

# PASSIVE HOUSE FOR SCHOOLS – FEASIBILITY STUDY

*DE-IDENTIFIED VERSION*

FOR

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# EXECUTIVE SUMMARY

The Passive House standard has slowly made its way around the globe, since its inception in the early 1990's. Founded from research into the relationship between thermal comfort and passive design, the standard's success is testament to the strength of concept.

Schools Infrastructure New South Wales have commissioned this report into the case for developing schools in NSW to the Passive House standard, using a current project as a prototype to test the concept. This report aims to establish the benefits of doing so, alongside the costs and risk, and to ascertain whether there is a rationale to further pursue this particular design approach as a means to enhance the offering of high quality, low-energy and healthy environments for children to learn.

This report also outlines the local market readiness to deliver Passivhaus sufficient to meet the needs of the government, meeting the key objective to *"deliver the very best school infrastructure so that the NSW public education system is one of the finest in the world"*. By providing a robust and complete discussion on the opportunities and benefits, alongside a balanced view on the impacts to design and construction; it is envisaged that, with this information, decision-makers in the sector can confidently pursue the standard for greater benefit.

Higher standards of building construction quality are required to benefit the overall health and wellbeing of society.

As we spend about 90% of our time indoors, the quality of the interior environment is more important than ever, and for schools – spaces that serve vulnerable and developing humans – the quality of environment can have considerable impact on the occupants.

The primary reasons for the application of Passivhaus fall largely into three areas: **health**, **economy** and **energy efficiency**. One of the key strengths is that, to date, it is the only standard where the built performance matches the design predictions quite closely, i.e. that there is no performance gap.

The site delivery of projects to the Passive House standard is by far the most critical aspect in terms of delivering to the requisite cost target. From experience, site impacts can entirely undermine any perceived cost benefits achieved and/or predicted during the design stage. This might include;

- Inadequate contractor engagement, including insufficient appreciation of the impact of design specifics (details) and product substitutions;
- Inadequate sub-contractor education and training;
- Changes to programme (lead time) or availability of specified products, required to achieve the performance parameters.

As such, performance targets must be clearly specified in early briefing, and held as firm targets throughout documentation and tender.

Two factors are key when comparing Passivhaus to standard practice:

1. The locally appropriate response for the particular building, including climate, typical construction methods and skill availability;
2. The comparable baseline for individual projects, i.e. building code compliance or 5 Star Green Star.

Some of the key benefits of building to the Passive House standard are direct and measurable. Direct savings include:

- reductions in energy consumption / costs;
- reduced ongoing maintenance;
- simplified or smaller infrastructure, including air conditioning.

Other cost savings are indirect or external to occupants and some may require a broader assessment of the system in which they occur. These might include:

- Increased attention of students, leading to potential for improved academic outcomes;
- Cost reductions due to build quality and durability;
- Costs reductions from streamlining the approach to complementary rating systems, such as Green Star;
- Potentially reduced programme costs, with the opportunity for enhanced outcomes from prefabrication or modularisation, and associated site time savings.

Both the local and international experiences on Passive House is that, in a new market, there is cost premium for increased specifications on the basic building elements. This includes improved window specifications, the introduction of ventilation systems and increased dedication to correctly delivering a continuous thermal and airtight envelope (including thermal bridging).

Many international markets have worn the path of a maturing market and eventually seen the Passive House market grow to support the delivery of cost parity or cheaper project.

Although the ultimate goal might be to deliver Passive House-type projects at nil capital premium, early projects in any region should expect a premium of up to 10%; however, this depends very much on the comparative baseline and the required improvements. In any case, the life cycle costs assessment is positive.

The provision of high-quality buildings has the potential to impact on factors far beyond the reach of traditional economic models, or simply hard to include in a model with discrete boundaries. Further discussion is required on how factors such as the following might be captured:

1. Comfort;
2. Health, including reduced absence of students and staff;
3. Occupant satisfaction and pride of place;
4. Impact on the local health sector;
5. Other social parameters, including benefits to children's education, worker productivity and staff health.

It is important to note that the Passivhaus approach differs fundamentally from standard building delivery; the delivery of excellent comfort and IEQ is the very basis on which the building is developed. The core driver of buildings for human health in occupation means that buildings often cannot be compared on metrics alone as the qualitative measures are not adequately represented. A building might show low energy use, and deliver very poorly on the provision of adequate internal conditions, let alone those optimised for health and learning.

It is highly recommended that SINSW builds school buildings to the Passive House standard.



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# 1. INTRODUCTION

The Passive House standard has slowly made its way around the globe, since its inception in the early 1990's. Founded from research into the relationship between thermal comfort and low-energy passive design, the standard's success is testament to the strength of concept.

Schools Infrastructure New South Wales have commissioned this report into the case for developing schools in NSW to the Passive House standard, using a recently built project as a prototype to test the concept against currently delivered construction. This report aims to establish the benefits of doing so, alongside the costs and risk, and to ascertain whether there is a rationale to further pursue this particular design approach as a means to enhance the offering of high quality, low-energy and healthy environments for children to learn.

This report presents the results of the Passivhaus modelling, plus analysis of the construction details for thermal bridging and moisture risks. In addition, options for overcoming any performance shortfalls are presented.

This report also outlines the local market readiness to deliver Passivhaus, sufficient to meet the needs of the Government, meeting the key objective to *"deliver the very best school infrastructure so that the NSW public education system is one of the finest in the world"* (SINSW, 2019). By providing a robust and complete discussion on the opportunities and benefits, alongside a balanced view on the impacts to design and construction; it is envisaged that, with this information, decision-makers in the sector can confidently pursue the standard for greater benefit.

Higher standards of building construction quality are required to benefit the overall health and wellbeing of society. As we spend about 90% of our time indoors, the quality of the interior environment is more important than ever, and for schools – spaces that serve vulnerable and developing young people – the quality of environment can have considerable impact on the occupants.

The primary reasons for the application of Passivhaus fall largely into three areas: **health**, **economy** and **energy efficiency**. One of the key strengths is that, to date, it is the only standard where the built performance matches the design predictions with accuracy, i.e. there is no performance gap.

Alongside the benefits of reduced cost of operation, there is now a widely accepted understanding that well designed internal environments can influence the health, wellbeing and productivity of occupants. A large body of research points to the importance played by high quality internal environments, which can be delivered by the Passive House standard, perhaps better than any other built environment tool.



## 2. CONTEXT

Local building practices have suffered from complacency and a weak building code. Despite regulations calling for minimum levels of thermal performance, gaps in building physics knowledge, true implementation of design solutions and lack of enforcement have enabled both designers and builders to deliver underperforming buildings, to the detriment of occupants, building operators and the industry. Over time, the culture of acceptance of low building quality has become the norm, and the holistic cultural shift required to correct the industry has become overwhelming.

For example, the current building stock experiences:

- high maintenance costs
- low residual value and high rate of building replacement;
- high running costs
- poor indoor environment quality, including an epidemic of mould and dampness (Lane, 2018);
- long-term health impacts on occupants;
- increased strain on the public health sector, due to potentially avoidable or worsened conditions including respiratory and integumentary conditions

The effective and efficient provision of environments that support health and learning outcomes is not just about active building systems, but the fundamental build quality. Building systems cannot prevent issues such as elevated CO<sub>2</sub> or VOCs, condensation and mould efficiently where the building envelope may, in fact, work against it.

In using the building code to deliver efficiency and comfortable buildings, the opportunity is lost for optimised building delivery that best serves the above, occupant-focussed objectives.

There is also a view that local climates, being comparatively mild, do not necessitate the application of high-performance standards. Despite this, Australian buildings exhibit some of the highest energy consumption rates in the world, and over 40% of this energy is directed towards heating and cooling. For example, in residential buildings the space conditioning load is estimated at approx. 35 GJ per household per annum, which is increasing over time due to house size increases, despite regulatory efforts around building envelope (DEHWA, 2008). As one of the largest, and increasing, energy demands, this presents a great opportunity for simple efficiency savings.

### 2.1 MEETING SINSW OBJECTIVES

In 2018, the NSW Government announced a \$500 million fund for the *Cooler Classrooms* program, specifically to provide air conditioning to schools. The impetus of the program is not just around cooling, but to deliver healthier and comfortable learning environments, as is evident from the program announcements (School Infrastructure NSW, 2019):

*“The NSW Government is committed to providing students with healthy and comfortable learning environments.”*



**Figure 1:** Nominated program outcomes - Cooler Classrooms (School Infrastructure NSW, 2019)

The provision of air conditioning systems does not, in isolation, ensure good IEQ, and it is identified in the programme's public messaging that the provision of fresh air, solar PV and occupant awareness measures may provide broader benefits.

The delivery of Passive House schools as part of the portfolio directly and effectively supports the above objectives, as well as providing resilient and robust assets with further benefits. These may be further explored and include the factors shown in Table 1 below.

**Table 1:** Benefits of the Passivhaus approach

<b>Energy Efficiency</b> <ul style="list-style-type: none"> <li>• Reduced running costs</li> <li>• Assists meeting energy/carbon targets</li> <li>• Smaller a/c plant</li> </ul>	<b>Thermal Comfort</b> <ul style="list-style-type: none"> <li>• Comfort year-round</li> <li>• No draughts</li> </ul>
<b>Health &amp; Wellbeing</b> <ul style="list-style-type: none"> <li>• Comfort year-round</li> <li>• Occupant satisfaction</li> <li>• Fresh air – natural and mechanical ventilation</li> <li>• Controlled CO<sub>2</sub> levels</li> <li>• Improved sleep quality</li> <li>• Reduced incidence of asthma + respiratory ailments</li> <li>• Mould &amp; condensation eliminated</li> <li>• Acoustic comfort enhanced</li> <li>• Improved cognitive function + education outcomes</li> </ul>	<b>Return on Investment</b> <ul style="list-style-type: none"> <li>• Reduced plant costs</li> <li>• Avoidance of infrastructure upgrades</li> <li>• Reduced maintenance costs</li> <li>• Increased durability &amp; longevity</li> <li>• Reduced hospital &amp; healthcare costs</li> <li>• Increased surety of delivery</li> <li>• Improved stakeholder relations</li> </ul>

Of particular note is the reduction in plant costs, including space requirements and capacity, and infrastructure costs, which may include substation upgrades or other infrastructure impacts.

## 2.2 EDUCATIONAL FACILITIES STANDARDS AND GUIDELINES

The NSW Department of Education provides the Educational Facilities Standards and Guidelines (EFSG) to assist project delivery teams and includes Design and Specification guides.

Broadly, there are no elements of the guides that would be compromised under the proposed design pathway, for Passivhaus-compliant school buildings. The Passivhaus standard places demands on the building envelope that can be seen as in alignment with the current EFSG.

Specifically, the Passivhaus approach serves the two drivers of ecologically sustainable development, and excellent value for money in a Whole of Life framework.

## 2.3 GREEN STAR

We understand that the Government has also recently made a commitment to benchmarking projects, and potentially formally rating, against the Green Star rating system. A 4 Star rating has been nominated as the minimum standard for new projects.

In 2016, the Australian Passive House Association (APHA) announced a collaboration with the Green Building Council of Australia to streamline recognition of common design outcomes between tools. In a world-first, the Crosswalk now enables Passive House Certified projects to achieve up to 30 points (of a total 100) under a deemed-to-satisfy pathway in Green Star. With a 4 Star rating requiring 45 points, the approach could significantly streamline delivery.

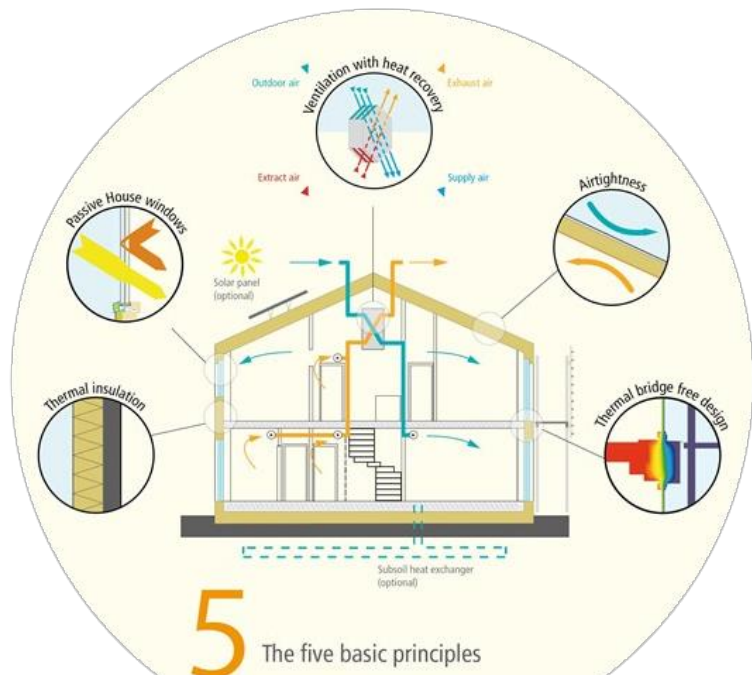


**Figure 2:** Movement at the top end of the market (e.g. Green Star), and regulatory change at the minimum compliance (NCC BCA) end seem to be bringing us closer to a refined pathway.

## 3. THE PASSIVE HOUSE STANDARD

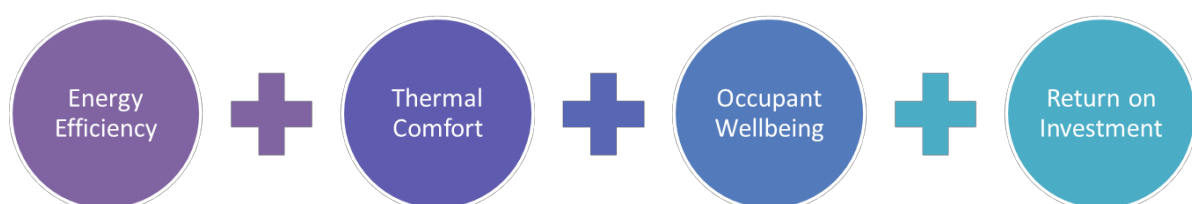
### 3.1 WHAT IS PASSIVE HOUSE?

Also known as Passivhaus, it better translates as 'Passive Building' and applies to any building typology. Passive House buildings are always comfortable, have excellent indoor environment quality and use around 75-90% less energy than a typical building. Passive House is not a brand name, but a simple, proven design and construct methodology, and is making waves in the Australian construction industry. The standard originated from research into international best-practice into building performance, combined with building physics, and is a package of measures with guaranteed results.



As we spend about 90% of our time indoors, the quality of the interior environment is more important than ever, and in social housing, where, statistically, people spend even more time in their homes, this space can have considerable impact on the occupants.

There are Passive House fire stations, schools, aged care facilities, hospitals, high rise office buildings, apartment towers and tens of thousands of homes. Passive House is a standard that targets thermal comfort and manages to deliver superior energy efficiency in one of the best win-win approaches to design. There is a particularly strong offering for owner-operators or owner-occupiers, the Passive House standard offers a significant benefit over typical construction standard, with the long term benefits far outweighing any premium for delivery.



**Figure 3:** The four pillars of Passive House

Passive House Certification is not mandatory, although offers a level of quality assurance and surety of performance that would be an attractive proposition in the delivery of educational facilities.



### 3.2 PERFORMANCE CRITERIA

The Passive House standard sets limits on heating and cooling demands or loads in a building, as well as the overall energy consumed by a building. There are also a small number of additional criteria around overheating, comfort and airtightness, aimed at delivering a package for optimised buildings with excellent efficiency, and, above all, superior indoor environment quality. These criteria are defined in Table 2, below.

The early definition of a Passive House was: “a building for which thermal comfort can be achieved solely by heating or cooling of the fresh air volume required to provide good indoor air quality anyway”. This implies that the building's ventilation delivers the fresh air required for occupants, not as a medium for carrying (or removing) heat energy. While this has evolved as Passivhaus has been refined for all climate types and building typologies, it's ethos remains.

The performance of Passive House buildings is modelled using open source, excel-based software, aimed at being readily useable and transparent in its approach. The model is sufficiently complex but easily interrogated.

The PHPP has also been developed and continually refined in parallel with dynamic simulation, as well as reference to global bodies of evidence and direct research.

**Table 2:** Passive House Criteria for specific climate (Passivhaus Institut, 2016)

Criterion	Typical limit	Limit criteria for building location
<b>Heating Demand</b> <b>Heating Load</b>	$\leq 15 \text{ kWh/m}^2\text{a}$ $10 \text{ W/m}^2$	$\leq 15 \text{ kWh/m}^2\text{a}$ $10 \text{ W/m}^2$
<b>Cooling* Demand</b> <b>Cooling Load</b>	$\leq 15 \text{ kWh/m}^2\text{a}$ $\leq 10 \text{ W/m}^2$	$\leq 23 \text{ kWh/m}^2\text{a}$ $\leq 11 \text{ W/m}^2$
<b>Primary Energy – Renewable</b> Heating, cooling, hot water, auxiliary elec., domestic/common electricity	$\leq 60 \text{ kWh/m}^2\text{a}$	
<b>Airtightness (at 50 Pa)</b>	$\leq 0.6 \text{ h}^{-1**}$	
<b>Frequency of overheating (&gt; 25°C)</b>	< 10%	

\* Adjustable limit that takes account of dehumidification in humid climates

\*\* Ave airtightness value of Australian dwellings built in the last 10 years is  $15 \text{ h}^{-1}$

With the broader uptake of renewable energy and the changing typology of projects, two additional, incremental levels of Passive House certification have been introduced. With each step, there is an extra level of efficiency, as well as a minimum level of energy generation. A Passive House Plus building could be considered close to net zero energy (for a single dwelling) and Premium is net positive energy.

### 3.3 WHY PASSIVE HOUSE?

The primary reasons for Passive House fall largely into three areas: **health**, **economy** and **energy efficiency**. One of the key strengths is that, to date, it is the only standard where the built performance matches the design predictions quite closely, i.e. that there is no performance gap. Most buildings typical consume 2 to 5 times more energy than predicted at design stage

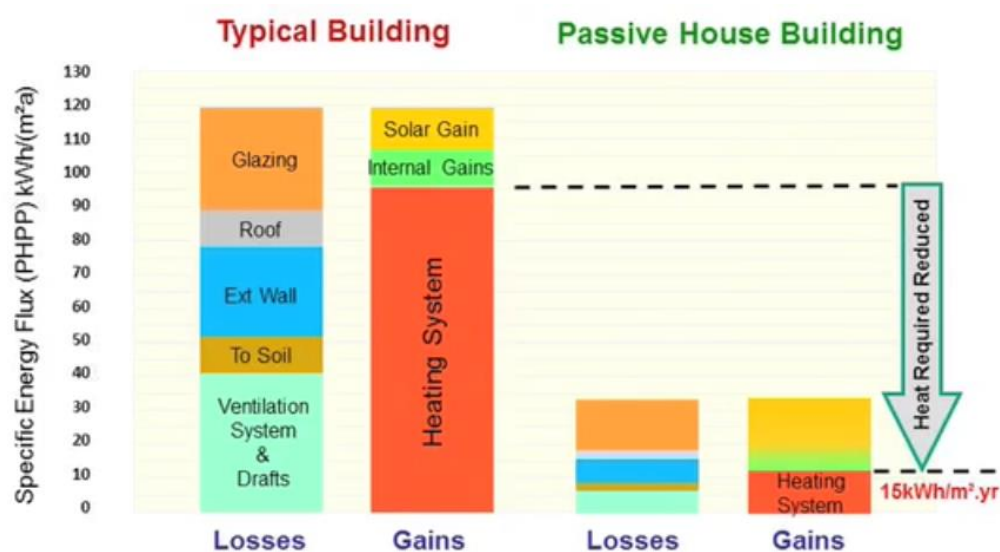


(Menezes, 2012), with many reasons including the oversimplification of modelling as well as lack of regulatory compliance.

