	S	Laundry	0.001	0.008	5.000	6.000	6.000	6.000	6.000	6.000
		Bed1	0.002	0.003	5.500	6.000	6.000	6.000	6.000	6.000
		Ensuite	0.003	0.004	0.500	5.500	6.000	6.000	6.000	6.000
		KL	0.001	0.003	6.000	6.000	6.000	6.000	6.000	6.000

frequent and repeated condensation events on a seasonal and annual basis, thereby increasing mould growth risk within the wall assembly.

The left (grey) panel presents results under continuous conditioning. Across all climates, from CZ 21 to CZ 66, baseline NCC-compliant assemblies exhibit predicted MI values exceeding 3.0. Upon application of interior vapour control, MI values are consistently reduced to within the safe range ($MI \leq 1.0$). Minor climate-related variation is observed, with MI values of approximately 4.0 for the CZ 21 case and up to 6.0 for the colder and more humid CZ 66. These results indicate that under continuous conditioning, interior vapour control is highly effective in mitigating mould risk for brick veneer wall systems across all studied climates.

The right panel presents the results for the unregulated temperature intermittent conditioning regime (Scenario B). In CZ 21, the predicted MI outcomes consistently indicate low risk, with values remaining below 1.0. Conversely, CZ 64 demonstrates predicted MI values ranging from 5.5 to 6.0. Notably, the NCC-compliant case for the ensuite yields a predicted MI of 0.50; however, the addition of an interior control layer results in a predicted MI of 5.5. In this instance, the mitigation strategy paradoxically reversed performance, suggesting it is ineffective under unregulated thermal conditions.

For CZ 66, MI values reach a peak MI of 6.0, with two cases at 5.5, reflecting an elevated risk of predicted mould growth. The application of interior vapour control and cavity ventilation fails to produce measurable reductions in the predicted MI across various room types, leaving substantial residual risk. Similarly, the interior control layer strategy

yields unchanged predicted MI values under this regime, likely due to the MI being saturated at the maximum simulation threshold of 6.0. These findings are particularly critical for CZ 66, where brick veneer wall systems exhibit negligible responsiveness to typical mitigation strategies, and NCC-compliant assemblies already indicate severe mould risk.

Table 16 analysis adopts the same structural configuration as the brick veneer assemblies to enable direct comparison of CFCS results. Under continuous conditioning (Scenario A), predicted MI values remain relatively consistent across wall configurations and climate zones. In CZ 21 and CZ 64, MI values ranged from near-zero to 5.0. The implementation of a ventilated cavity resulted in a marked decrease in MI; furthermore, when an internal vapour control layer was integrated, either independently or in combination with the cavity, all MI values were successfully attenuated to below 1.0.

Whereas in CZ 66, values increased to between 5.5 and 6.0. In the absence of mitigation measures, performance consistently reaches the maximum MI of 6.0, indicating a high risk of mould growth. The application of mitigation strategies such as the inclusion of an internal vapour control layer, or the combined use of a vapour control layer and a ventilated cavity, generally reduces predicted MI values, although the extent of improvement varies across cases. In contrast, the application of a ventilated cavity alone does not result in a significant reduction in MI in CZ 66.

On the right side, the unregulated temperature intermittent conditioning regime (Scenario B) exhibits the highest overall predicted MI

Table 13

Bio-hygrothermal performance of CFCS wall system in assessed climate zones.

Mould Growth Index 0.000 6.000			Climate / Cavity / Exterior membrane / Interior membrane															
			CZ21				CZ64				CZ66NCC4				CZ66NCC6			
			No		Yes		No		Yes		No		Yes		No		Yes	
Plan Ori	Wall ori	Room	Class 4-1 (175...		Class 4-1 (175...		Class 4-1 (175...		Class 4-1 (175...		Class 3-1 (139...		Class 3-1 (139...		Class 3-1 (139...		Class 3-1 (139...	
			No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
N	N	KL	0.015	0.030	0.005	0.015	0.075	0.100	0.150	0.175	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
		Bed3	0.006	0.030	0.005	0.013	0.075	0.075	0.125	0.150	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
	S	Bed1	0.006	0.030	0.005	0.015	0.250	0.300	0.200	0.175	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
		KL	0.020	0.040	0.040	0.015	5.000	0.500	4.000	0.200	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
E	N	Bath	0.005	0.025	0.004	0.010	0.060	0.075	0.125	0.175	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
		Bed 2	0.006	0.030	0.006	0.013	0.075	0.095	0.150	0.195	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
		Bed1	0.006	0.030	0.013	0.060	0.060	0.075	0.125	0.165	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
		Bed3	0.006	0.030	0.006	0.013	0.075	0.085	0.125	0.175	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
		Bed4	0.006	0.030	0.005	0.013	0.075	0.095	0.150	0.175	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
		ENS	0.005	0.025	0.004	0.010	0.060	0.075	0.125	0.165	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
		Toilet	0.005	0.025	0.005	0.013	0.060	0.075	0.125	0.165	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
	S	Bed1	0.006	0.040	0.006	0.015	0.300	0.350	0.200	0.175	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
		KL	0.060	0.040	0.013	0.015	5.000	0.500	0.500	0.200	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000
		LDY	0.004	0.025	0.004	0.010	0.095	0.200	0.100	0.175	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000

Table 14

The compared results of moisture accumulation of the two conditioning scenarios.

