LOW CARBON LIVING
CRC

RP1041: Improving the thermal performance of dwellings for carbon positive and healthy homes

Understand the local climate, design for it and build to perform

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- conformity with the principles of the Australian Code for the Responsible Conduct of Research (NHMRC 2007),

and provided constructive feedback which was considered and addressed by the author(s).

Contents

List of Tables

List of Figures

Acronyms

ABCB	Australian Building Code Boards
ASBEC	Australian Sustainable Built Environment Council
BASIX	Building Sustainability Index
CO_2	Carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DTS	Deemed-to-satisfy
EFMY	Ersatz Future Meteorological Year
ERV	Energy recovery ventilation
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel for Climate Change
LBNL	Lawrence Berkeley National Laboratory
NatHERS	Nationwide House Energy Rating Scheme
NCC	National Construction Code
NSW	New South Wales
PVC	Polyvinyl Chloride
SHGC	Solar Heat Gain Coefficient
SRES	Special Report on Emissions Scenarios

Executive Summary

Energy consumption in the building sector is significant as people are spending a considerable amount of time indoors. The share of the residential sector's energy consumption is around 11% of the total energy consumed in Australia (Commonwealth of Australia 2017) to fulfil household energy requirements. The largest share of that energy consumption is used to maintain indoor thermal comfort (Pipkorn 2019). In future, energy demand for maintaining thermal comfort within a dwelling, particularly for space cooling, will be higher due to global warming (and localised urban heat island effects) if the building design and construction methods are not appropriated to address this requirement urgently.

Decarbonising Australian dwellings would require a significant reduction or elimination of energy consumption for space conditioning. The Australian Government has taken initiatives to improve thermal performance of the building shell through the National Construction Code (NCC). However, the actual energy performance (at post-occupancy stage) of dwellings is often higher than the estimated energy consumption at the design stage (Ding, Upadhyay et al. 2019). Among many factors which influence space heating and cooling energy consumption in dwellings, the impact of changing climatic conditions cannot be ignored.

This study maintains that understanding the local climate is the significant step in developing energy efficient design and construction methods to address the growing energy needs in a dwelling. This study provides a guideline for improving thermal performance of the dwellings while ensuring that a healthy indoor environmental condition is maintained. Taking a case study of Richmond in NSW, the study will first analyse local climatic conditions (*understand the local climate*), then it will recommend strategies for a suitable design for that climate (*design for the local climate*) and finally it will discuss building compliance issues that are important for an energy efficient building (*build to perform*).

The first part of the study, *understand the local climate*, highlights the changing climatic conditions. It demonstrates that by comparing the current NatHERS weather file with the future climate scenario for 2030 based on the CSIRO Mk3.5 model. The model takes an A1B (medium CO_2 emissions peaking around 2030) of the Intergovernmental Panel for Climate Change (IPCC)'s Special Report on Emissions Scenarios (SRES) with an assumption of a moderate rate of global warming (Gordon, O'Farrell et al. 2010, Clarke, Heady et al. 2014). Climate data is presented in a simplified graphical form which will help inform built environmental professionals about the future climate outlook.

The second part of the study, *design for the local climate*, outlines adaptive design strategies that would suit future climatic conditions. Future climate scenarios suggest a longer warm period with increased (heat) discomfort conditions and a shorter cool period in Richmond. AccuRate, a NatHERS accredited software, is used to simulate the thermal performance of a dwelling using the current NatHERS weather file and also the future climate scenario. The results of the simulation demonstrate a significant rise in the cooling load and a drop in the heating load. An optimised design for 2030 is developed by upgrading to energy efficient construction systems. However, the high performing design for 2030 does not comply with the current BASIX heating threshold when modelled in the current NatHERS weather file. This highlights the need to revise current legislation to encourage a better design that suits the future climate context.

The third part, *build to perform*, discusses design and construction issues which are often ignored or get less priority at the design or construction stages. These issues, however, significantly influence overall thermal comfort condtions in dwellings. The issues covered in this part are related to building assemblies, building airtightness, insulation installations, air-conditioning ducting and ventilation in the dwellings.

This study presents an adaptive approach for designing and constructing an energy efficient dwelling with a healthy indoor environment that responds to future climatic conditions embraced by the medium CO_2 emissions scenario.

Introduction

Energy consumption reduction in buildings is one of the major challenges as they consume a significant proportion of total energy demand. Globally, the residential sector is responsible for about a quarter of the total final energy consumption (International Energy Agency 2014). Australian dwellings consumed around 11% of the total energy (Commonwealth of Australia 2017) to fulfil household energy requirements. In the State of New South Wales (NSW), dwellings also consumed around 11% of the total energy – the largest contributor of greenhouse gas (GHG) emissions in NSW. The largest share of energy consumption in dwellings is to maintain indoor thermal comfort (Pipkorn 2019). Energy demand for space conditioning, particularly for cooling is on the rise, as Australia has experienced record-breaking summer temperatures in recent years (Ding, Upadhyay et al. 2019). Moreover, the impact of global warming and the localised urban heat island effect will be responsible for further increase in energy consumption in dwellings if building design and construction methods are not addressed urgently.