### 3.3.1 ECONOMIC OPPORTUNITIES

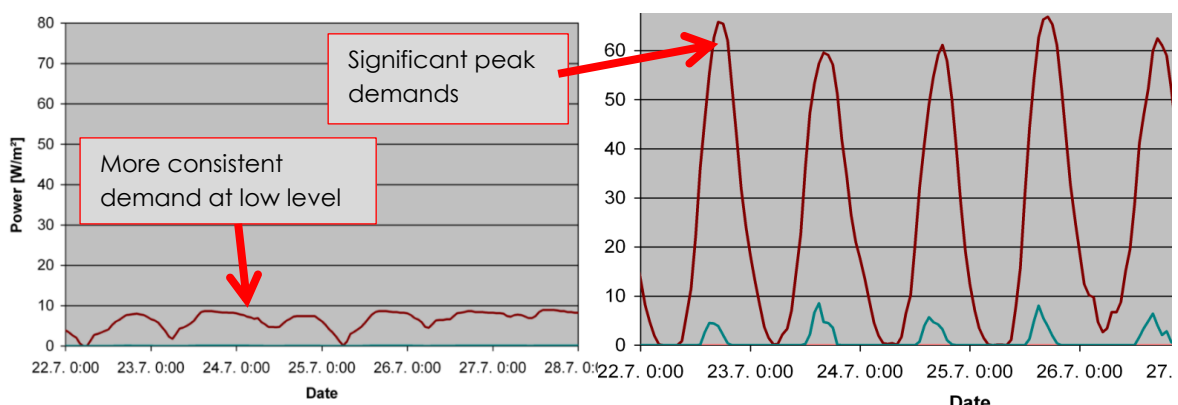
Passive House buildings incur reduced heating and cooling energy demands, and there is also a design cap on overall energy use, including domestic hot water, appliances and lighting. Typically, a building in a climate such as northern NSW would be comfortable using a passive approach for much of the year. The financial impact of this should not be understated.

Fundamental to any decision to pursue the Passivhaus standard will be the potential to significantly impact the experience of occupants. As depicted in Figure 4, the net requirement for winter heating can be drastically reduced by minimising the impact of the elemental components of a building.



**Figure 4:** The impact of good design – the heat balance, with the red bar representing the winter heating requirement. (Passivhaus Institut, 2016)

In addition, the major impact on cooling is the size of the system. While the system may operate more often, it will be much smaller and be required to provide small intervention to optimise comfort. The charts below show the impact on the cooling loads in a building designed to Passivhaus and per typical construction in a hot climate with low thermal standards of construction (Spain).

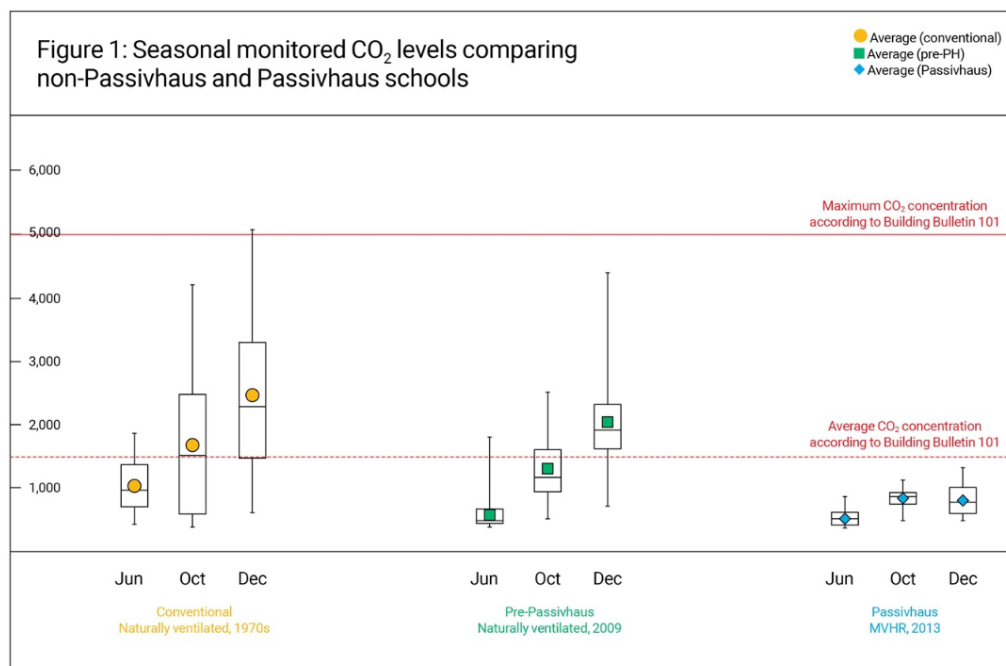


**Figure 5:** Peak cooling loads for Passive House and standard construction buildings (Kaufmann, 2016)

Besides the direct implications of reducing operational costs, the potential to free up maintenance funds for capital investments will assist in solving funding shortfalls for other projects. The acceptance of this systemic view to assessing return on investment may require broad evaluation and collaboration between government portfolios to optimise funding.

### 3.3.2 HEALTH & EDUCATIONAL OPPORTUNITIES

The international experience is that Passivhaus school buildings deliver excellent IEQ where students have greater support for learning activities, when directly compared to prior environments; the monitoring data tends to support subjective views. Early monitoring data from Australian schools shows comparable CO<sub>2</sub> levels to the “conventional” schools in the chart in Figure 6. We note that greater than 1,500 parts per million (ppm) is considered poor air quality, and begins to affect cognitive function.



*"We feel that our children are more alert and attentive in lessons due to the amount of daylight in classrooms and the fresh air throughout the school. The fact that the new school is built to Passivhaus standards means that learning has been enhanced. Our pupils are comfortable, secure and stimulated by their new environment; hence they learn very well!"*, Sara Morris, Head Teacher at Oak Meadow Primary School

**Figure 6:** Monitoring results and occupant feedback from UK Passivhaus schools (Hines, 2016)

Evidence of broad scope studies have also shown that the direct cost of investment in Passivhaus measures can be more than recouped through reduced hospital admissions and social costs, in addition to the direct savings (Vidal, Guardian, 2013).

Greater climate change resilience and lower risk of failure in the face of sporadic events (e.g. storms, blackouts) also enables the department to have faith that students could remain in place in such buildings during events; indeed, the facility might be used as a local refuge during these occurrences. Reports from Passive House-style buildings in New York indicate that, during heat waves or blizzard, and combined with a blackout, they could stay comfortable and habitable for up to a week, compared to just a few days for standard construction (Urban Green Council, 2014).

In the future, climate change will only serve to exacerbate the number of deaths due to extreme weather events, with heatwaves that are predicted by IPCC, CSIRO and BOM to increase (CSIRO, 2014). Passive House buildings provide greater future-proofing for significantly less investment than any other technical approach available.

Of course, creating high performance buildings is null and void if the performance of the building does not actually deliver. Indeed, this is actually one of the main points of failure of the current regulatory requirement; even those buildings that are designed to achieve high performance are not validated for the as-built product. In many instances this might also be a failure of the modelling process, in that there are several assumptions made – necessarily so to enable the industry to utilise modelling software en masse – that the industry is not set up to deliver in practice.

### 3.4 REGULATORY AND INSTITUTIONAL ADOPTION OF PASSIVHAUS

Across the world, and to a limited extent locally, there has been expansive uptake of the Passive House standard as a minimum standard for delivery of all types of buildings. For example, in many parts of Central Europe Passive House is required by local and regional governments for all civic buildings, including public schools, and, in some areas, this is extended to residential homes.

Since 2007, all public administration buildings in Frankfurt, Germany, must be built to the Passive House standard. Since this time, many other municipalities and governments have followed suit, including the state of Bavaria, Hamburg and Leipzig, among many others (IPHA, 2018). Other jurisdictions adopting and incentivising the standard include New York City, Vancouver, Dún Laoghaire (Ireland), Luxembourg and Oslo.

Locally, Monash University has declared that all new buildings will achieve Passive House Certification, as a direct strategy to deliver its Net Zero commitment. Other organisations, including members of the Victorian Housing Consortium, are exploring their opportunities to do the same, as a measure to address housing cost, quality and resilience in the face of climate change.

## 4. COSTS AND BENEFITS

To enable robust decision-making at the government level, robust data needs to be provided. The Passive House building standard is a people-first standard developed as an economically balanced approach to building physics.

Although the ultimate aim might be to deliver Passive House-type projects at nil capital premium, early projects should expect a premium of up to 10%; however, the life cycle costs assessment is positive.

And cost parity really needn't be thought of as a limiting long-term goal; opportunities exist to innovate or refine the approach to construction and to make savings here that would deliver projects to comparable or better rates than budgeted. Costings from off-site fabrication specialists, for example, indicate that buildings can be delivered at cost parity to current budgets, even without factoring in savings from potential site efficiencies. This applies to single dwellings up to large scale projects but needs to be rigorously tested with real projects.

### 4.1 COST SAVINGS

Some of the key benefits of building to the Passive House standard are direct and measurable. Direct savings include:

- reductions in energy consumption / costs;
- reduced ongoing maintenance;
- simplified or smaller infrastructure.

Other cost savings are indirect or external to occupants and require a broader assessment of the system in which they occur. These might include:

- Savings to the local health organisations, including public hospitals and government services;
- Cost reductions due to build quality and durability;
- Costs reductions from streamlining the approach to complementary rating systems, such as NABERS and Green Star;
- Potentially reduced programme costs, with time on site drastically cut with prefabrication or modularisation.

#### 4.1.1 MINIMISING MAINTENANCE COSTS

Passive House buildings tend to be simpler, with fewer and/or smaller mechanical requirements. Due to the reduced reliance on heating or cooling systems, they also incur less run hours. Overall, it should be expected that there is less maintenance, and capital cost of replacement is also reduced.

Simple maintenance of heat recovery systems can be undertaken by unskilled trades or occupants, with filters generally cleaned or replaced at 6- or 12-month intervals (depending on local conditions). The process for this is very simple.

## 4.2 COST PREMIUM

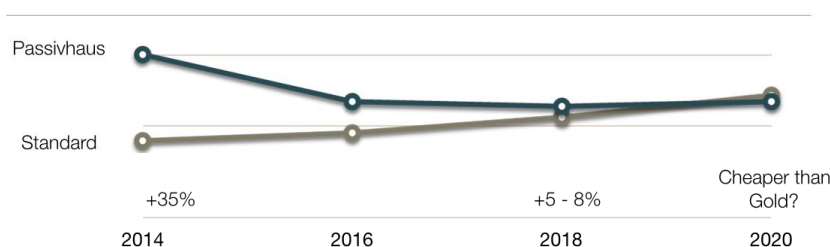
Both the local and international experiences on Passive House is that, in a new market, there is cost premium for increased specifications on the basic building elements. These are shown below.

There are fundamental differences to the design of standard projects that will represent additional cost. One of these is the addition of heat recovery to the ventilation system, which is not required by the local building code and is not common practice to include. This premium may be offset in part by the elimination of traditional exhaust systems, and reduced capacity requirements of heating and cooling systems

Extra Costs:	Potential for Cost Reduction:
Windows: increased specifications	Air conditioning systems
Mechanical ventilation with heat recovery	Heating systems
Increased insulation & thermal bridge abatement	Elimination of exhaust systems
Certification (if desired)	

Many international markets have worn the path of a maturing market and eventually seen the Passive House market grow to support the delivery of cost parity or cheaper project. In Vancouver, regulatory concessions have enabled Passive House to gain exposure, and the construction premium for private dwellings was reported at approximately 2-7% (RDH Building Science, 2014), though the market has moved significantly since the analysis was reported. Broad scale analysis by the European CEPHEUS project in the early 2000's indicated a cost premium of 3-8%, which is now long out of date in the mature European market.

### Capital Costs



**Figure 7:** The Scottish market experience for Passivhaus delivery (John Gilbert Architects)

### 4.2.1 PREMIUM OF LARGE-SCALE TERTIARY SECTOR PROJECTS

Recently, data has been released for the first of Monash University's committed Passive House projects. The three projects are quite different in scale and typology. The premium, presented below, has been assigned by the Quantity Surveyor on the projects (Dean, 2018). It is also worth noting that the University's commitment to Passivhaus followed the delivery of a test project – a retrofit to house the University's property division – that was delivered to near-Passivhaus standard with no additional budget.

#### a) Monash Peninsula Residential Student Accommodation

This building is a 150-bed, 6,500m<sup>2</sup> GFA building on the Peninsula campus. Notable features included cross-laminated timber structure, pod bathrooms and extensive

renewables. A premium of **12%** has been extracted from the project costing (GMP), with the majority of this premium attributable to design decisions, such as the extensive external shading and scaffolding. Other elements include:

- Airtightness taping & testing: 0.5%
- Below slab insulation: 0.3%
- Solar PV: 0.4%
- Mechanical services: 1.2%

b) Monash Chancellery Building

This \$68m, 5,700m<sup>2</sup> GFA building is located on the Clayton campus, and houses the Chancellor, Vice-Chancellor and their staff, with extensive art features and a sculptural atrium inside. A premium of **11%** has been attributed to the Passive House approach. A breakdown is not available for this project.

c) Monash Teaching & Education Building (TEd)

This building is the largest of the Monash projects, at \$165m and 17,500m<sup>2</sup> GFA. A premium has not yet been reported.

What is clear from the above projects is that none of them are low-budget projects, ranging from \$5,700-\$11,900 per square metre. Partially, this is due to the University's high-quality architectural aspiration, which places a level of inefficiency on current delivery. This is well above the anticipated \$2,500-\$3,500/m<sup>2</sup> achievable.

### 4.3 DELIVERY RISK & COST IMPACT

The risk of not delivering a Passive House building, despite efforts in design, depends on several interrelated factors. These might include:

- Comfort for the building's occupants, though this is nearly always improved on 'business as usual'
- Adequate capacity of HVAC systems (if provided);
- Infrastructure capacity, e.g. electrical loads for heaters;
- Perceived failure in the market of the concept as a whole;

The party taking on the risk varies per contract, though the price of construction may vary accordingly. A contractor will, inevitably, price in the risk on non-conformance and potential for subsequent defect remediation.

While there are examples, internationally, of failures in the sector, these can be interrogated and can largely be attributed to shortcomings in the design and construction approaches. For example, overheating of homes in the UK – not a traditional issue in leaky, uninsulated homes and in a historically cooler climate – gained media coverage for a very small number of projects. It was almost exclusively due to failures in solar control, but with some cultural expectations of lower temperatures.

### 4.4 REDUCING THE COST RISK

There are many ways that the cost 'risk' – the unknown premium at the time of design – can be mitigated and managed.

One of the most important factors is the strength of the market signal given to the broader sector; where the government indicates that they will develop, and continue to demand, high-

performance buildings, the market will respond more effectively and with reduced cost risk, which will be reflected over time in project costs.

The most effective means of doing this is to integrate the design and construction teams (early contractor engagement) and to undertake detailed analysis at the design stage. The Passive House or ESD consultant should also have early and broad involvement, ensuring adequate opportunity to fulfil their important role. Essentially, a project will be detailed with far more specificity and at an earlier phase than in the typical design process, achieving a greater surety for all parties:

- For the **design team**, that they have considered all variables and will be delivered a compliant project of the desired quality;
- For the **Passive House consultant**, that they are not relying on assumptions (conservative or not) that might render the as-built product non-compliant;
- For the **contractor/builder**, that they have a well-defined project with fewer unknowns;
  - o Typically, design might be 'indicative' and show general concepts and layouts, with many details to be delivered on site. This increases risk of non-compliance and cost impacts considerably;
  - o The supply chain can be managed from earlier in the project, with less "wishful thinking" on specifications regarding performance, availability or lead times;
- For the **client**, that they will be delivered the project per the brief and budget;
  - o This might include the government, including where there might be a reliance on broad, systemic impacts to establish project cost benefits, e.g. health system or tenant support cost reductions;
- For the **occupants**, that they will occupy and learn in a high-performance building and receive the benefits as predicted.

A number of projects have also identified the use of an accredited expert on the team, be it an experienced Certified Passive House Designer or Building Certifier, as a key role to deliver successful projects with cost efficiency.

As well as the above, planning for and enabling clear, honest and consistent lines of communication throughout the project is a clear requirement for success.

It has also been reported that repetition is the key to cost (Bridgestock, 2018), which is to be expected as this reflects developing maturity in delivery from all parties involved.

#### 4.5 COSTING QUALITATIVE FACTORS

The provision of high-quality buildings has the potential to impact on factors far beyond the reach of traditional economic models, or simply hard to include in a model with discrete boundaries. Further discussion is required on how factors such as the following might be captured, as required:

1. Comfort;
2. Health;
3. Occupant satisfaction and reduction in complaints;
4. Impact on the local health sector;
5. Other social parameters, including benefits to children's education, worker productivity and sleep quality.



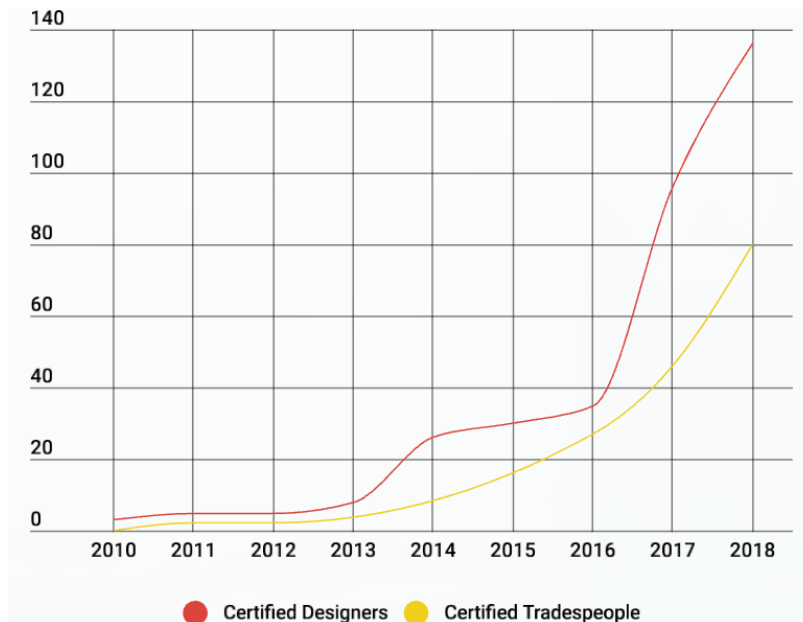
## 5. IMPLEMENTATION

The site delivery of projects to the Passive House standard is by far the most critical aspect in terms of delivering to the requisite cost target. In our experience, site impacts can entirely undermine any perceived cost benefits achieved and/or predicted during the design stage. This might include;

6. Inadequate contractor engagement, including insufficient appreciation of the impact of design specifics (details) and product substitutions;
7. Inadequate sub-contractor education and training;
8. Changes to programme (lead time) or availability of specified products, required to achieve the performance parameters.

### 5.1 AVAILABILITY OF SUITABLE PROFESSIONALS

The local education space has moved dramatically in the last 4 years. Pre-2014, candidates for the Passive House Designer course had to travel to Europe or New Zealand to complete the training. As a result, uptake was incredibly low, with just 5 Designers and 2 Tradespeople nationally. The Australian Passive House Association hosted the first local course in early 2014, with 14 students, and now there are two accredited trainers to offer accreditation. Since 2016, BHI have offered Designer and Tradesperson courses. Figure 8 shows the growth in Certified practitioners since 2010, with the bulk (>50%) located in Victoria; this growth is expected to be maintained as training is expanded across Australia.