Conditioning	Wall	CZ 21	CZ 64	CZ 66 (NCC 4)	CZ 66 (NCC 6)
Scenario A	brick veneer	N	N	N	N
	CFCS	N	N	N	N
Scenario B	brick veneer	N	N	Y	Y
	CFCS	N	N	Y	Y

values and the greatest dispersion across room types and climates. In CZ 21, predicted MI outcomes remain broadly consistent with those observed under other intermittent conditioning regimes. In contrast, CZ 64 demonstrates the lowest predicted mould risk across all four conditioning regimes, with mitigation performance intermediate between fully intermittent scenario, although a decline in mitigation effectiveness is still evident.

For CZ 66, baseline assemblies frequently reach the upper limit of the MI scale, reflecting elevated mould growth risk under sustained high indoor humidity conditions. The application of interior vapour control or cavity ventilation independently does not result in measurable reductions in predicted MI across multiple room types, and residual risk remains evident. The combined InM. + C strategy similarly produces unchanged MI values under this regime, likely due to the MI being

capped at a maximum value of 6.0 within the simulation framework. These results are particularly concerning for CZ 66, where CFCS wall systems exhibit limited responsiveness to mitigation strategies, and NCC compliant assemblies already indicate severe mould risk. Overall, the Scenario B represents a performance with higher MI value compare with continuous conditioning scenario.

5. Discussion

This study investigated the hygrothermal and bio-hygrothermal performance of timber-framed clay brick veneer and CFCS external wall systems when subjected to intermittent room based interior temperature and moisture conditioning. For comparison purposes, the external wall systems were evaluated under both intermittent and continuous conditioning regimes, aligned with a 7-star building energy rating. This approach directly contrasts with the continuous profiles prescribed by ASHRAE 160, AIRAH DA07, and EPC protocols, which assume indoor temperatures are regulated consistently. By utilizing a customized climate profile that reflects intermittent conditioning with no temperature control, this analysis revealed significant discrepancies in moisture accumulation and mould risk outcomes compared to steady-state assumptions.

The comparisons presented in Section 4.0 highlight the gap between regulatory assumptions and actual building operation, particularly under intermittent and unregulated temperature conditioning. Furthermore, the results indicate that mitigation strategies effective

Table 15

Comparison of the hygrothermal performance of the brick veneer wall under two conditioning scenarios.

Conditioning- Plan orientation- Wall orientation- Room- CZ NCC Case				Scenario A		Scenario B							
				NA	LDY	E				N			
						S				S			
						B1	KL	EnS		B1	S	KL	
CZ21	CZ6	NCC		4.000	0.001	0.002	0.001	0.003		0.003		0.010	
	InM.	+ C.		0.015	0.008	0.003	0.003	0.004		0.003		0.003	
CZ64	CZ6	NCC		4.500	5.000	5.500	6.000	0.500		5.500		6.000	
	InM.	+ C.		0.015	6.000	6.000	6.000	5.500		6.000		6.000	
CZ66	CZ4	NCC		6.000	6.000	6.000	6.000	6.000		6.000		6.000	
	InM.	+ C.		5.500	6.000	6.000	6.000	6.000		6.000		6.000	
Scenario A	CZ6	NCC		6.000	6.000	6.000	6.000	6.000		6.000		5.500	
Bed 1													
En-suite													
Kitchen													
Laundry													
				0	3	6	0	3	6	0	3	6	0
				MI	MI	MI	MI	MI	MI	MI	MI	MI	MI

under continuous conditioning do not perform equivalently under intermittent conditioning; the commonly suggested mitigation measures were insufficient to achieve safe MI predictions for the studied climates and wall assemblies. These findings underscore the need for further investigation into indoor moisture management strategies that are compatible with energy-efficient building design and the intermittent conditioning regimes that exist in many cool-temperate, temperate and warm temperate climate zones that utilise a permanently conditioned hygrothermal simulation certification framework. These findings indicate that the intermittent conditioning pattern poses an overall higher risk of interstitial moisture accumulation and mould growth compared to continuous conditioning within the studied climates and wall systems, particularly in the higher humidity and cooler climate zones such as CZ 66. Adopting climate-adaptive design strategies is essential for mitigating environmental risk and ensuring long-term project viability, a conclusion that aligns critically with current architectural and engineering research [56,57]. The analysis, which focused on critical monitoring points for interstitial mould risk, showed that while mitigation strategies, such as employing a cavity, an exterior or interior vapour control layer, or a combination, were effective under continuous conditioning, their efficacy varied under intermittently uncontrolled temperature conditioning. Specifically, the inclusion of an interior membrane, proved high effectiveness under continuous conditioning. However, for the clay brick veneer wall system, applying an interior membrane often exacerbated moisture-related issues, leading to higher

MI. This observation is consistent with previous experimental findings that suggested the use of vapour-open wall assemblies or high-vapour-permeability building materials [57–60].