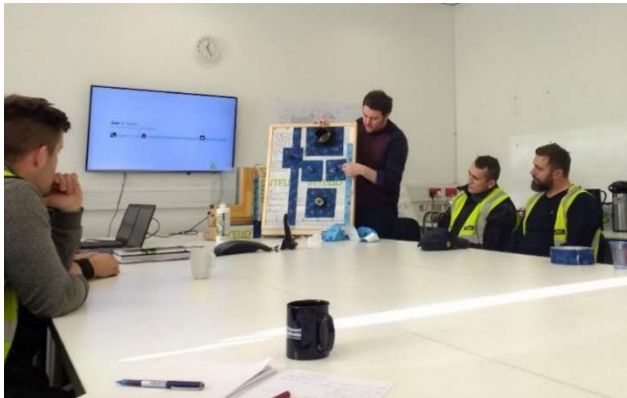
**Figure 8:** Increasing numbers of Certified practitioners in Australia, due to dedicated efforts in education

### 5.2 UPSKILLING THE CONSTRUCTION INDUSTRY

Australia is fast adopting Passive House, however there are some knowledge gaps that need to be filled to deliver Passive House on-site. Many strategies and suggestions have flowed from both local and overseas projects, with the primary issue being education and training.



It is recommended that the project involves an advisor on the project to help establish the skilling program with local builders, to peer review design and specifications and supply chain solutions align with Passive House that may assist with reducing build costs for these homes.



There is a dedicated effort from a number of construction companies to fundamentally overhaul the way they work, with many dedicating their efforts to Passive House-only construction. Almost exclusively, these are residential builders. Some larger developers are exploring Passive House, testing the market to determine appetite to offer a speculative or upgrade product offering.

### 5.3 LOCALLY AVAILABLE PRODUCTS

The market in Australia is developing quickly; in just a short period (approx. 5 years) the number of certified products available has grown markedly, and the number of available providers for either importing or locally manufacturing components has also rapidly increased.

#### 5.3.1 CONSTRUCTION SYSTEMS

Utilising pre-certified Passive House construction systems – walls, roofs and/or floor elements – has the immediate potential to reduce complexity of delivering a certifiable project. There is currently one certified product in Australia, manufactured in Melbourne by CARBONlite, but at least three others in the investigation phase to become Certified and start producing for local projects. One of these providers plans to deliver cross laminated timber (CLT) panels to a volume of at least 1,000 homes per year, with manufacture in north-west Tasmania.

As most of these known approaches are modular or panelised, there is also a significant potential to reap the associated benefits of this type of construction:

- reduced time on site;
- enhanced construction efficiency, e.g. minimal weather impacts; and
- reduced costs associated with material wastage.

As an example, the CARBONlite process can deliver panels within 4-6 weeks and assemble a large home on site in under 5 days. A number of non-residential buildings have also been delivered using the technology.



**Figure 9:** CARBONlite panels pre-assembled in the factory (left) and a cut-away sample of the panel showing window install (right)

### 5.3.2 WINDOWS

There are a number of suppliers looking at developing their products to cater for the ultra-high-performance market, and a number also directly adopting international (typically European) strategies and technologies for the Australian market. There are approximately 10 Passive House Certified European products available on the market. Some are imported directly by developers or builders undertaking their own projects and wouldn't be available through these channels for market projects. Channels would need to be established, potentially with the manufacturer directly or with third-party suppliers.

These include:

- Ultimate Windows – a fabricator of uPVC windows based in Albury, who have been in operation for decades but have more recently brought in a European profile (Deceunick) to deliver the performance required for Passive House.
- Logikhaus – a Canberra based supplier of the complete Passivhaus range of products (MVHR, panels and windows). Their capacity would cater for an active market;
- European Timber Windows – a local manufacturer of high-quality timber windows using double and triple glazing, with
- Other manufacturers and suppliers active in the local market, but that have not been tested on Certified projects, include Binq Doors & Windows, EuroTrend Windows & Doors, Paarhammer and European Timber Windows.

European products available on the market include Unilux, Optiwin, Döpfner and Kneer Südfenster. Many projects have been very successfully delivered using the suppliers.

For fully imported products, the risks to any project include that the imported product does not arrive in useable condition, and that the glazed unit (for punched windows) arrive on site glazed, and therefore rely on precise rough openings for installation.



**Figure 10:** Window materials available vary per fabricator, with comparable performance but varying cost (image: Unilux)

### 5.3.3 VENTILATION SYSTEMS

There is a strong presence in the Australian market for residential scale, Passive House–certified ventilation units, though this has settled at a small number of high-quality suppliers readily serving the local market for the last three years.

The list includes:

- Steibel Eltron – direct;
- Zehnder – through the Fantech network nationally;
- Swegon – through IdealAir;
- Paul – through the Fantech network nationally;
- Brink – through Plus Energy Living (Sydney);
- Atrea – through Logikhaus (Canberra);
- SystemAir – through Laros (Canberra).

For centrally serviced multi-residential projects, i.e. using a single ventilation unit, the selection is smaller. However, the need to use central services is limited, and this type of approach suits Class 3 buildings or those with a deliberate direction towards removing systems interaction (controls, simple maintenance) from occupants and/or individual residences. This is rarely required or desired.

Other ventilation units with heat recovery are available from suppliers such as AirChange, Lunos and LTG (IdealAir). Quality varies across available units.

Providers such as Steibel Eltron, Brink, Zehnder and Atrea have reported that they have capacity to deliver high volumes of units (>200) within 6-8 weeks plus transport time from Europe (4 weeks by sea freight).



## 6. PASSIVHAUS FEASIBILITY ASSESSMENT

This assessment is intended to confirm whether the current specification of the building envelope is satisfactory and advise any required upgrades to fulfil the requirements of the Passivhaus standard.

Using the available design documentation and other information as provided, the building has been assessed using the Passive House Planning Package (PHPP). This verified, excel-based tool prepares an energy balance and calculates the annual energy demand of the building based on the user input relating to the building's characteristics. From this tool, the user can determine whether a project meets, or does not meet, the requirements of the Passive House standard.

This assessment is intended to inform the specification of the building envelope, required systems and mode of operation that would fulfil the requirements of the Passivhaus standard, as a means of pursuing an ultra-efficient, healthy and comfortable building. All modelling targets compliance with the Passivhaus Classic level of the standard.

### 6.1 PROJECT INFORMATION

*Most of the information in this section has been omitted to de-identify the specific project that was studied.*

The thermal envelope is applied to all conditioned space.

The designPH plugin for SketchUp has been used to model the building's geometry, to facilitate accurate export into the PHPP tool.

It is important to note that the Passivhaus approach differs fundamentally from standard building delivery; the delivery of excellent comfort and IEQ is the basis on which the building is developed. The core driver of buildings for human health in occupation means that buildings often cannot be compared on metrics alone as the qualitative measures are not adequately represented. A building might show low energy use, and deliver very poorly on the provision of adequate internal conditions, let alone those optimised for health and learning.

## 6.2 PHPP MODELLING

The following table details the modelling inputs for the building, showing both the results of the building as designed, and with simple upgrade measures to meet Passivhaus compliance. This confirms a pathway to achieving a comfortably Certifiable Passivhaus project is available.

All existing building specifications are taken from the documentation provided, including drawings and schedules. Refer section 7.2 of this report for full detail of calculated wall performance of existing building.

**Table 3:** Existing building performance and Passivhaus upgrade parameters

	Existing Building	Passivhaus Building
<b>Thermal envelope*</b>		
Exterior wall – typical	U0.70 / R1.45 Metal stud wall, R2.5 insulation	U0.39/ R2.56 Timber stud wall, R2.5 insulation
Floor – typical	U0.35 / R2.88 Concrete slab with 75mm XPS	U5.12 / R0.20 Concrete slab on ground
Roof – typical	U0.71 / R1.41 Metal structure, R5.0 insulation	U0.223 / R4.48 Timber rafters, R5.0 insulation
Glazing	Glass: U3.60, g-value 0.65 Frame: U8.50	Glass: U2.50, g-value 0.50 Frame: U3.50
Shading	As documented	As documented
Entrance door(s)	Same as glazed elements	Same as glazed elements
Airtightness	10 ACH (conservative estimate)	0.6 ACH (compliance level)
<b>Mechanical Systems</b>		
Ventilation	Naturally ventilated only (heat recovery = 0%)	Heat recovery rate ≥ 80%
Air conditioning	Reverse cycle split, heat and cool	Reverse cycle split, heat and cool
Domestic hot water	Heat pump, COP approx. 4.2	Heat pump, COP approx. 4.2

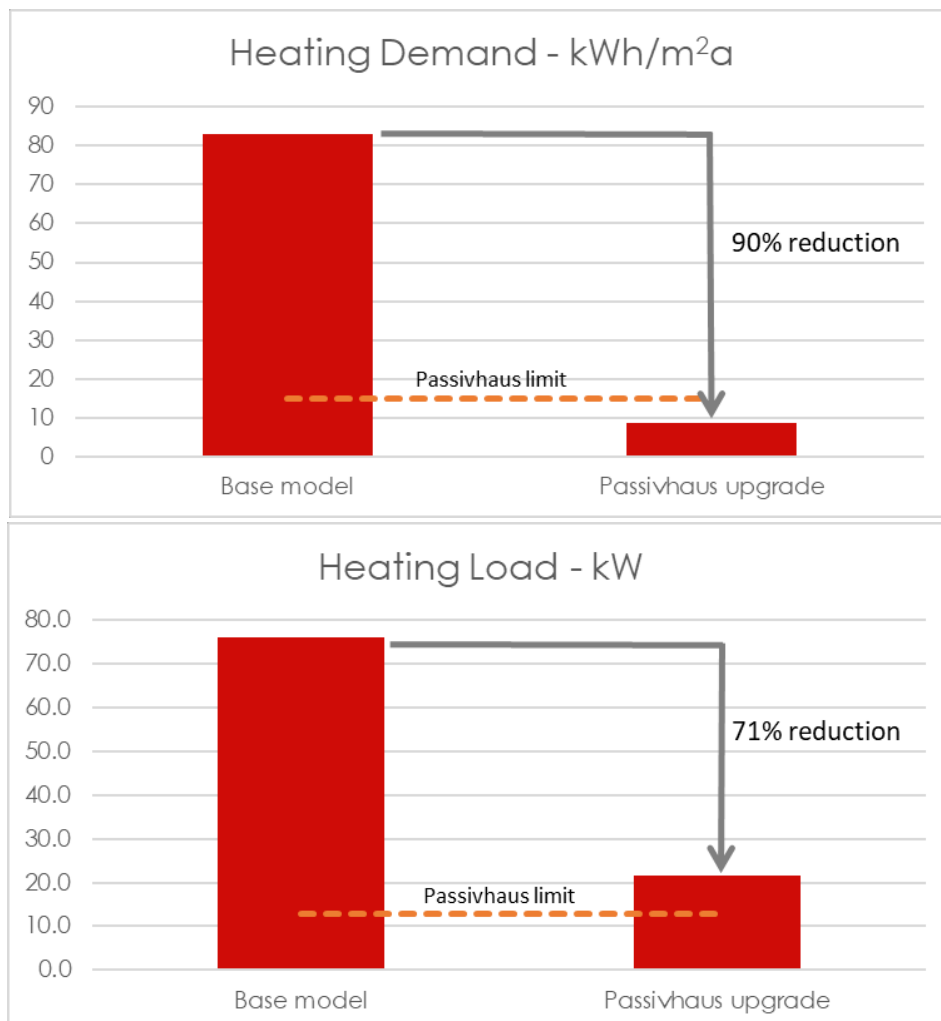
\*R-value units: m<sup>2</sup>K/W; U-value units: W/m<sup>2</sup>K

The modelling in the PHPP has confirmed that the current design does not meet the Passive House standard, but that a reasonably simple suite of measures can be used to achieve compliance.

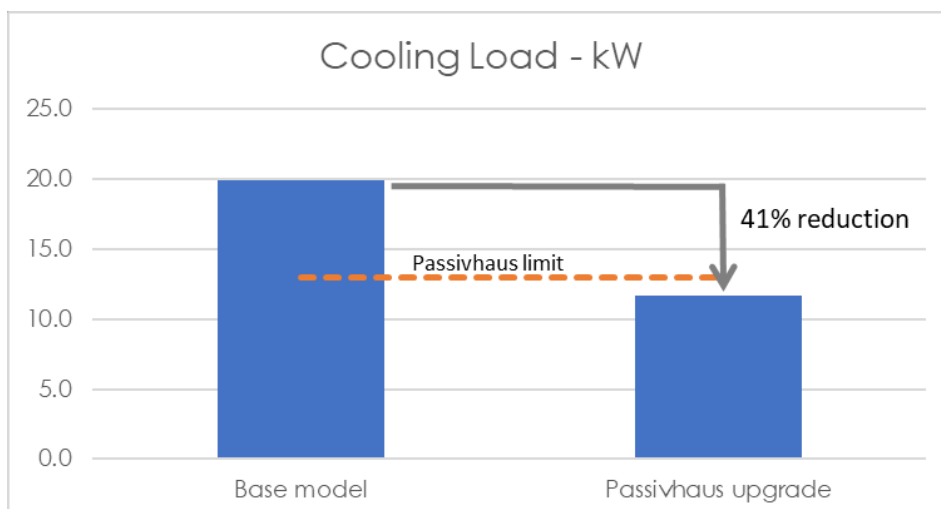
The following, simple suite of measures might be used, in this case, to bring the building up to a compliant specification:

- Airtight envelope, including windows – to 0.6 ACH;
- Increased glazing specification – frames and glass;
- Change of walls and roof to timber construction;
- Coupled ground floor slab – remove insulation;
- Provide continuous insulation to remedy thermal bridges;
- Utilise ventilation with heat recovery in mechanical systems solution.

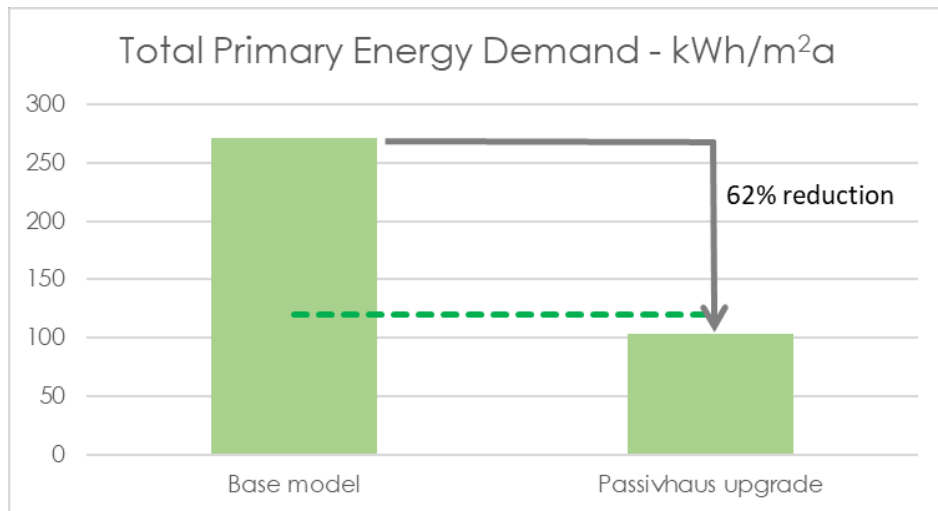
The following charts depict the substantial savings in energy demand (kWh) and plant capacity that might be met under the approach outlined here. As shown for the heating criterion, the project would – in this proposed solution – meet the demand pathway but not the load pathway.



**Figure 11:** Heat demand (top) and heat load (bottom) reduction potential



**Figure 12:** Cooling load, total reduction potential



**Figure 13:** Total energy demand (primary) for the building, reduction potential

As demonstrated, substantial savings are possible. These translate through to operational savings for the schools, as well as reduction in costs for development where infrastructure upgrades or additions might be avoided.



## 7. THERMAL BRIDGE MODELLING

Part of the holistic assessment of the building, as required by the Passivhaus methodology, includes the consideration of thermal bridges in the envelope. In this instance, to demonstrate the magnitude and consequence of the thermal bridging in the design, a sample of both the junction and regular, or repeating, thermal bridges have been assessed.

A thermal bridge is an area where there is anticipated to be an increase in heat lost or gained that is not accounted for with system U- or R-values. This normally occurs where there is a change in the insulation level or a junction between building elements. The most prominent bridges occur where there are structural elements penetrating the insulation, or where a window frame is installed in a wall. Some thermal bridging is unavoidable; however, significant heat loss (or gain) can occur that will affect the building in two ways:

- Significant heat loss or gain, affecting internal comfort; and/or
- Reduced surface temperatures, resulting in condensation. This can then lead to mould or other condensation related issues like material damage or rot.

Thermal bridges should be designed out as far as reasonably practicable, though some are tolerable. A continuous line of insulation is required to encapsulate the building to avoid thermal comfort issues and moisture-related impacts of heat transfer.

Generally, a thermal bridge greater than 0.04 W/mK is "poor"; additionally, a surface temperature lower than 12.6°C indicates risk of internal surface mould (at typical winter conditions of 20°C and 50% relative humidity).

For the studied building, four typical thermal bridges were selected for assessment.

### 7.1 THERMAL PERFORMANCE OF JUNCTIONS

The models included:

1. Slab edge at intermediate floor (section detail, e.g. detail 4 on drawing 5050);
2. Roof to wall junction (section detail, e.g. detail 2 on drawing 4502);
3. Slab edge at ground interface (section detail, e.g. detail 3 on drawing 5050); and
4. Wall to wall junction (plan detail, e.g. detail 2 on drawing 4502).

Full methodology and results are contained in Appendix B, with the summary table below. As shown, most details represent poor practice and result in substantial energy losses.

**Table 4:** Junction thermal bridge modelling results

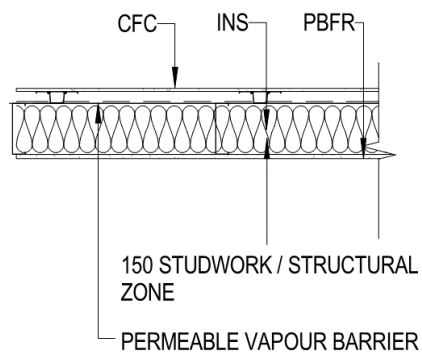
Detail description	$\Psi$ -value (W/mK)	Minimum surface temp. (°C)
1 - Slab edge, intermediate floor	0.64	17.5
2 - Roof to wall junction	0.31	14.5
3 - Slab edge at ground	0.13	14.6
4 - Wall to wall in plan detail	0.25	12.9

This thermal bridge analysis indicates that the minimum internal surface temperatures are adequate to prevent conditions suitable for mould growth.



## 7.2 THERMAL PERFORMANCE OF STUD WALLS

In addition to the junction modelling presented above, the real thermal performance of the envelope was modelled to demonstrate the actual thermal performance of this wall construction. With metal studs, the *actual* (not ideal) performance of the wall, with R2.5 batts, is severely compromised. The building code has not called for consideration of the regular thermal bridges in a wall, such as studs and other members, but the 2019 iteration of the code will now do so. Historically, the industry drastically over-estimates the actual performance of construction. In the holistic approach of Passivhaus energy and comfort modelling, the standard ISO 6946 is used, which accounts for all bridging.



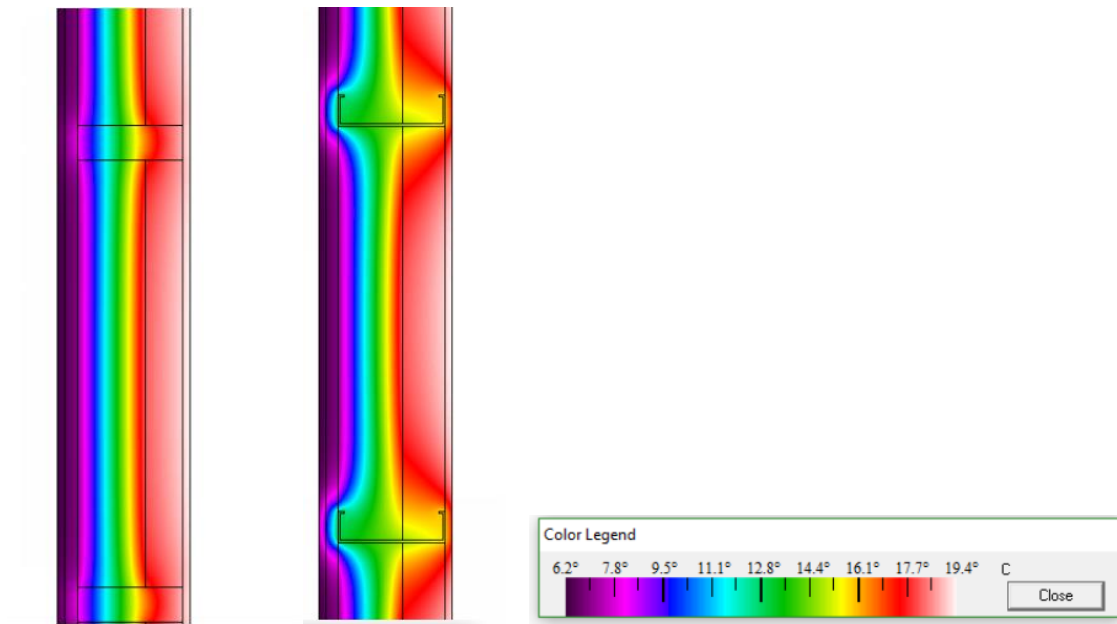
**Figure 14:** Typical wall section – wall type WT-E/02

Although the detail depicts 150mm insulation in the wall, the architectural schedules further define the makeup of this wall with R2.50 90mm insulation in the stud cavity.

A thermal analysis of the wall performance is shown in Figure 15 below. The temperature profile depicted indicates the thermal impact of using a highly conductive material for structural elements, being the steel. Because of the regular thermal bridging caused by this high-conductivity material, the total R-value ( $R_t$ ) is less than half that predicted by the design team. By comparison, with timber studs in direct substitution for metal, the performance is affected much less.

**Table 5:** Thermal performance modelling results of stud wall

Detail description	U-value (W/mK)	Minimum surface temp. (°C)
"Idealised" thermal performance	<b>3.60</b>	not assessed
Exterior wall with steel studs	<b>1.45</b>	15.8
Exterior wall with timber studs	<b>2.56</b>	18.6



**Figure 15:** Thermal modelling of wall section for metal studs (left) and timber studs (right)

In addition to the thermal detriment, the metal studs also result in potential for low internal temperatures during winter, which may cause comfort issues as well as conditions that are conducive to mould growth. As shown in Table 5, the internal surface temperature can fall below 17°C, which may present radiant comfort issues.

## 8. MOISTURE BASED RISKS

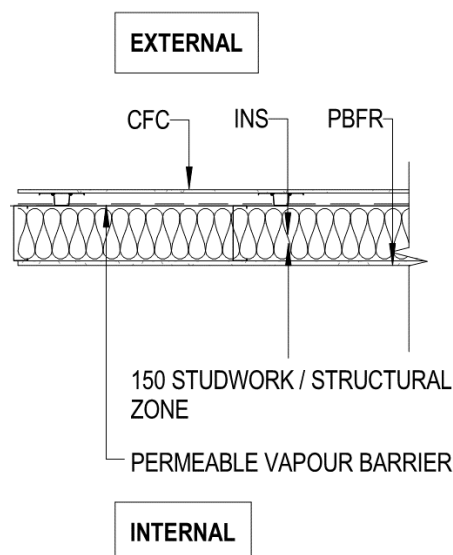
The moisture-related risk of the wall build-up has been assessed with dynamic simulation of both heat and moisture, or hygrothermal analysis. Full detail of this assessment, including methodology and detailed results, is presented in Appendix C.

This analysis is intended to identify the potential for:

- Surface condensation or mould risk;
- Interstitial condensation or mould risk;
- risk of material corrosion.

This type of analysis is not typically called for, with this area of building physics much not well understood, even though the effects of poor performance are commonly seen across the sector. The NCC 2019 calls for hygrothermal analysis under a new part, Part F6.

To demonstrate potential for vapour transfer and internal condensation issues, the same wall construction was modelled as for the thermal assessment in section 7.2, replicated below.



**Figure 16:** Wall section for hygrothermal modelling

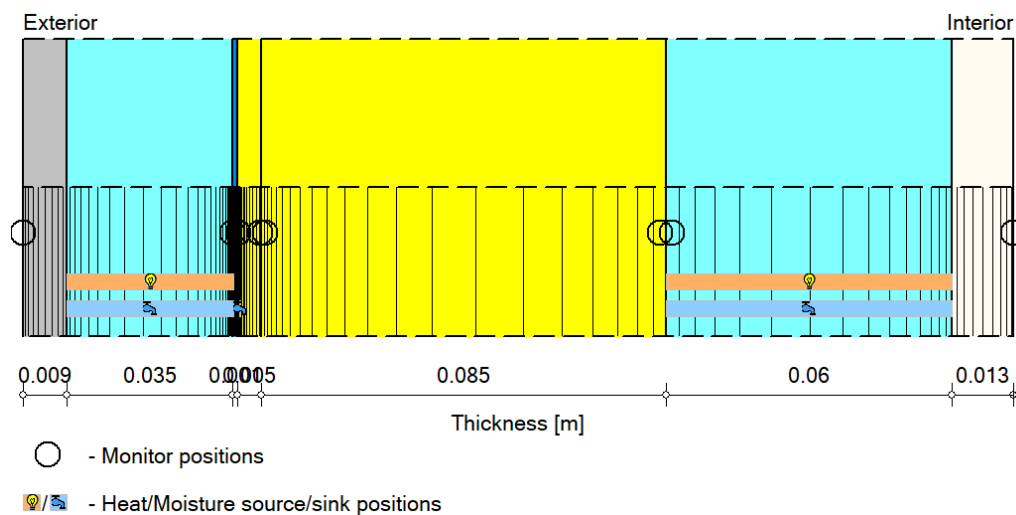
The design is not an uncommon detail, and, while it represents a version of standard practice found in the local industry, it does not result in good performance outcomes. It is an example of a cost-driven solution, one that delivers savings on labour and materials for contractors but severely compromises building function, comfort and durability. This is largely due to minimal prevention of vapour transfer into the wall from inside (the dominant condition), thermal bridging due to metal (high conductivity) studs and a vapour barrier on the outside. The risk associated with this installation, commonly realised, is material deterioration, mould or fungal growth, or structural damage to materials, over time.

## 8.1 ASSESSING POTENTIAL FOR MOULD GROWTH

The potential for failure depends, critically, on the conditions under which the building operates as well as the materials it is constructed from. The input of materials into the model, therefore, are paramount to determining the risks associated with moisture.

Of particular concern is the data available for the external sarking, deemed “vapour open” by the manufacturer due to physical perforations, but for which varying datasheets have been submitted over the course of the last 12 months in response to product queries. This sarking, where nominated as “breathable” is not weathertight, and where nominated as “weathertight” is not breathable; thus, the purpose of installation is not clear. It cannot fulfil its both functions in one product variation.

In this analysis, we have used the manufacturer’s claimed performance, but we have doubts over the suitability of this product and would recommend substitution for a product with third-party verified performance.



**Figure 17:** Modelled assembly of external wall in the WUFI software

### 8.1.1 MODEL VARIATION A: WALL AS-BUILT, WITH AIR CONDITIONING

To test the anticipated ideal operation of the construction, the wall was modelled per construction documentation and with air-conditioning running (heating and cooling). This was to test the most complimentary conditions.

This model indicated that, where internal temperatures are maintained at comfort conditions, there is low risk of surface mould, but that moisture in the insulation layer may be an issue.

### 8.1.2 MODEL VARIATION B: WALL AS-BUILT, WITHOUT AIR CONDITIONING

To test whether the model behaves differently without control of indoor conditions, the internal conditions have been adjusted to allow for a greater fluctuation in both temperature and humidity, within the bounds of anticipated conditions for a room of this types and in the situated climate.

This model indicates a higher likelihood of condensation behind the external sarking, but the risk of internal mould conditions remains low.

### 8.1.3 MODEL VARIATION C: WALL WITH SMART BARRIER, WITHOUT AIR CONDITIONING

This model removes the risk of condensation within the wall construction by restricting vapour movement into the wall from both sides. While the material on the outside remains the same, a better install quality is assumed, and a “smart” vapour barrier is added behind the plasterboard layer on the inside. This smart layer restricts vapour transfer into the wall during winter but allows the wall to dry to the inside during summer.

### 8.1.4 RESULT SUMMARY

Table 6, below, summarises the results of the hygrothermal analysis and iterations. Again, we draw attention to the material information available for the specified product and note that the performance is in doubt. The ideal specification is for a detail that prevents the vapour transfer into the wall, i.e. a smart barrier to the inside of the thermal layer.

Any risk of mould in the insulation layer is entirely dependent on material, being bioavailable as a substrate on which mould can grow. As the specified insulation material is glasswool, it is expected that mould will not inherently be able to grow here without additional nutrient material, e.g. dust or paper backing.

All charts are included in Appendix C.

**Table 6:** Summary results of hygrothermal analysis, wall type WT-E/02

	<b>Model A:</b> As-built, with air-conditioning	<b>Model B:</b> As-built, without air-conditioning	<b>Model C:</b> With smart vapour barrier, no air-conditioning
Risk of interstitial condensation	Moderate: likely condensation at outer layer of insulation	Moderate: likely condensation at outer layer of insulation	Low
Risk of mould at plasterboard surface	Low	Low	Low
<b>Overall risk</b>	<b>Moderate</b>	<b>Moderate</b>	<b>Low</b>

For the wall type, the potential for mould at the internal surface was also observed, utilising the Isopleth charts generated in WUFI. The below charts depict the mould risk, assessing the internal ceiling surface and the moisture content, indicating risk of either material degradation or mould.

The isopleths charts show that, at all times and across all models, the risk of mould at the wall surface is below the prediction curves, i.e. low risk of mould. This is true for a specific range of conditions, such as there being no substrate for growth.

## 9. ACHIEVING A COMPLIANT ENVELOPE

There are many ways to achieve a Passive House compliant building envelope. The key decisions are structural system, thermal bridge mitigation and air tightness strategy from that flow the usual considerations of insulation, window selection, shading and fire requirements; all are interlinked.

As discussed in the preceding two chapters the use of structural steel in the current design creates some challenges around thermal bridges and condensation formation. While a technical solution is possible to any situation it is often easier to begin from first principles.

Timber, especially Cross Laminated Timber (CLT) is a practical structural material system for most buildings below 10 storeys (and some beyond that). CLT consists of a series of timber planks bonded together, each layer is perpendicular to the previous. Panel thicknesses vary from 90mm upwards depending on the technical requirements. The panel sizes vary depending on the building design and transport requirements but are often entire walls.

### 9.1 STRUCTURE & THERMAL BRIDGES

There are several locations in the building where structural thermal bridges would pose significant challenges to mitigate in concrete or steel; where floors flow from inside to out and where roof overhangs occur. A timber structure would be a cost-effective solution to mitigating thermal bridges at these repeating details.

As timber is approximately 350 times less conductive than steel, any structural element that projects through the thermal envelope has much less impact. This would greatly simplify the design of a Passive House compliant building envelope.

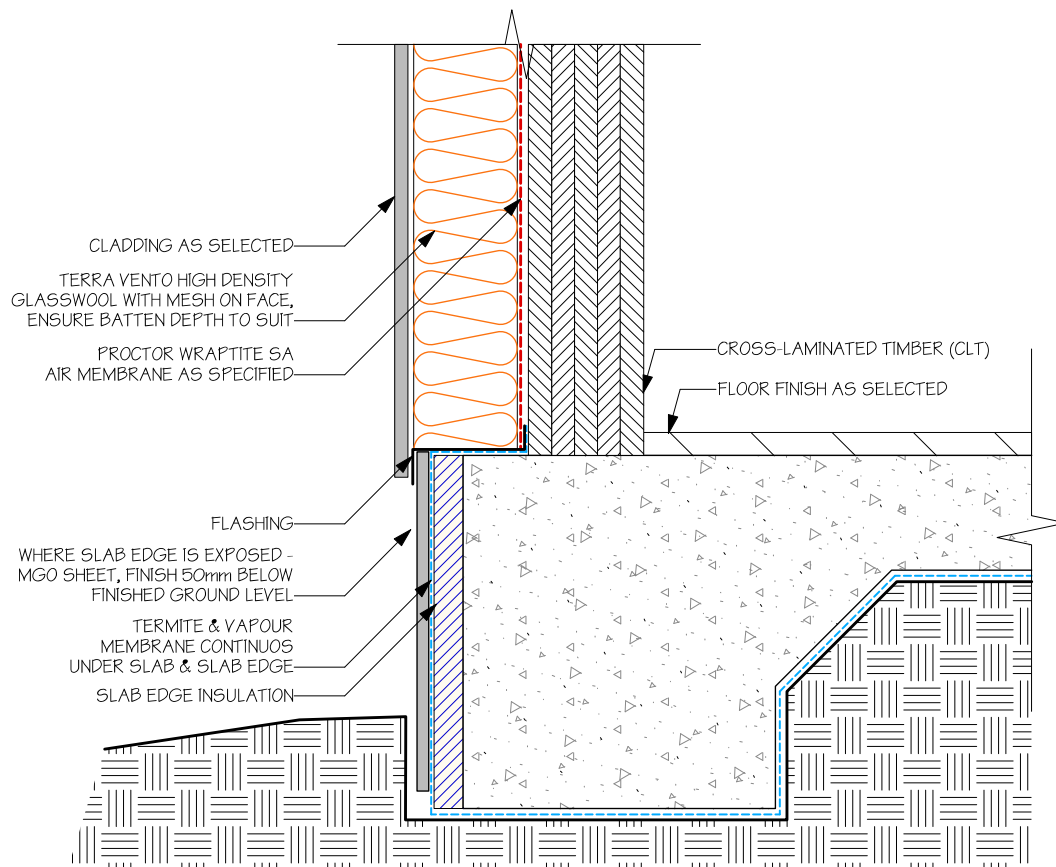
The spans achievable by CLT are well suited to school construction. It is a common material choice in the UK and in New Zealand. New connector fittings are frequently becoming available, a new spider connector allows 7m spans without the need for any beams.

The CLT panels can be used for outdoor corridors with appropriate membranes and protection against termite attack is also easily resolved at the slab edge.

The slab edge needs to be insulated to avoid cool temperatures and their associated condensation risk. Most Australian buildings do not insulate slab edges as they are usually used as inspection points for termite activity. The detail below utilises a specific termicide-impregnated membrane to prevent termite entry via the slab edge.

Panelised structural systems such as CLT have well documented advantages in terms of on-site speed, apartment buildings have been assembled at a rate of one level per day. This applies equally to schools.

The advantages bought by off-site manufacture of wall, floor and roof panels also necessitates adequate time allowances for manufacturing and delivery. Depending on manufacturing location lead times can vary with European sourced product requiring up to 20 weeks. Experience shows that the discipline required to order so far in advance is a useful driver for complete documentation, better design resolution on the drawing board and results in less changes on site.



**Figure 18:** Insulated slab edge detail with termite protection

## 9.2 AIRTIGHTNESS

Achieving air tightness is arguably the biggest challenge in the current Australian construction industry. There are various viable strategies that are usually interrelated to the structural system selected.

CLT has the advantage of being a large flat surface; it is also quite air tight in its own right. As a natural material timber requires protection from water, various membranes exist that can provide this, they can also supplement or deliver the primary air tightness function. Two readily available membrane, Proctor Wraptite SA and Pro Clima Adhero, are self-adhesive, ensuring applications to a large planar element is quite straightforward.

The robustness of the air tight membrane is a concern especially in the current market where awareness is low by global standards. The location of the air tight membrane on the external surface of the CLT reduces the risk of damage during construction. Anecdotally, most membrane damage occurs from plumbing and electrical trades, these works rarely occur outside of the building.

Air tightness is measured once the membrane and windows are installed, this allows for any mitigation measures to be undertaken while the membrane is accessible.

### 9.3 INSULATION & FIRE

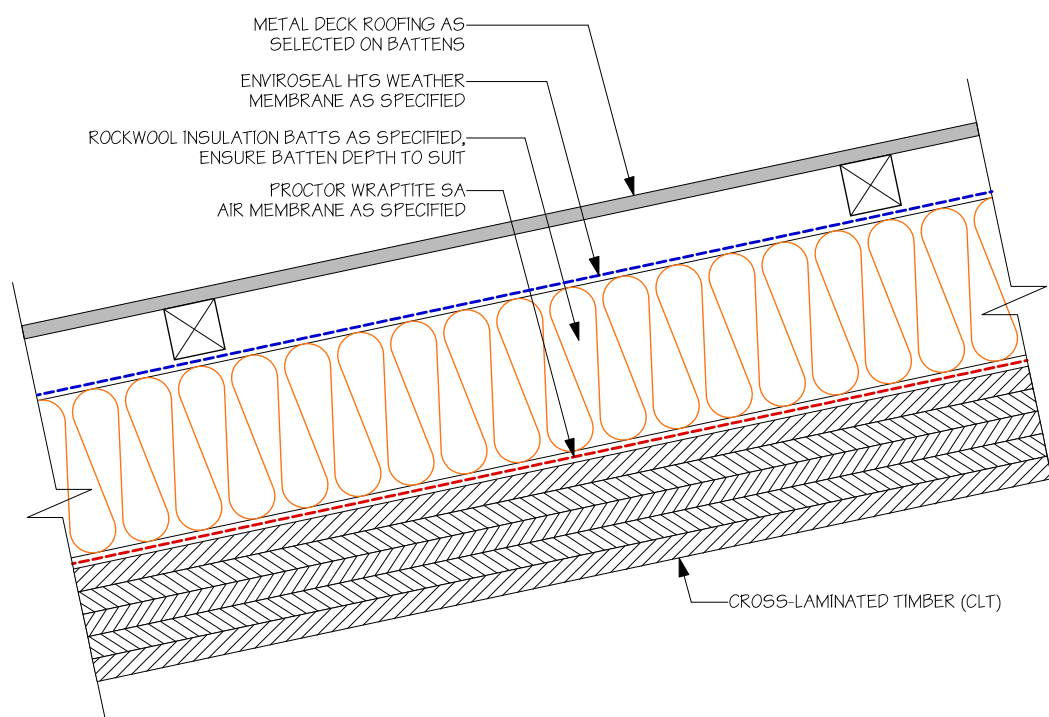
While timber is non-conductive, it does not provide sufficient insulation on its own to achieve comfort; insulation is required. In order to reduce condensation risk the insulation is placed outboard of the CLT structure and the air tight membrane.

Various insulation products are available that can perform the task however recent changes to the National Construction Code have limited the options to a small handful. Current best practice is to use either rockwool or high-density fibreglass insulation; both are non-combustible.

The insulation is placed between battens that are fixed to the CLT panels, the battens act as support structure for the cladding. From a Passive House perspective, the cladding is largely irrelevant. The longevity and robustness of the structure is provided by the membranes and insulation, the cladding is acting only as rain screen.

Aesthetically almost any look is possible although costs would vary between approaches; from sheet products through to blockwork.

Roofs can be insulated in a similar way to walls. As condensation is guaranteed to form on the underside of metal deck roofing the installation of the weather membrane is of critical importance. This is within the capabilities of the current Australian construction industry.