The findings of this study reveal significant implications for the assessment and design of energy-efficient residential buildings under EPC frameworks and international moisture control guidelines. While traditional EPCs and international standards such as ASHRAE 160 assume continuous indoor temperature control, Australian households predominantly rely on intermittent conditioning with frequent fluctuations in indoor temperature. Such conditions are not fully captured by standardised EPC assessments, contributing to the well-documented “performance gap” between predicted and actual building performance, as noted in studies [61–63].

International studies in highly insulated and airtight dwellings have similarly reported increased moisture retention and heightened mould risk under variable occupancy and ventilation patterns [58,59]. A distinct contrast was observed when comparing the results from the studied wall systems with those predicted by continuously conditioned systems (e.g., ASHRAE Standard 160 and DA07), where no moisture accumulation was evident. In contrast, under the intermittent conditioning scenarios modelled in this study, multiple instances of significant moisture accumulation were observed in both wall assemblies, particularly in CZ 66 of NCC CZ 4. This finding aligns with previous research that wall layers significantly impact internal thermal behaviours [64]. These findings demonstrate that current standard guidelines and EPCs

Table 16

Comparison of the hygrothermal performance of the CFCS wall under two conditioning scenarios.

Conditioning- Plan orientation- Wall orientation- Room-		Scenario A		Scenario B							
		N		E				S			
		S		S				S			
		NA	LDY	B1	KL	EnS	B1	S	KL		
CZ21	CZ6	NCC	5.000	0.004	0.006	0.060	0.005	0.006	0.020		
	+ cavity	4.000	0.004	0.006	0.013	0.004	0.005		0.040		
	+ Interior M.	0.050	0.025	0.040	0.040	0.025	0.030		0.040		
	InM. + C.	0.015	0.010	0.015	0.015	0.010	0.015		0.015		
CZ64	CZ6	NCC	5.500	0.095	0.300	5.000	0.060	0.250	5.000		
	+ cavity	4.500	0.100	0.200	0.500	0.125	0.200		4.000		
	+ Interior M.	0.070	0.200	0.350	0.500	0.075	0.300		0.500		
	InM. + C.	0.015	0.175	0.175	0.200	0.165	0.175		0.200		
CZ66	CZ4	NCC	6.000	6.000	6.000	6.000	6.000	6.000	6.000		
	+ cavity	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000		
	+ Interior M.	5.500	6.000	6.000	6.000	6.000	6.000	6.000	6.000		
	InM. + C.	5.500	6.000	6.000	6.000	6.000	6.000	6.000	6.000		
	CZ6	NCC	6.000	6.000	6.000	6.000	6.000	6.000	6.000		
	+ cavity	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000		
	+ Interior M.	0.100	6.000	6.000	6.000	6.000	6.000	6.000	6.000		
	InM. + C.	0.050	6.000	6.000	6.000	6.000	6.000	6.000	6.000	1 null	
Scenario A		0	3	6	0	3	6	0	3	6	0
Bed 1		MI	MI	MI	MI	MI	MI	MI	MI	MI	MI
En-suite											
Kitchen											
Laundry											

may inadequately address the moisture-related risks associated with intermittent uncontrolled temperature conditioning in real building applications [65].

In the latest ASHRAE Standard 160–2021 (Criteria for Moisture-Control Design Analysis in Buildings), the treatment of indoor humidity and conditioning has evolved to be more performance-based. While the standard suggested a hard limit of “under 50% RH” for intermittent conditioning scenarios, particularly for systems that operate intermittently or have specific dehumidification goals. The results of this research offer more actionable insights into how temperature control management strategies influence mould risk under realistic operating conditions. In doing so, this research supports the development of more explicit guidance and practical approaches for effective indoor moisture management, complementing and strengthening the intent of ASHRAE Standard 160 within the context of contemporary high-performance residential design.