**Figure 19:** CLT roof detail

### 9.4 WINDOWS & SHADING

As outlined above, most current Australian window products are highly conductive and unsuitable for a Passive House building. However, there are several local manufacturers who can provide the necessary quality and an increasing number of importers of product that is often more competitive.



The practical challenge of importing windows revolves around timing with 8-20 lead times depending on manufacturing location. As with longer lead times for CLT this can have advantages.

The window performance itself would require U values in the low 1's and double glazing would suffice in this location and many others in NSW.

The installation of windows in a Passive House needs to ensure the air tightness of the building is not compromised. This is achieved by taping the windows to the air tight membrane. The tapes have good resistance to UV exposure (usually 6 months) and have been tested to function and avoid delamination for 100 years. The creation of an air tight seal around windows inherently prevents the ingress of wind driven rain.

Air tight buildings require greater consideration of shading to avoid the risk of overheating. As with conventional design a combination of roof overhangs and bolt-on shade structures can be utilised.

A CLT structure generally has the capacity to allow for mounting brackets for shade devices to be fixed to the outside of the panels only i.e. no penetration to inside. This ensures that any thermal bridge is minimised, and that the condensation risk is eliminated. There is a recently completed example of this at Gillies Hall at Monash University, Melbourne; a 150-bed student accommodation certified Passive House (refer to the case studies in section 11 for more information).



**Figure 20:** Gillies Hall, Monash University. Photo: Peter Clarke

## 10. SUMMARY AND RECOMMENDATIONS

The current delivery of buildings has commendable design and performance targets; however, as shown, the potential for the constructed product to meet these aspirations is low. Thermal comfort, durability and hygiene are compromised under the current approach, largely attributable to the material selection and specification. All current design parameters are typical practice in the local industry.

The primary reasons for Passive House fall largely into three areas: **health**, **economy** and **energy efficiency**. One of the key strengths is that, to date, it is the only standard where the built performance matches the design predictions quite closely, i.e. that there is no performance gap. The opportunity presented to the stakeholders in this approach should not be underestimated, with health, learning and economic benefits available.

It is highly recommended that SINSW builds school buildings to the Passive House standard.

## 11. CASE STUDIES



# The Wade Institute at Ormond College, Melbourne

## PASSIVE HOUSE CASE STUDY

**TIMEFRAME:** COMPLETED FEB 2016

**GROSS INTERNAL FLOOR AREA:** 580 M<sup>2</sup>

**CONSTRUCTION TYPE:** CONCRETE SLAB & ROOF WITH LIGHTWEIGHT WALLS

**COSTS:** \$4.2M APPROX.

**ARCHITECT:** LOVELL CHEN

**WORDS:** LOVELL CHEN

## METRICS

Heating Demand	12.0 kWh/m <sup>2</sup> a
Heat Load	10.0 W/m <sup>2</sup>
Cooling Demand	- kWh/m <sup>2</sup> a
Cooling Load	- kWh/m <sup>2</sup> a
Airtightness	< 0.6 h <sup>-1</sup>
Primary Energy (PE)	111 kWh/m <sup>2</sup> a

## Embodying the Intent

Designed to embody the values the Wade Institute strives to impart to its students of the Masters of Entrepreneurship — creativity and sustainability — Lovell Chen's teaching building in the grounds of Ormond College presents a series of contrasts. By turns it is serious and celebratory, garden pavilion and university cloister, structurally innovative yet simple in form. The building combines unconventional teaching spaces with a roof-top tennis court, a Passive House approach, flexibility, and a coherent design response to the complex architectural context of its site.

The L-shaped teaching building provides two main working spaces, with offices and ancillary rooms, all on one level. One of the tennis courts it

replaces has been 'lifted', creating usable space between two massive exposed concrete slabs — the roof and floor of the building. Both slabs slope gently, gathering rainwater from the court. The upper slab seems to defy gravity, supported on seemingly too-light steel mesh columns inside the building, and tied to the ground at its perimeter by further mesh columns. Full height glazing surrounds the teaching spaces, making the building transparent.

The feeling inside is a surprising combination of tranquillity and energized possibility. The minimal columns and the glazing contribute to the feeling of lightness, while the Passivhaus approach to detailing, plus the perimeter walkway created by the extended roof slab, bring a sense of

protection. Passivhaus focuses on achieving low energy usage through high levels of insulation and building seal, avoiding heat/cold bridges and using mechanical ventilation heat recovery. It requires precise detailing but delivers an extraordinarily positive experience for users.

Adaptable to multiple format or use, the larger teaching space is open plan. The end wall is for projection, and the floor is finished in cork. By contrast, the smaller seminar room is more sumptuous, though deceptively simple at first glance. Here, the walls are triple glazed, and the floor is covered in leather. One half of the floor can be raised by hydraulic lifts to form a seating rake. Raiseable benches have multiple uses.

## Key Features

Includes:

- Thermal mass - reduces internal temperature fluctuations and reduces the risk of overheating in summer;
- Excellent daylight and tranquil views, with the building in a garden setting;
- Triple glazed windows with timber frames, total U-value <1.0 W/m<sup>2</sup>K
- Simplified construction techniques, with site-poured slab & prefabricated wall sections;
- Innovation in structural design.
- Retention of the footprint of the existing amenity, with the tennis court 'elevated' to the roof.





## Further Resources

- Lovell Chen Website <http://www.lovellchen.com.au/lc/wade-institute/>
- Article on the Fifth Estate <https://www.thefifthestate.com.au/innovation/case-studies/case-study-australias-first-passivhaus-educational-building>





# Gilles Hall, Frankston

## PASSIVE HOUSE CASE STUDY

**TIMEFRAME:** COMPLETION FEB 2019 (IN CONSTRUCTION)

**GROSS INTERNAL FLOOR AREA:** 5,190 M<sup>2</sup>

**CONSTRUCTION TYPE:** CROSS LAMINATED TIMBER (L1-5), CONCRETE (GROUND)

**COSTS:** \$60M APPROX.

**ARCHITECT:** JACKSON CLEMENT BURROWS

**WORDS:** MONASH UNIVERSITY

## METRICS

Heating Demand	7.0 kWh/m <sup>2</sup> a
Heat Load	5.0 W/m <sup>2</sup>
Cooling Demand	- kWh/m <sup>2</sup> a
Cooling Load	- kWh/m <sup>2</sup> a
Airtightness	< 0.6 h <sup>-1</sup>
Primary Energy (PE)	148 kWh/m <sup>2</sup> a

## The Building

Monash University are developing a 158-room residential complex on their Peninsula campus. The building, to be ready for occupation in February 2019, will provide students with modern, high-quality, sustainable residences.

Professor David Copolov AO, Pro Vice-Chancellor (Major Campuses and Student Engagement) said that the new Residential complex is a welcome addition to Monash's Peninsula campus.

"The availability of quality student accommodation is one of the key

components that underpin our desire to establish Monash Peninsula as Australia's leading centre of allied health education and research, and to expand our campus' contribution to and engagement with the Frankston and Mornington Peninsula region,

"The new residential facility will not only help to attract more students but will also provide a sound and attractive residential focus for them to make the campus their base. We are especially proud of the environmental features of this exciting new building, whose design gives effect to our strategy for a sustainable future," he said.

Monash's Peninsula campus is the third largest of Monash's urban campuses and comprises the University's major presence in the Frankston and Mornington Peninsula region, catering to approximately 3,600 students.

The highly ambitious construction program leaned heavily on the prefabrication elements, while the ground floor's concrete construction enabled the build to start while awaiting shipment of the CLT from Europe.

## Low Energy Design

Includes:

- A cross laminated timber (CLT) structural system that more than halved the embodied carbon, relative to a concrete structure.
- In combination with an extensive rooftop solar photovoltaic system, the building is all-electric and net zero ready;
- includes rain water harvesting and water sensitive urban design, notably the creation of a landscaped dry-creek bed that provides additional opportunities for recreation, manages storm water flows and connects into the natural waterways of the campus;
- The building is delivered entirely without heating, and has only one small cooling system in the Head's apartment;
- Delivers excellent acoustics and noise separation of dwellings.

## Achievements

In applying the Passivhaus standard, the design team has not only omitted active systems from the student apartments, but also delivered comfort conditions for up to 100% of the year.

Extensive solar control measures, by way of external shading, combined with simple ceiling fans in each apartment, means that the building delivers comfort 100% of the time, compared to a predicted 50% of the time in a code-compliant dwelling with fans.

In other on-campus dwellings, summer conditions can reach up to 45°C; as the University was keen to avoid active cooling throughout, the refined measures offered by the Passivhaus standard stood out

### PROJECT BRIEF

With comfort issues in their code compliant and Green Star rated dwellings, Monash University were keen to explore alternative measures. With a significant push to reduce carbon intensity, and the recent release of their Net Zero Initiative, the Passive House standard is helping to deliver on the University's ambitious targets.



## Key Features

- Fabric** – CLT walls with external insulation and cladding, to a total R-value of 3.75 m<sup>2</sup>K/W, plus a highly architecturally driven design and distinctive shading system; CLT insulated roof construction achieves an R-value of 7.8 m<sup>2</sup>K/W and an insulated floor (concrete slab on ground) achieves R-1.2 m<sup>2</sup>K/W. Windows in student rooms are timber framed, plus some curtain wall elements in the common areas and on ground floor. The average U-value is 1.40W/m<sup>2</sup>K.
- Material Selection and Components** – CLT allowed for the project to be erected very quickly, with a very tight construction program of 10 months. The ground floor is concrete, enabling construction to start while awaiting shipment from Europe; The project's timing meant that local products were not quite ready when the project went to construction, although it is now expected that materials and products could be locally sourced in entirety.
- Building services:** no heating or cooling is installed in the building (save for one unit in the Head's apartment), with the thermal performance to be ensured using passive means. Each dwelling has a small kitchen and ensuite, and the central MVHR serves all rooms. The in-room facilities, designed to enable independent living, are a major source of energy use and had to be refined to meet the project's overall energy intensity limit. Each dwelling is fitted with a ceiling fan.

## Further Resources

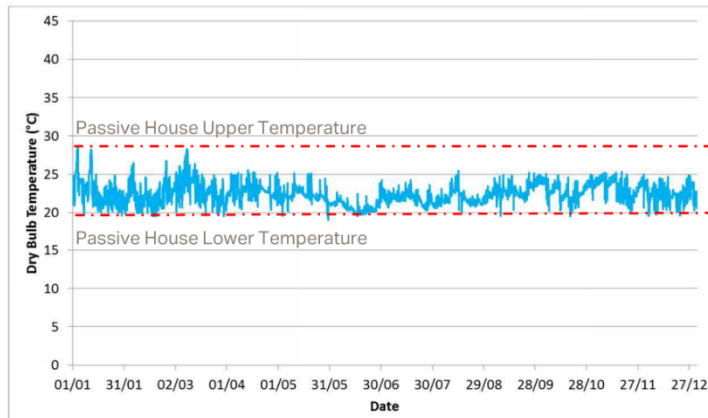
- Monash University (<https://www.monash.edu/news/articles/peninsula-student-accommodation>)
- JCBA Architects (<http://www.jcba.com.au/news/monash-peninsula-accommodation>)
- The Fifth Estate (<https://www.thefifthestate.com.au/innovation/building-construction/monash-to-cut-the-gas-target-passive-house-and-go-100-per-cent-renewable>)

## Passive House

Max DB temperature = 28.4°C

Min DB temperature = 18.9°C

Max Mean Radiant temperature = 28.3°C

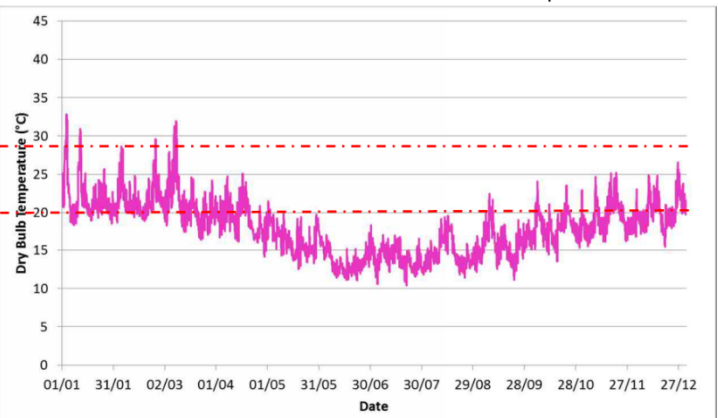


## Code Compliant

Max DB temperature = 32.8°C

Min DB temperature = 10.4°C

Max Mean Radiant temperature = 32.4°C







# Oak Meadow Primary School (UK)

## PASSIVE HOUSE SCHOOL BUILDING CASE STUDY

**TIMEFRAME:** COMPLETED SEPTEMBER 2011

**GROSS INTERNAL FLOOR AREA:** 2,205M<sup>2</sup>

**CAPACITY:** 420 STUDENTS

**COSTS:** £4.9M (AU\$7.8M IN 2011)

**ARCHITECT:** ARCHITYPE UK

**WORDS:** ARCHITYPE LTD **IMAGES:** ARCHITYPE LTD

## METRICS

Heating Demand	15.0 kWh/m <sup>2</sup> a
Heat Load	12 W/m <sup>2</sup>
Frequency of Overheating	7%
Climate Zone	Cool Temp.
Airtightness	0.48 h <sup>-1</sup>
Primary Energy (PE)	113 kWh/m <sup>2</sup> a

## The Project

Oak Meadow Primary School is one of the 1st three primary schools in the UK to receive Passivhaus certification in February 2012. Designed and built to the rigorous Passivhaus standard the two-form entry primary school (420 children) also includes facilities for a local 'Mast Agency Support Team'.

The building orientated on an East-West axis has been modelled to meet the technical demands associated with Passivhaus, which has influenced every decision about form, design and detailing, whilst ensuring focus has remained on simplifying and optimising the design.

The school has been constructed from a simple and robust palette of materials including; timber cladding, zinc roofing, timber windows and doors externally, timber screens, natural linoleum, organic paints and stains internally. Architype have been providing a series of 'soft landing' sessions, easing the occupiers into the building operations and guiding them to achieve optimal use of the building.

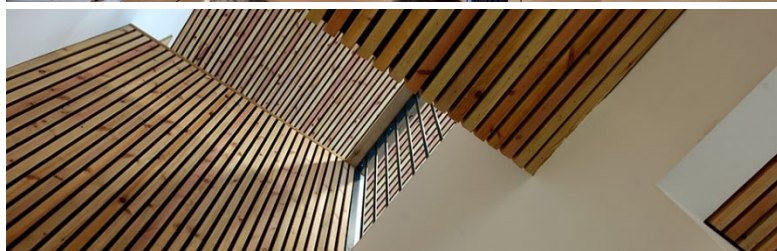
## Further Resources

- Architype Ltd Website (<https://www.architype.co.uk/project/oakmeadow-primary-school/>)
- Passivhaus Database ([https://passivehouse-database.org/index.php?lang=en#d\\_2953](https://passivehouse-database.org/index.php?lang=en#d_2953))

The children are more alert in the afternoon and are more attentive because the air is so fresh and comfortable. The daylight is just fantastic. It has raised our spirits; the children and teachers love our Passivhaus school.

Sara Morris, Headteacher





# APPENDIX A: PHPP MODELLING

Modelling has been undertaken on a sample project in the SINSW portfolio. The subject school is recently completed and has been subject to testing to establish what changes, if any, would be necessary or advisable to upgrade to the Passivhaus level of performance.

This assessment is intended to confirm whether the current specification of the building envelope is satisfactory and advise any required upgrades and to outline the required systems and mode of operation that would fulfil the requirements of the Passivhaus standard.

The supplied documentation information package from SINSW was used in this assessment, including architectural construction drawings, schedules and specifications.

## A.1 LIMITATIONS

We note that this assessment is preliminary in nature, with many assumptions made to facilitate a full PHPP calculation at this early stage of design. These assumptions are detailed in the following report. A full assessment can only be undertaken with all construction details documented, ready for certification; however, this assessment is concerned with directing the documentation and other elements of the project's design to achieve the desired performance level.

Due care and skill has been exercised in the preparation of this report. Any assumptions necessary for this assessment is detailed in the following. As noted above, this review encompassed an examination of existing documentation and relies on the information obtained from the listed documents. However, no liability is accepted for the accuracy or otherwise of this information.

Using the available design documentation and other information as provided, the building has been assessed using the Passive House Planning Package. This verified, excel-based tool prepares an energy balance and calculates the annual energy demand of the building based on the user input relating to the building's characteristics. From this tool, the user can determine whether a project meets, or does not meet, the requirements of the Passive House standard.

Measures required to meet the requirements of the standard are detailed in the following section; it should be noted that this assessment uses a number of necessary assumptions to reach this conclusion. These are also detailed in the following report.

## A.2 PROJECT INFORMATION

Building type	School building – primary		
Location	Northern NSW		
Climate Data	Location-specific, generated from Meteonorm software for the PHPP (uncertified dataset)		
Treated Floor Area (TFA)	Total: 1,297.3 m <sup>2</sup> approx. (measured)		
	Envelope A 621.1m <sup>2</sup>	Envelope B 374.6m <sup>2</sup>	Envelope C 301.6m <sup>2</sup>
Airtightness	0.6 h <sup>-1</sup> assumed (Passivhaus compliance)		

### A.3 PHPP MODELLING

The following table details the assumptions further to those earlier specified, required to complete a preliminary PHPP model. Please advise if any of these should be changed.

- No significant elements for thermal mass other than floor slabs (incl. ceiling contribution) are currently included. All internal walls are noted as lightweight with plasterboard or similar non-massive component;
- Planned number of occupants (for most of the year) is based on furniture layouts, with 1 student per desk;
- Light power density < 5 W/m<sup>2</sup>;
- A solar photovoltaic installation of 40kWp is shown for the building. This is not critical to compliance in a Passivhaus Classic scenario;
- The arrow shown on the plan indicates the true north for application of solar impacts;
- It is assumed intake for the MVHR unit involve limited outdoor sections (<2.0m). The MVHR is located inside the envelope, along with all duct runs;
- No dedicated exhausts, e.g. bathroom, kitchen, laundry, have been included and are not required in the building. All exhausts will, in the first instance, be designed for integration into the central MVHR system, with NCC compliance to be assured;
- Thermal bridges: thermal bridges have the potential to make or break the Passive House compliance. Within highly efficient buildings, the effect of thermal bridges is amplified and can account for a significant quantity of heat transfer across the envelope;
- Energy efficiency measures to achieve the total energy limit for the building (60kWh/m<sup>2</sup>a PER) have not been considered in this assessment but are anticipated to be met. For example, this might include efficient lighting and appliances, e.g. refrigerators, computers and printing equipment. Renewable energy, such as solar hot water or photovoltaics, should be considered and will have a positive impact.

The overall results are shown below in Table 7.



**Table 7:** PHPP modelling results, actual and upgraded building fabric and systems

		Combined Results		
		Treated Floor Area:		1297.3 m2
		Base model	Improvement	Passivhaus upgrade
Space heating	Heating demand kWh/(m²a)	83	90%	9
	Heating load W/m²	59	71%	17
	Heating load - TOTAL kW	76.0		21.7
Space cooling	oling & dehum. demand kWh/(m²a)	28	45%	15
	Cooling load W/m²	15	41%	9
	Cooling load - TOTAL kW	19.9	41%	11.7
Airtightness	Test result n <sub>50</sub> 1/h	10.0	94%	0.6
Non-renewable Primary Energy (PE)				
	PE demand kWh/(m²a)	271	62%	103
	PE demand - TOTAL kWh/a	351630	62%	133529
Primary Energy Renewable (PER)				
	PER demand kWh/(m²a)	161	70%	49
	Generation of renewable energy (footprint) kWh/(m²a)	83	0%	83
COMPLIANT?		NO		YES

## APPENDIX B: THERMAL BRIDGE MODELLING

The key used in this report is as follows, using colours to indicate acceptance of results:

Parameter	Poor Performance	Tolerable (accepted)	Compliant
Psi-value result (w/mK)	$\geq 0.10^*$	0.04 – 0.10*	$\leq 0.04$
Surface temperature result (°C)	$\leq 12.6$	12.7 - 16.9	$\geq 17$

\*This range is an approximation only. Results are to be inputted into the PHPP to check for compliance as tolerance in transmission heat losses may differ.

### B.1 MATERIAL CONDUCTIVITY

The conductivities of the different materials used in the thermal modelling are outlined below.

Colour	Material	Conductivity (W/mK)	Emissivity
	Concrete	1.4	0.9
	Fibre Cement	0.17	0.9
	Frame Cavity CEN Simplified	varies	0.9
	Frame Cavity Slightly Ventilated NFRC 100	varies	0.9
	Generic Ground	2	0.9
	Glass (plate or float)	1	0.84
	Glasswool insulation and with steel studs	0.11	0.9
	Glasswool insulation	0.038	0.9
	Oriented Strand Board (OSB)	0.13	0.9
	Pine, Spruce, Fir, Larch and Mahogany	0.14	0.9
	Plasterboard	0.16	0.9
	Steel, rolled	50	0.6

### B.2 THERMAL BRIDGE MODELLING METHODOLOGY

An analysis has been undertaken to calculate the linear thermal transmittance ( $\psi$  value) of representative details using THERM 7.6.1.1. Psi-values are correct to 'ISO 10211- Thermal bridges in building construction, heat flows and surface temperatures' and 'BR 497 Thermal bridging conventions for calculating linear thermal transmittance and temperature factors methodology'.

#### B2.1 Background

##### B2.1.2 Temperature Factor

The Temperature Factor ( $f_{Rsi}$ ), a ratio used to assess risk of surface condensation should be maintained above 0.55 as the limit value. Larger temperature differences due to lower interior surface temperature accelerate local fouling in the form of mould growth. The minimum internal surface temperature must be kept above 12.6°C to avoid the risk of mould.

#### B2.2 Methodology

##### B2.2.1 Psi-value

The linear thermal transmittance (Psi-value) is equal to the total two-dimensional thermal coupling coefficient of the building component ( $L_{2D}$ ), subtracting the sum of the one dimensional thermal coupling coefficient of the building component elements that make up the junction ( $\Sigma L_{1D}$ ) as shown in Equation 1 and 2.

$$\Psi = L_{2D} - \Sigma(L_{1D}) \qquad \Psi = \frac{Q_{2Dim} - Q_{1Dim}}{\lambda \Delta \theta}$$

**Equation 1 & 2:** Psi-value equation

This is done by modelling the total junction heat flow ( $\Sigma L_{1D}$ ), which is presented as 'System' in the results tables. Then the heat flow for each individual construction build-up is also modelled separately, which is presented as 'Wall' in the results tables. Dimensions of the individual construction lengths are taken as 3 times wall width or minimum 1m, dimensions are measured externally to thermal line.

As per Equation 3 the thermal coupling coefficient (L) of the building components is calculated by dividing the heat flow by the difference in surface boundary temperatures.

$$\phi = L(\theta_i - \theta_j)$$

**Equation 3:** Thermal coupling coefficient equation

As per 'BR 497 Thermal bridging conventions for calculating linear thermal transmittance and temperature factors methodology' for modelling install Psi-values of junctions around openings, window frames and glazing systems were modelled as an adiabatic boundary at the frame of the opening where the frame overlaps with the rest of the construction, this includes the vertical connection of the frame with any integral sill.

## B.3 RESULTS

The thermal bridge results are included on the following pages.



## 1-Slab Edge 4/5050

2D model		1D model A (U <sub>i</sub> )						1D model B (U <sub>i</sub> )						Psi-value		Condensation Risk			
L <sub>2D</sub> (W/m)	error (%)	Element	U (W/m <sup>2</sup> K)	R (m <sup>2</sup> K/W)	L (m)	Q=ULdT (W/m)	error (%)	Element	U (W/m <sup>2</sup> K)	R (m <sup>2</sup> K/W)	L (m)	Q=ULdT (W/m)	error (%)	Q2D-Q1D (W/m)	Psi W/mK	T <sub>int,min</sub> °C	T <sub>ext</sub> °C	T <sub>int,sur,min</sub> °C	f <sub>Rsi</sub>
28.83	7.20	Upper Wall	0.34	2.95	2.10	9.96	0.00	Lower Wall	0.34	2.95	2.10	9.96	0.00	8.91	0.64	20.0	6.0	17.5	0.82



Figure 1: Thermal Bridge Location

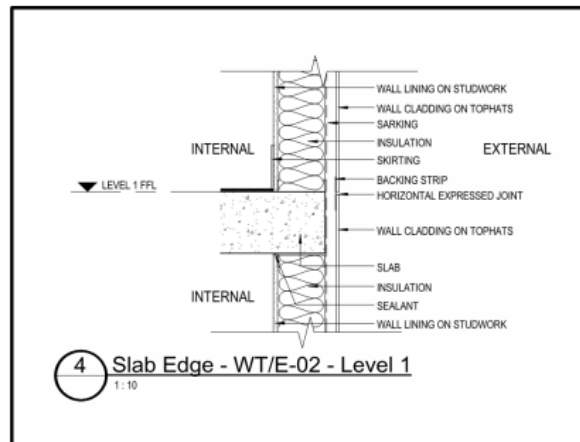


Figure 2: Detail

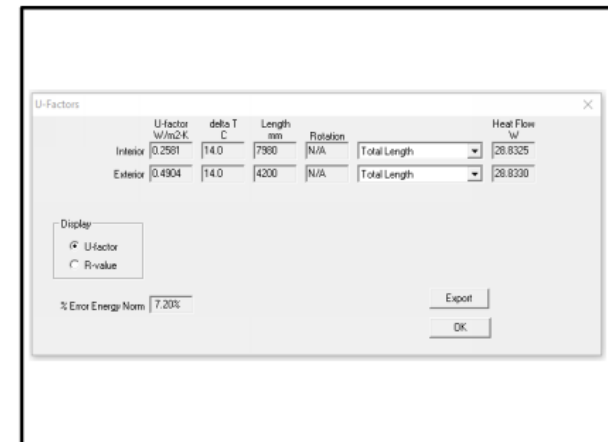


Figure 3: THERM Output

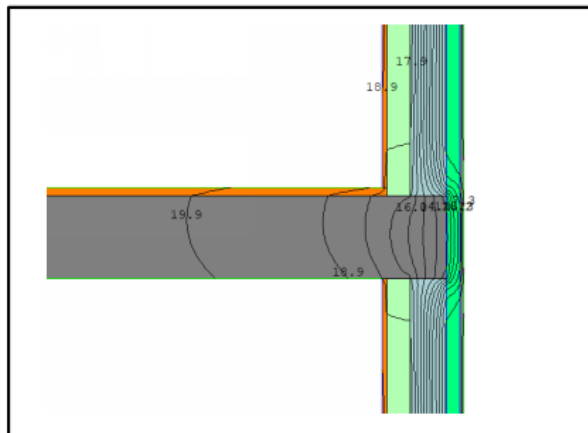


Figure 4: Isotherm lines

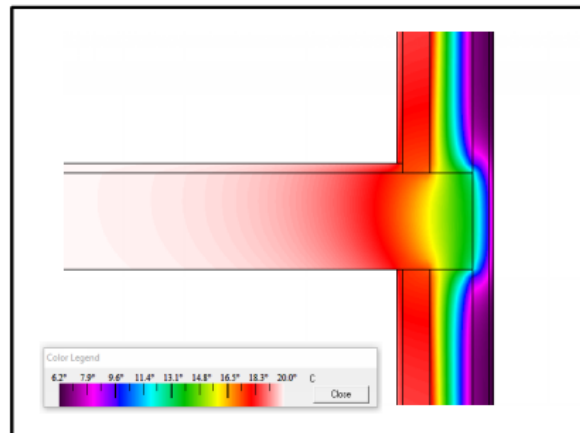


Figure 5: Colour Infrared

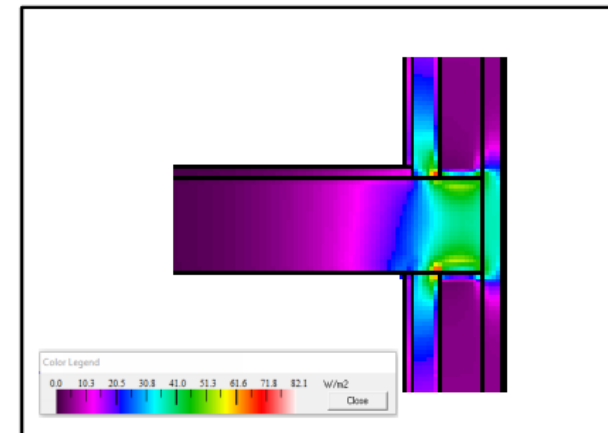


Figure 6: Colour Flux

## 2-Roof Wall-Section 2/4502

2D model		1D model A ( $U_i$ )						1D model B ( $U_i$ )						Psi-value		Condensation Risk			
$L_{2D}$ (W/m)	error (%)	Element	U (W/m <sup>2</sup> K)	R (m <sup>2</sup> K/W)	L (m)	Q=ULdT (W/m)	error (%)	Element	U (W/m <sup>2</sup> K)	R (m <sup>2</sup> K/W)	L (m)	Q=ULdT (W/m)	error (%)	Q2D-Q1D (W/m)	Psi W/mK	$T_{int,min}$ °C	$T_{ext}$ °C	$T_{int,sur,min}$ °C	$f_{Rsi}$
64.19	9.50	Wall	0.76	1.31	2.16	23.08	4.40	Roof	1.24	0.81	2.12	36.73	15.37	4.37	0.31	20.0	6.0	14.5	0.61

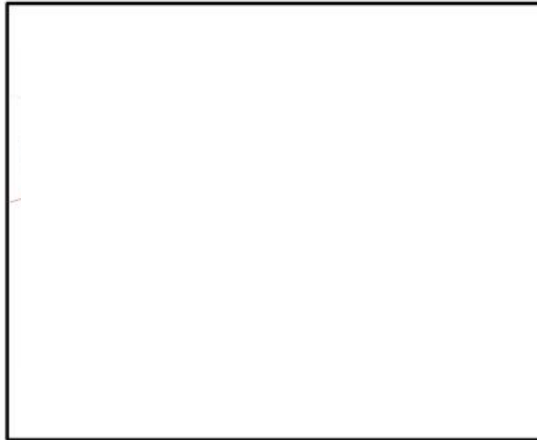


Figure 1 Thermal Bridge Location

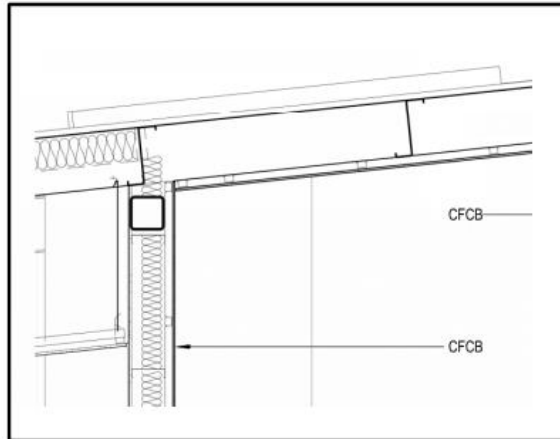


Figure 2 Detail

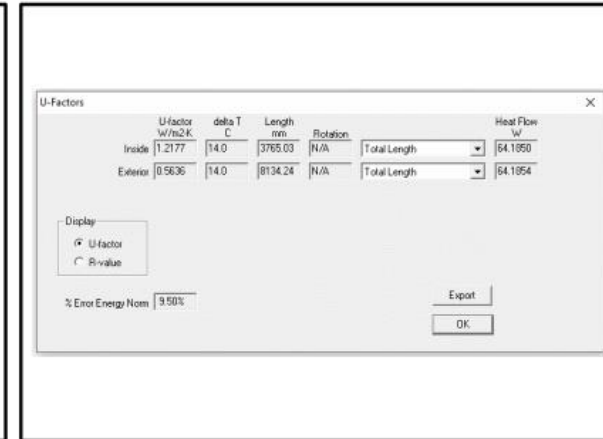


Figure 3: THERM Output

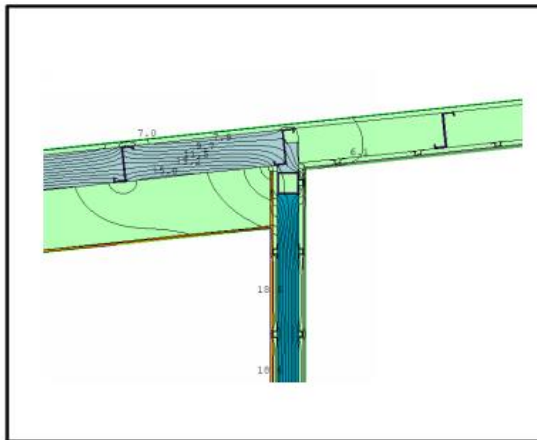


Figure 4 Isotherm lines

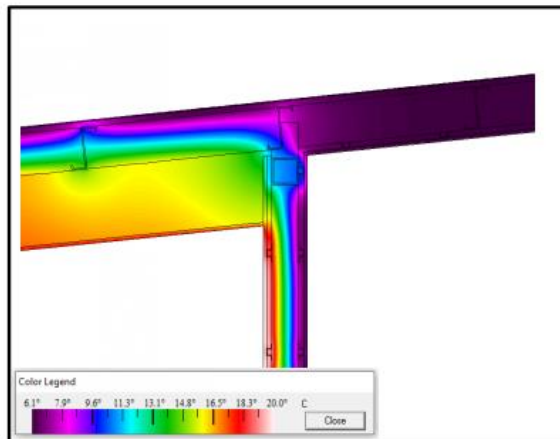


Figure 5 Colour Infrared

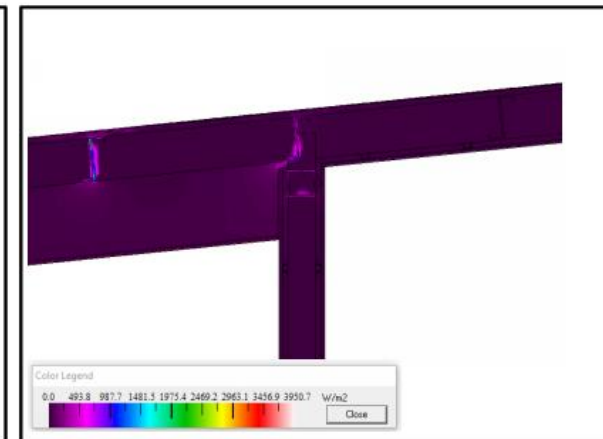


Figure 6: Colour Flux

### 3- Slab Edge, Ground 3/5050

2D model		1D model A ( $U_t$ )						1D model B ( $U_t$ )						Psi-value		Condensation Risk			
$L_{2D}$ (W/m)	error (%)	Element	U (W/m <sup>2</sup> K)	R (m <sup>2</sup> K/W)	L (m)	Q=ULdT (W/m)	error (%)	Element	U (W/m <sup>2</sup> K)	R (m <sup>2</sup> K/W)	L (m)	Q=ULdT (W/m)	error (%)	Q2D-Q1D (W/m)	Psi W/mK	$T_{int,min}$ °C	$T_{ext}$ °C	$T_{int,sur,min}$ °C	$f_{Rd}$
45.62	7.45	Wall	0.34	2.96	2.15	10.16	0.00	Ground Slab	0.60	1.66	3.99	33.59	7.10	1.86	0.13	20.0	6.0	14.6	0.61

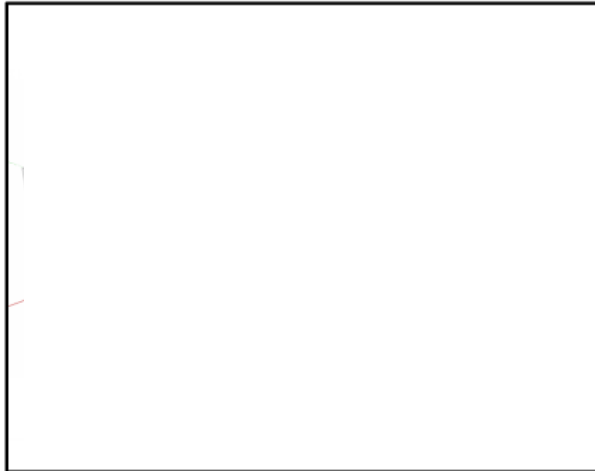


Figure 13: Thermal Bridge Location

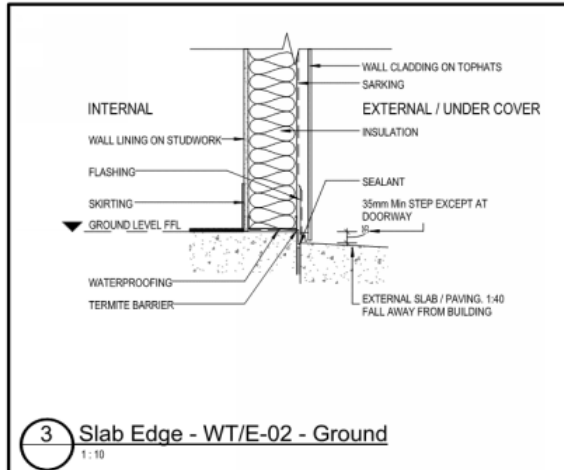


Figure 14: Detail

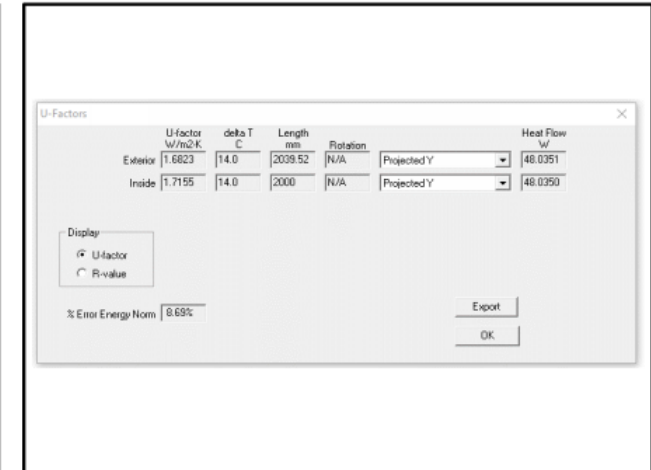


Figure 15: THERM Output

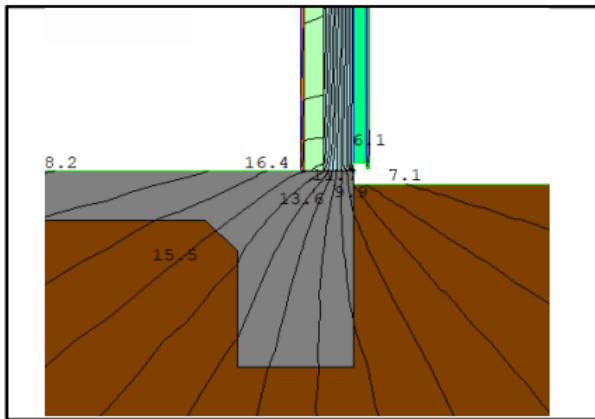


Figure 16: Isotherm lines

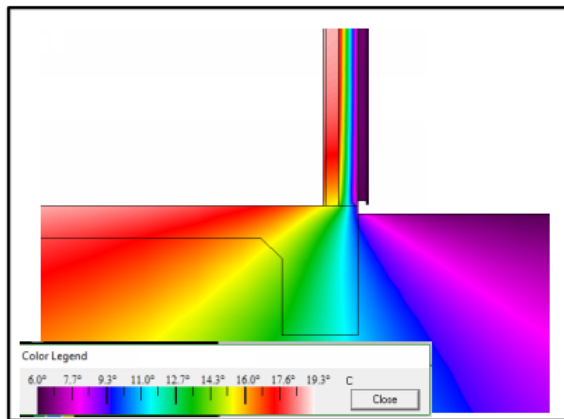


Figure 17: Colour Infrared

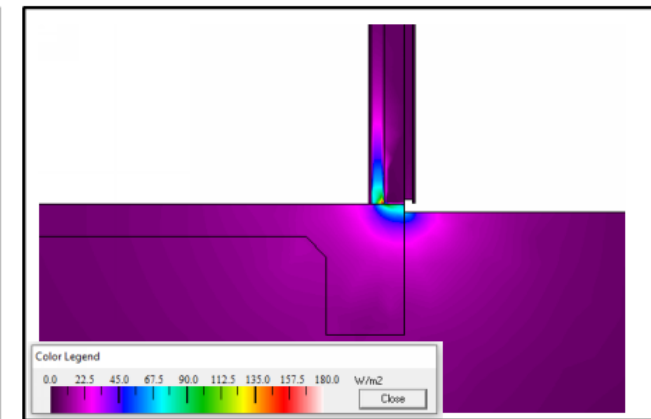


Figure 18: Colour Flux



5- Exterior Wall with Steel Studs

1D model A (U <sub>i</sub> )						Condensation Risk			
Element	U (W/m <sup>2</sup> K)	R (m <sup>2</sup> K/W)	L (m)	Q=ULdT (W/m)	error (%)	T <sub>int,min</sub> °C	T <sub>ext</sub> °C	T <sub>int,sur,min</sub> °C	f <sub>Rsi</sub>
Wall	0.69	1.45			7.92	20.0	6.0	15.8	0.70