It is important to acknowledge several limitations associated with the quantitative findings of this study. The simulated analysis relies on a simplified “perfect wall” model and a climate dataset derived from a single-year simulation iterated over a decadal period, which not fully capture long-term climatic variability. Additionally, moisture accumulation and MI values were reported to two decimal places, potentially

limiting the resolution of minor differences in results. A further limitation arises from the inherent constraints of the WUFI simulation, where the maximum MI is capped at 6.0, likely underestimating the true extent of mould growth that could occur under real-world conditions. The results are also specific to the material properties used in the simulation. To address the limitations inherent in computational modelling and to strengthen the validity of these findings, on-site, long-term monitoring and empirical validation are strongly recommended [58]. Further research is warranted to explore effective mitigation strategies that can minimize the MI to an acceptable level within an intermittently non-regulated temperature conditioned regime. The results also indicated that, during specific seasons, factors such as wall orientation and room type induce statistically significant variations in internal temperature profiles, and moisture accumulation variations. As increasing numbers of nations, including China and several European countries, propose intermittent conditioning as a key strategy for achieving energy savings in the pursuit of sustainable energy-efficient buildings, the moisture-related vulnerabilities identified in this study become globally relevant for ensuring the long-term health and durability of the worldwide residential. It should be noted that computer-based building energy rating programs calculate an average temperature for all room surfaces based on all inward and outward energy flow, from which it creates an

interior environmental temperature. This research has used this environmental temperature as the air temperature on the inside surface of the exterior wall. In reality, differences may exist between the calculated environmental temperature and the air temperature near the surface of the exterior wall. This aspect requires further investigation.

In the context of building physics and hygrothermal performance, control concepts range from simple “set-and-forget” systems to highly intelligent, data-driven frameworks. The results presented in this research are grounded in the fixed schedules required for standard energy certification. However, other control strategies like Rule-Based Control (RBC) [66] and Demand-Controlled Ventilation (DCV) [67,68] offer targeted mitigation for mould and air quality by reacting to real-time sensor data. Furthermore, Model Predictive Control (MPC) represents the most sophisticated approach, leveraging weather forecasts to achieve maximum energy efficiency and hygrothermal safety [69–71]. However, many of these approaches are not currently discussed within residential building regulatory development working groups. Given the prevalence of intermittent conditioning strategies in Australian residential settings, the stark divergence observed between these simulation-based findings and the predictions based on continuous conditioning standards (e.g., ASHRAE Standard 160, EPCs) is highly significant. The observed discrepancies between predicted and actual indoor environments highlight the need for next-generation EPCs to incorporate dynamic, operational data, including intermittent conditioning patterns, and numerical requirements. By integrating these factors, EPCs can more accurately reflect building performance, guide effective mitigation strategies, and ensure that energy-efficient buildings also support occupant health. Advancing EPC frameworks in this manner will not only improve their predictive reliability but also provide a stronger evidence base for policy, design, and regulation, helping to achieve both energy efficiency and healthy, resilient indoor environments.

6. Conclusion

The investigation into the hygrothermal performance of 7-Star timber-framed wall systems reveals a critical disconnect between regulatory standards and real-world structural resilience. While these assemblies are designed to achieve high EPC ratings through increased airtightness and thermal resistance, this research demonstrates a marked divergence between their theoretical efficiency and their actual performance under the intermittent conditioning profiles typical of Australian households. Specifically, the findings confirm that intermittent conditioning imparts a substantially higher risk of interstitial moisture accumulation and subsequent mould growth, particularly within the cold, humid climatic regime. Furthermore, the study critically showed that some prescriptive moisture mitigation strategies, such as the application of an interior moisture control layer, can be ineffective or even counterproductive in specific wall assemblies under dynamic, uncontrolled intermittent conditions. While variations in wall orientation and room type exerted a measurable influence on internal temperature profiles, the dominant determinant of hygrothermal risk is the complex interaction between the local climate and the conditioning pattern employed.

These results are critically important as they expose a fundamental inadequacy in current building standards, EPCs and hygrothermal guidelines, which often fail to accurately model the dynamic operational reality of modern, energy-efficient Australian homes. A singular focus on achieving airtight building envelopes for energy conservation, without simultaneously implementing robust ventilation and moisture management strategies, risks compromising IEQ. This oversight increases the probability of accelerated building degradation and potentially adverse health outcomes for occupants, particularly as the industry universally shifts towards highly insulated, energy efficient buildings.

To ensure the creation of truly resilient and healthy indoor environments, a strategic shift is required: moving beyond the static metrics

of current EPCs toward an integrated, holistic design approach. Future high-performance buildings must balance the “on paper” star rating with a comprehensive recognition of building health. Ultimately, the most sustainable buildings of the future will be those that recognize that true energy efficiency is intrinsically tied to optimal durability and occupant well-being.

CRedit authorship contribution statement

Guan Liqun: Writing – original draft, Writing – review & editing, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dewsbury Mark:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Hartwig Kuenzel:** Writing – review & editing, Supervision, Software. **Wallis Louise:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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