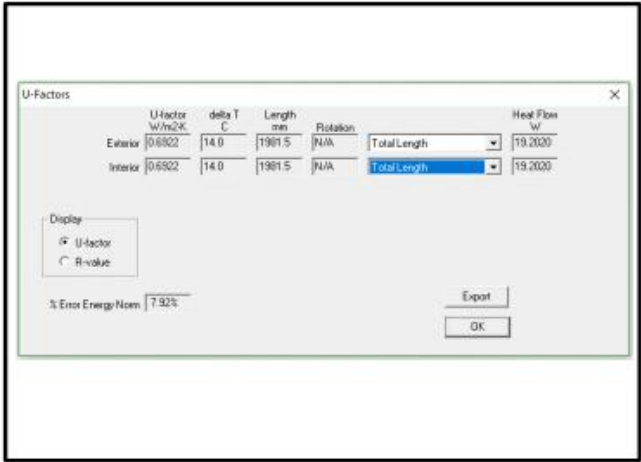


Figure 3: THERM Output

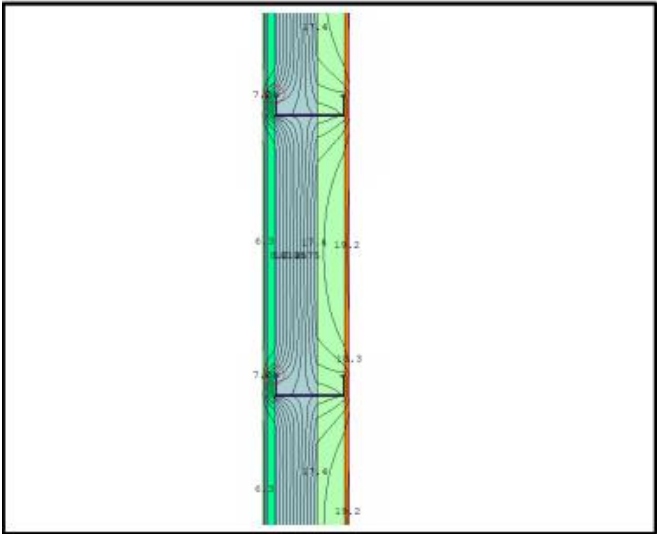


Figure 4 Isotherm lines

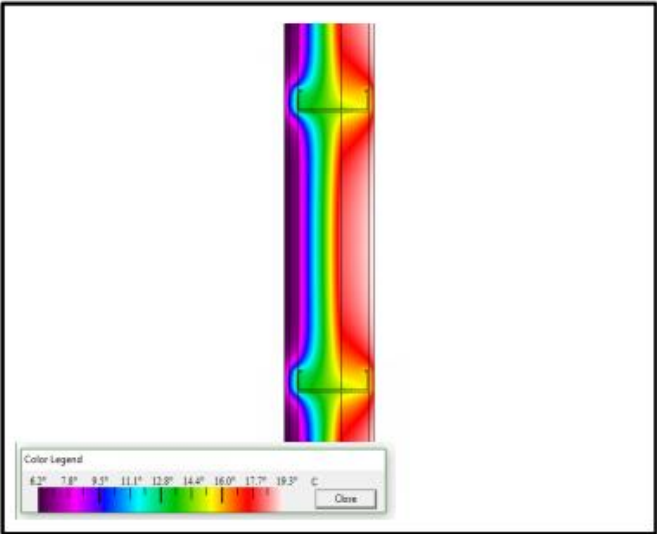


Figure 5: Colour Infrared

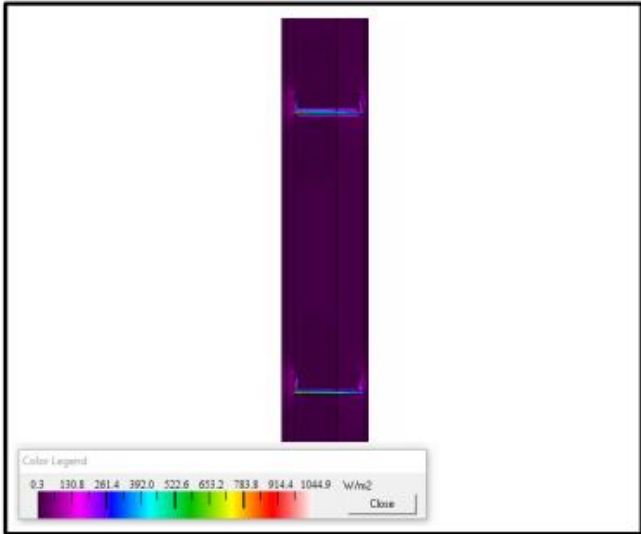


Figure 6: Colour Flux

## 6- Exterior Wall if Installed with Timber Studs

1D model A ( $U_i$ )						Condensation Risk			
Element	U ( $W/m^2K$ )	R ( $m^2K/W$ )	L (m)	Q=ULdT (W/m)	error (%)	$T_{int,min}$ °C	$T_{ext}$ °C	$T_{int,sur,min}$ °C	$f_{Rsi}$
Wall	0.39	2.56			2.71	20.0	6.0	18.6	0.90

U-Factors							
	U-factor $W/m^2K$	delta T °C	Length m	Rotation	Total Length	Heat Flow W	
Exterior	0.3881	14.0	1981.5	N/A	Total Length	10.7660	
Interior	0.3881	14.0	1981.5	N/A	Total Length	10.7660	

Display  
☒ U-factor  
☐ R-value

% Error Energy Norm 2.71%

Export OK

Figure 3: THERM Output

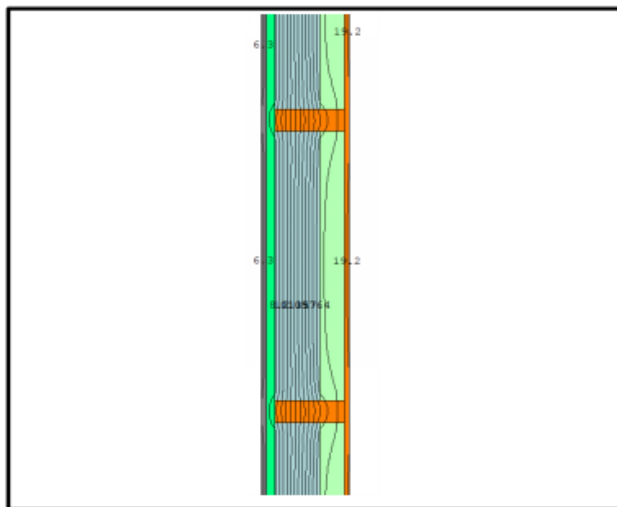


Figure 4 Isotherm lines

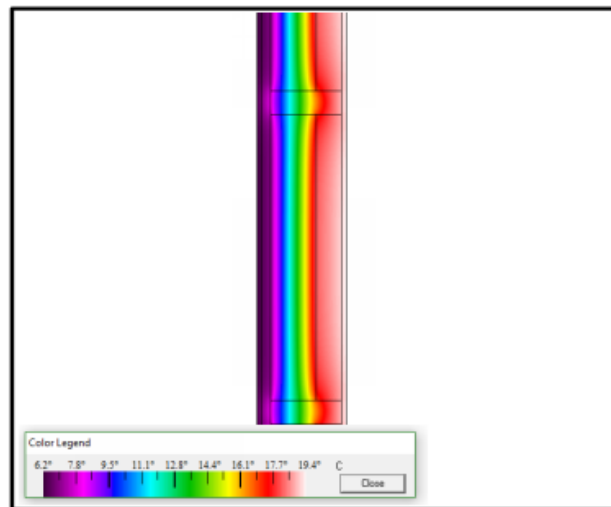


Figure 5: Colour Infrared

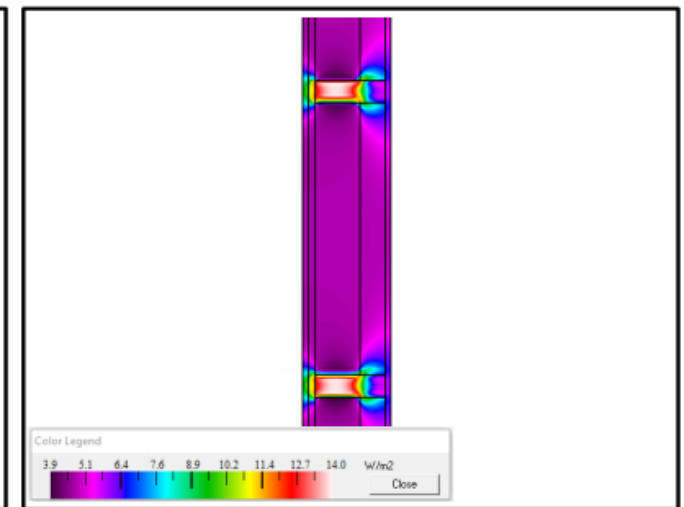


Figure 6: Colour Flux

## APPENDIX C: HYGROTHERMAL MODELLING

The moisture-related risk of the wall build-up has been assessed with dynamic simulation for both heat and moisture

The WUFI software performs dynamic simulations of coupled heat and moisture transfer. The methods have been validated world-wide and provide realistic simulation of hygrothermal conditions in building components and buildings under actual climate conditions. WUFI Pro is the standard tool for assessing hygrothermal performance of one-dimensional building envelope cross-sections and was used for this analysis.

### C.1 SOFTWARE

This assessment has been completed using WUFI Pro, an industry standard 1-D transient hygrothermal model which provides an approximation of heat and moisture conditions within a construction over a given time period. Note that as WUFI Pro is a 1-D model, construction sections which are not homogeneous in one dimension have not been considered. This includes wall junctions and corners. Additionally, bridging elements such as studwork are not considered; thermal performance in these areas will typically be poorer due to thermal bridging aspects. Similarly, hygric performance will typically be poorer due to reduced thermal performance, and higher potential for poorer workmanship at junctions (e.g. poor sealing). Further to the above, WUFI Pro, as with all models, engineering calculations, and experiment (aside from direct field observation) is at best an accurate approximation of what is expected in reality. This represents the pinnacle of applied science for hygrothermal issues in building constructions.

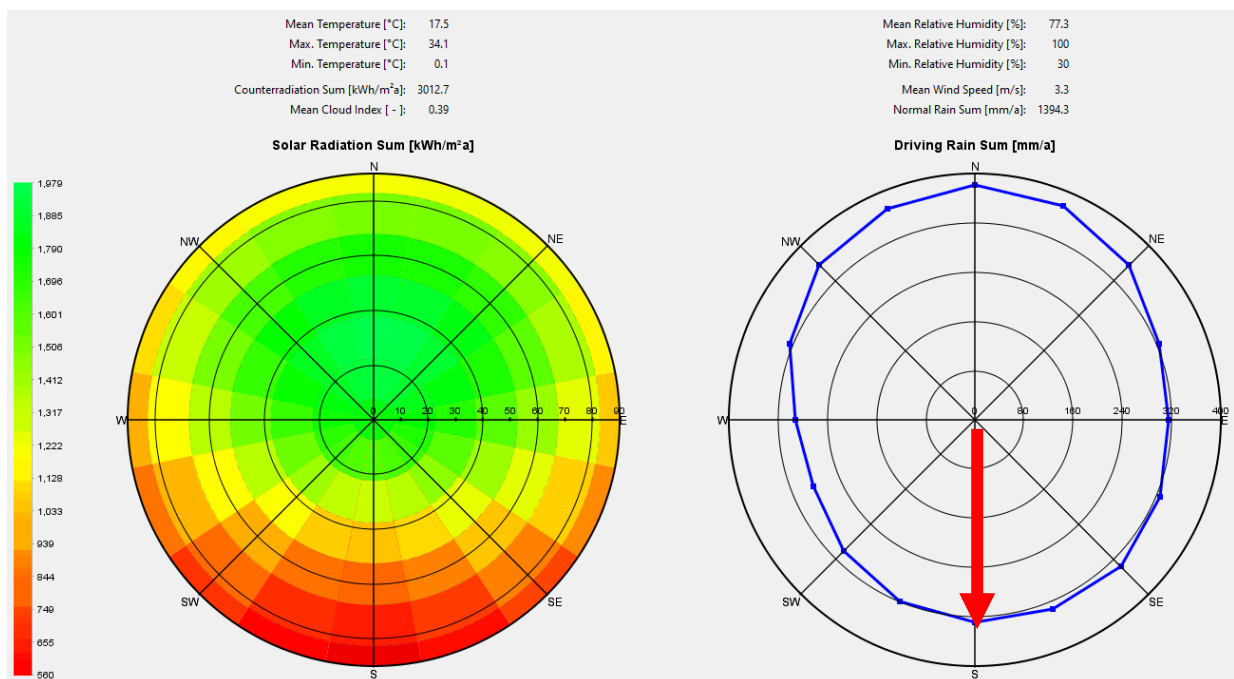
### C.2 MODELLING ASSUMPTIONS & INPUT DATA

WUFI Setting	Setting	Note
Orientation	South	Worst case for driving rain and solar exposure
Inclination	90°	Vertical wall
Driving rain coefficients	ASHRAE Standard 160	Exposure category: Medium Rain exposure factor (FE) = 1.0 Rain deposition factor (FD) = 0.5
Daily average outdoor temperature (maximum)	23.8	From Bureau of Meteorology for specific location
Air Change Source (ACH)	0 - 10 ACH	Air change sources are placed into the air cavities appropriate to their location
Ext Heat Resistance	0.0588 m <sup>2</sup> K/W	Standard external wall value assumed
Ext Short-Wave Radiation Absorptivity	0.68	Red brick, per design renders
Ext Adhering Fraction of Rain	0.7	Default value for vertical walls
Interior Heat Resistance	0.125 m <sup>2</sup> K/W	Wall
Interior sd-Value	0.1 m	Gypsum Board



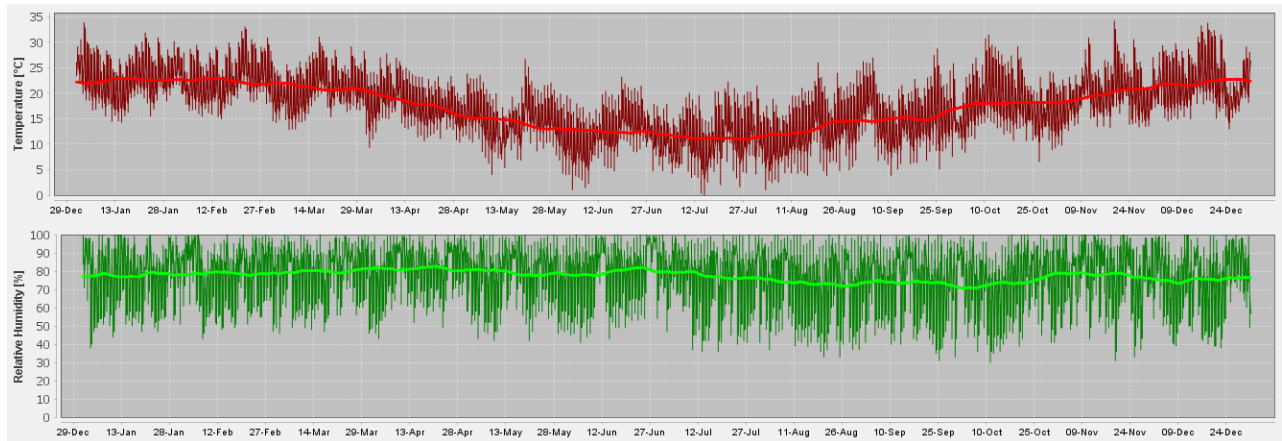
Initial Relative Humidity	80%	Conservative assumption, assuming some building wetting during construction period
Outdoor Climate	Location specific, NSW	WAC data generated from Meteonorm software. Conditioned temp: 20°C (winter) - 24°C (summer)
Indoor Climate	ASHRAE 160 Method	Moisture generation rate: 0.050kg/s per person Air exchange rate (infiltration): 2 ACH
Calculation Period	5 years	-

All above modelling inputs remained constant throughout the modelling process.









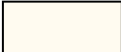
**Figure 21:** Weather data for building location (WUFI-WAC file)

As a result of the above solar radiation and driving rain weather data, a high-risk orientation (south) has been identified and is the subject of this study only. All other orientations will have comparatively lower risk, as this orientation has high driving rain and low passive solar drying potential.



**Figure 22:** Local external temperature (°C) and relative humidity (%) generated via Meteonorm 7.2

**Materials:**

	- Fibrecementboard	0.009 m
	- Air Layer 40 mm; without additional moisture capacity	0.035 m
	- vapour retarder (sd=1m)	0.001 m
	- Mineral Wool (heat cond.: 0,04 W/mK)	0.005 m
	- Mineral Wool (heat cond.: 0,04 W/mK)	0.085 m
	- Air Layer 60 mm; without additional moisture capacity	0.06 m
	- Interior Plaster (Gypsum Plaster)	0.013 m

**Figure 23:** Material properties for the modelled assembly

### C.3 RESULTS

The outputs from the models showed, qualitatively, that the potential for condensation exists in the as-built condition but that it can be controlled by controlled air-conditioning. In practice, this is unlikely.

The detailed charts for all modelled options are presented below. Figure 24 shows the chart for the as-built condition. Each chart shows the range of temperature (red) and relative humidity (green) in each building element.

## Model A: As-built with air-conditioning to control indoor conditions

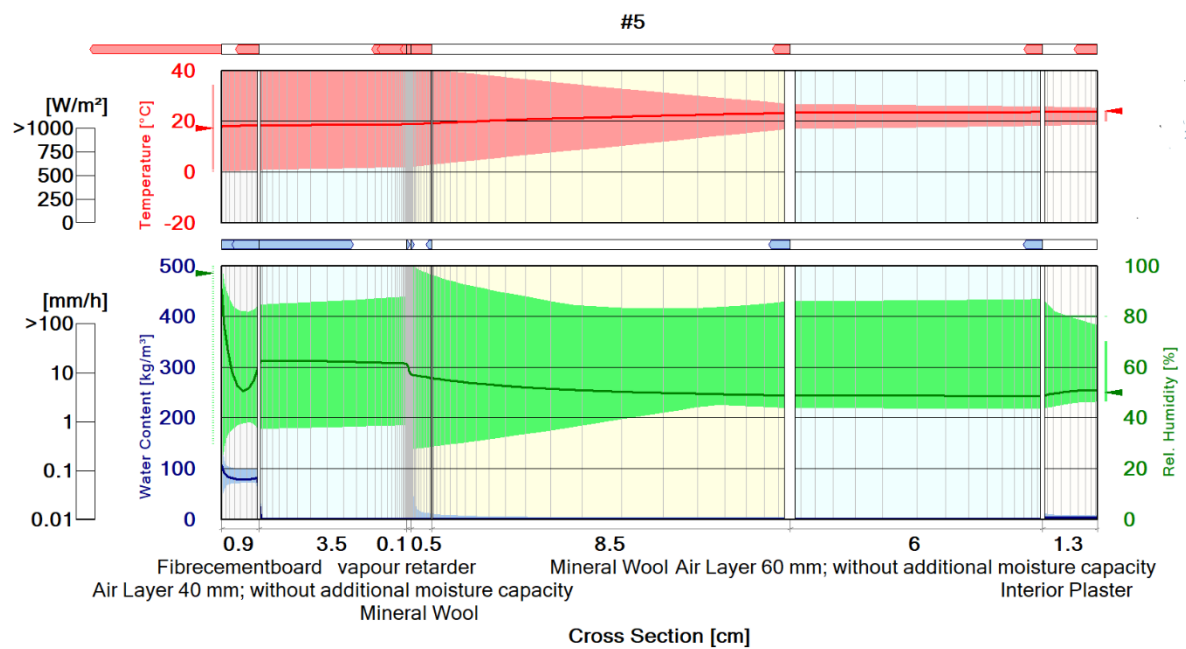


Figure 24: Relative humidity and temperature over time, Model A

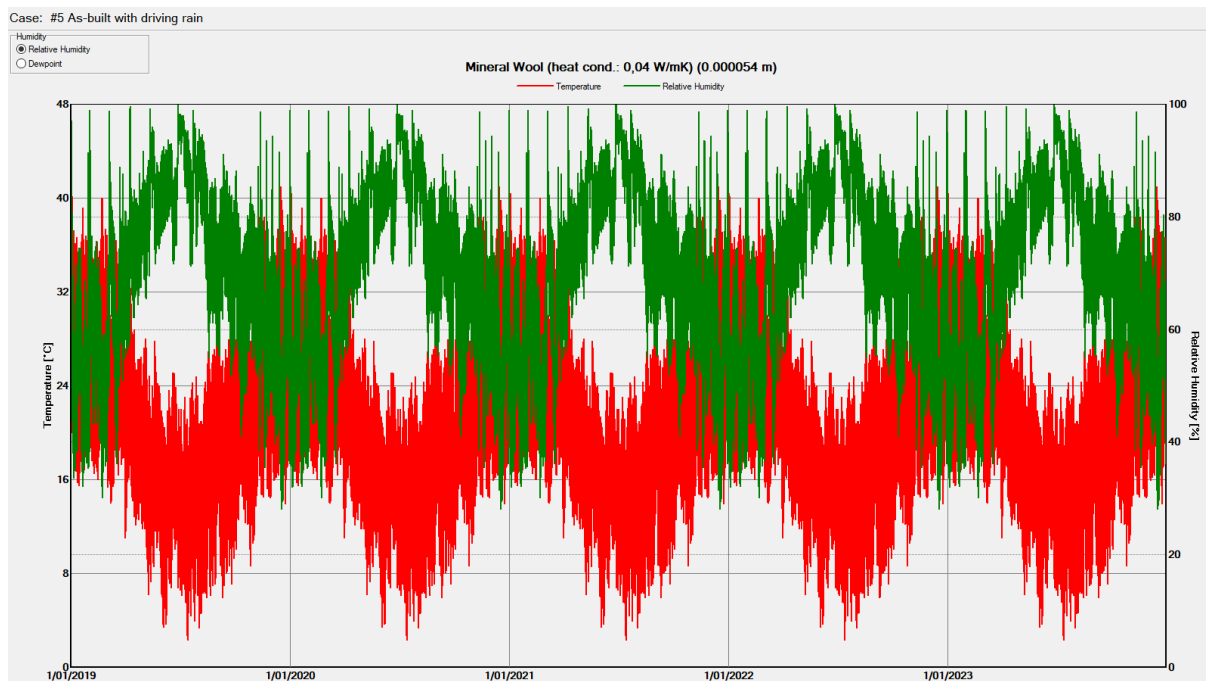


Figure 25: Temperature and humidity in the outer layer (5mm) of the insulation, Model A

This model shows likelihood of saturation (100% RH) at some periods throughout the analysis, particularly in the outer layer of insulation. This saturation is cyclical, and therefore dries out regularly.

## Model B: As-built without air-conditioning

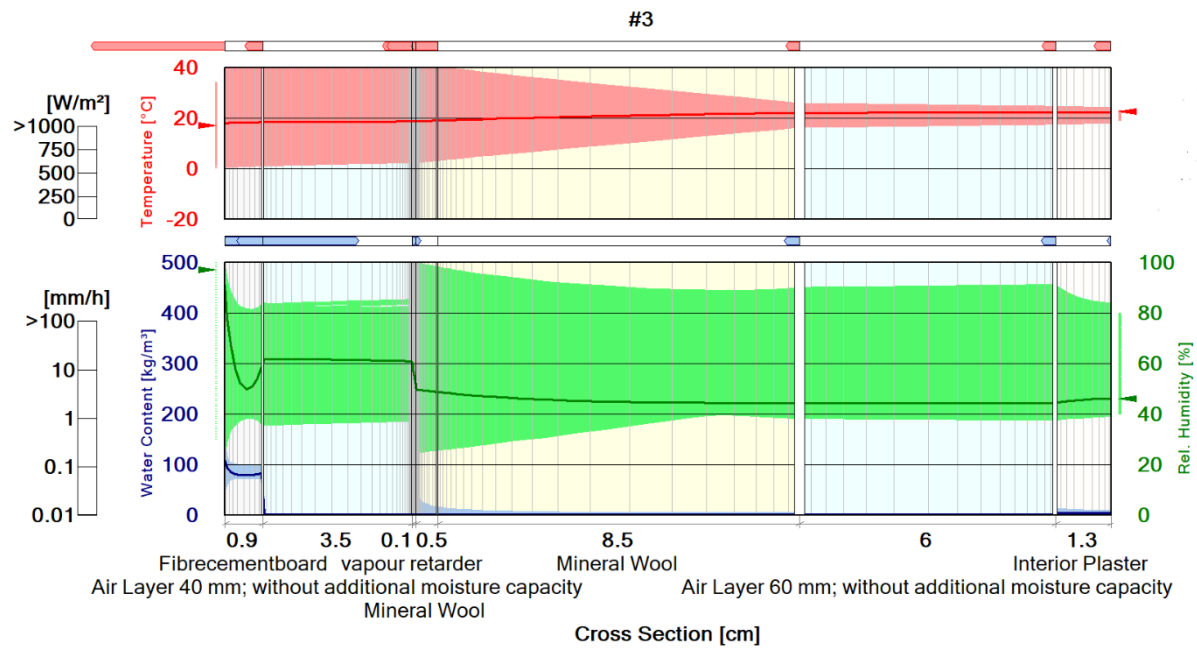


Figure 26: Relative humidity and temperature over time, Model B

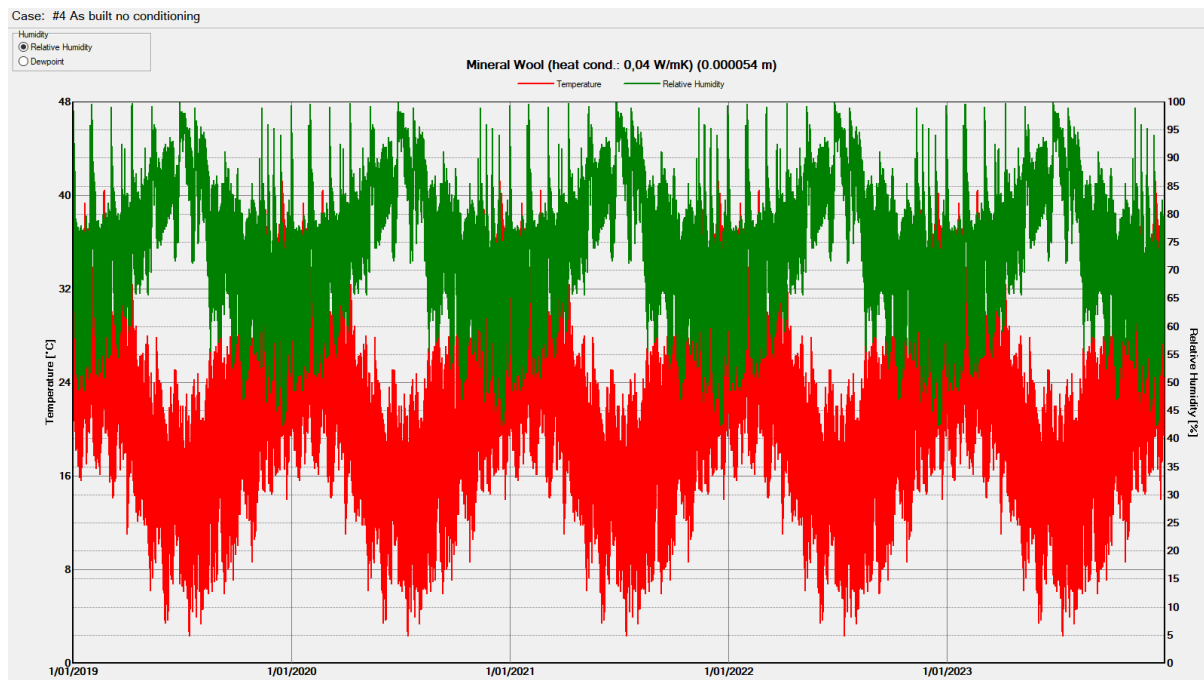
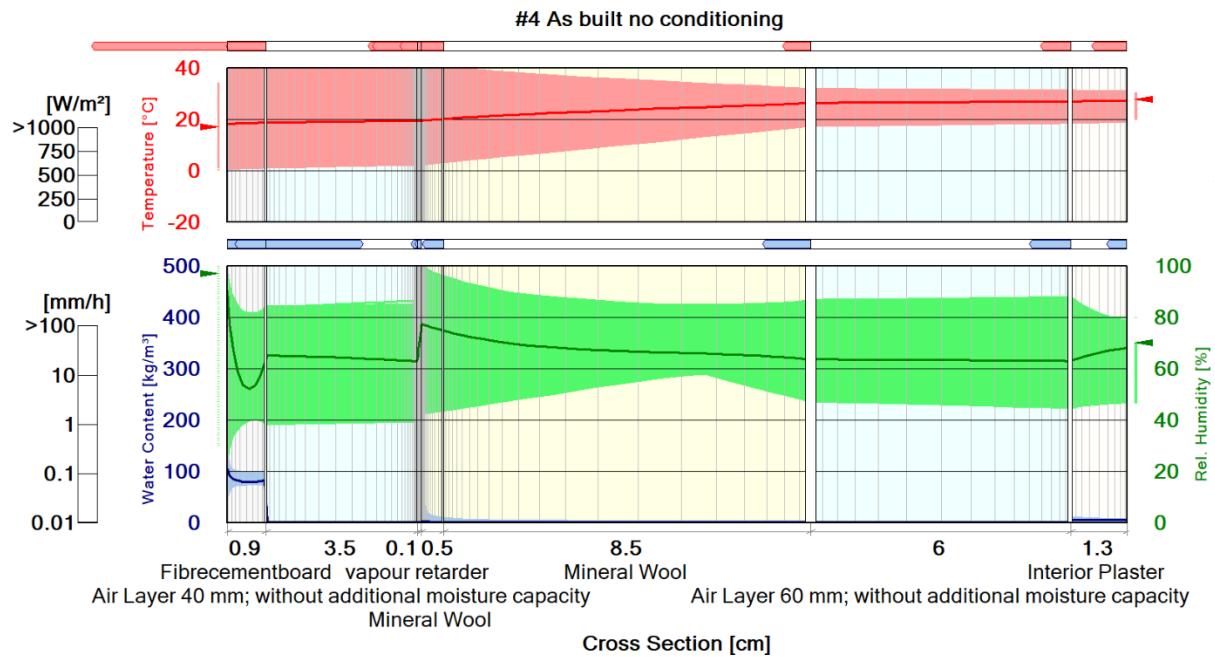


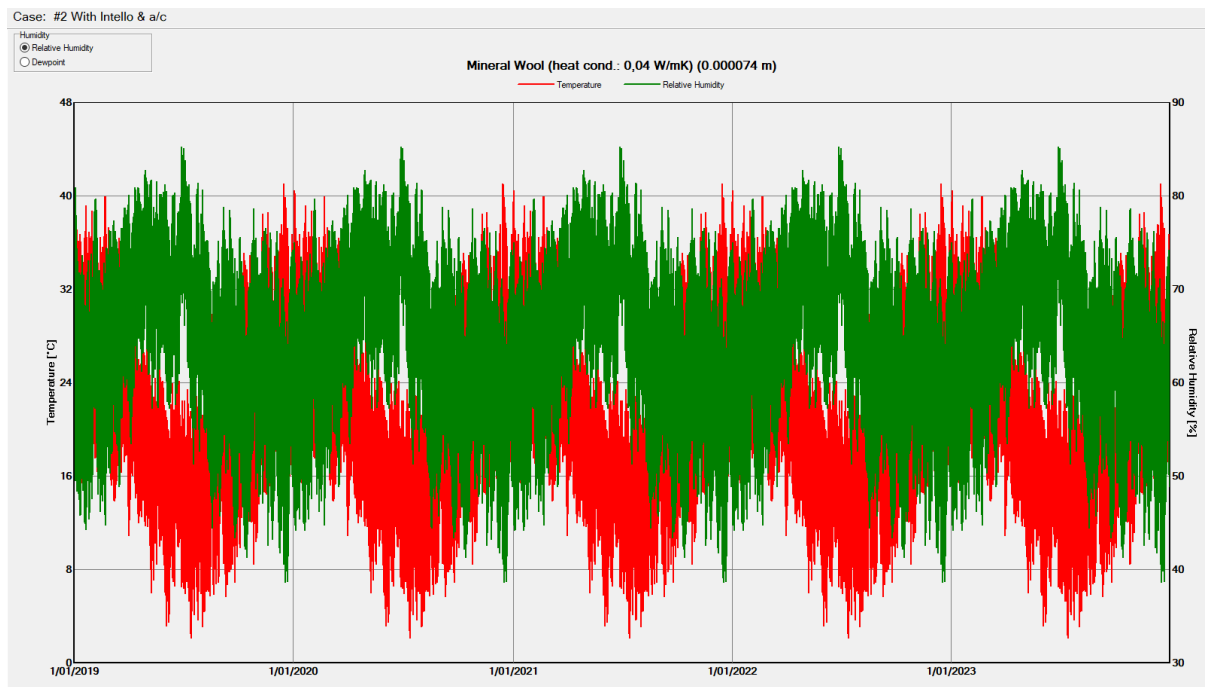
Figure 27: Temperature and humidity in the outer layer (5mm) of the insulation, Model B

This model shows increased likelihood of saturation (100% RH) from the previous case (Model A) at some periods throughout the analysis, particularly in the outer layer of insulation. This saturation is cyclical, and therefore dries out regularly.

## Model C: As-built with inclusion of smart air & vapour barrier to inside



**Figure 28:** Relative humidity and temperature over time, Model C



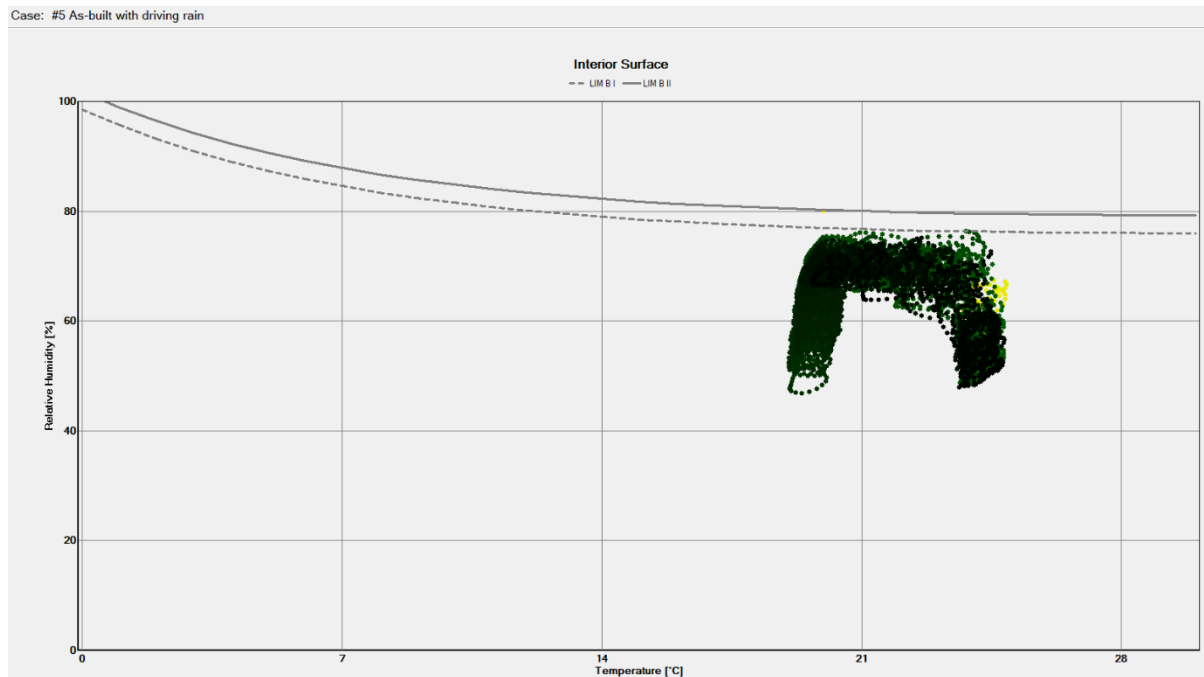
**Figure 29:** Temperature and humidity in the outer layer (5mm) of the insulation, Model C

The level of humidity in this version of the construction is much lower and remains below 80%, indicating that this construction is low risk.

### C.4 ASSESSING POTENTIAL FOR MOULD GROWTH

For each installation typology, the potential for mould at the internal surface was also observed, utilising the Isoleth charts generated in WUFI. The below charts depict the mould risk, assessing the internal ceiling surface and the moisture content, indicating risk of either material degradation or mould.

A “safe” determination occurs where the green chart of remains below the LIM (Lowest Isopleth for Mould) curves across the entire simulation (5 years).



**Figure 30:** Isopleths (mould risk) for as-built scenario (Model A), assessed at the internal surface

The isopleths charts show that, at all times and across all models, the risk of mould on the inner wall surface is low. This is true for the modelled detail, it is important to note that areas of substantial thermal bridging may cause low temperature that support mould growth. These specific conditions have not been captured in the modelled undertaken.