Previous research also suggests various strategies to reduce energy consumption in dwellings, including focussing on the building design to significantly reduce energy consumption for space heating and cooling. Beyond Zero Emissions and Melbourne Energy Institute (2013) presents a series of energy reduction strategies and a road map to decarbonising the Australian building sector. More recently, Build to Perform (Australian Sustainable Built Environment Council and ClimateWorks Australia 2018) outline building energy reduction strategies through stringent building codes to encourage current buildings to perform well in future climates.

The above-mentioned reports argue for significantly reducing or eliminating energy requirements for space conditioning through high performing building envelopes. However, the recommendations of these studies are prescriptive and give a very little opportunity for designers or builders to understand the main issues that need to be addressed in order to achieve energy efficiency. Among many factors that influence energy efficiency in buildings and their thermal performance, the most important ones are: local climate change, building design and construction quality.

This study takes the case of Richmond in Western Sydney and presents a framework by analysing the local climatic conditions in Part 1 (*understand the local climate*), then recommend suitable design strategies for that climate in Part 2 (*design for the local climate*) and finally discusses building compliance issues that are important for an energy efficient and healthy building in Part 3 (*build to perform*).

Part 1 - Understand the local climate

Local climate is an important factor in building energy efficiency considerations. Harsh climatic conditions necessitate buildings to be isolated from the outdoor environment and thermal comfort to be maintained using mechanical means. On the other hand, composite climates require flexible design solutions whereby the buildings can be isolated during uncomfortable conditions and opened to the outdoors when the weather is favourable.

Within the Greater Sydney Area, there are three NatHERS climate zones; i.e. climate zone 56 (Mascot) which primarily covers eastern Sydney and coastal areas, climate zone 17 (Sydney CBD) and climate zone 28 (Richmond) which covers a wide geographical area from the north-west to south-west of the Greater Sydney Area. Weather data from Richmond is used for building energy simulation from west of Port Macquarie to west of Wollongong in NSW. However, variations in local geographical conditions, terrain and micro-climate in the 500 km stretch are not uncommon and greatly influence building design and its performance. In the last few years, the majority of residential construction has been taking place in Western Sydney; therefore, this study takes Richmond climate data for further analysis. The extent of NatHERS climate zone 28 and the location of Richmond in the context of the Greater Sydney Area is shown in Figure 1.

Figure 1: Location of Richmond RAAF base weather station in the context of NatHERS climate zone 28. The inset map shows the Greater Sydney Area (Source: Google image 2019).

Generally, Richmond experiences both warm and cool periods, whilst historically, the cool period was the most dominant. However, a seasonal shift in local weather patterns has been observed in Richmond, as the cool period has shrunk and the warm period has extended. In recent years (2016-2018), Richmond has experienced around 1.2K* annual average temperature rise compared to the NatHERS weather file which is used for building energy simulation for thermal comfort. The temperature anomaly was the highest in the warm period (Dec-Mar) with 1.7K and the lowest in the cool period (Jun-Aug) with 0.8K higher than the NatHERS weather file (Figure 2). The NatHERS weather file is used by the National Construction Code (NCC) of Australia for building energy efficiency assessment. A recent report (Ding, Upadhyay et al. 2019) outlined a discrepancy in weather data used in the NatHERS tool which has resulted in significantly higher energy consumption at post-occupancy stage. Therefore, it is necessary to understand the future climate outlook for Richmond to develop carbon neutral or carbon positive buildings in this climate zone.

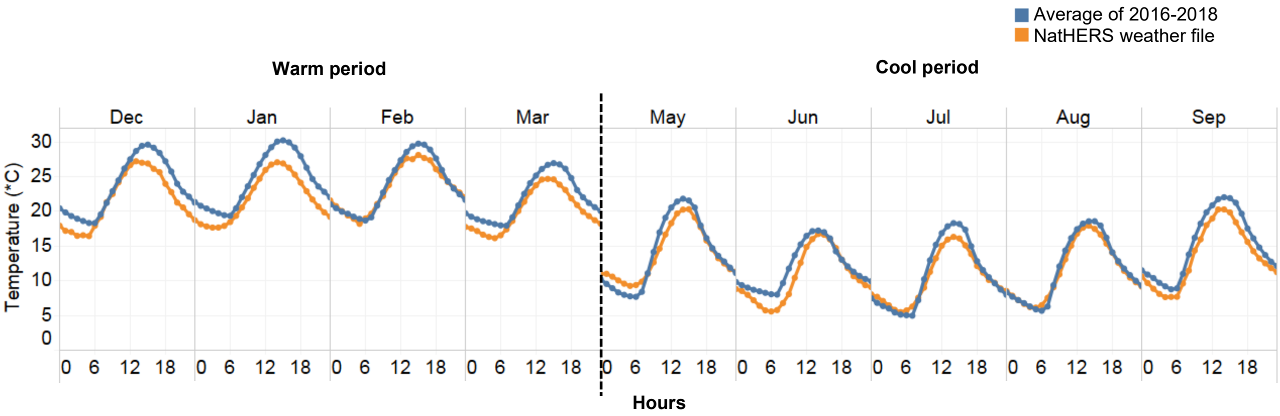

Figure 2: Temperature anomaly between the NatHERS weather file and the average of the last three years (2016-2018) in NatHERS climate zone 28 (Richmond)

1.1. Current and future climate outlook of Richmond

For carbon neutral or carbon positive buildings, it is important to consider future climatic scenarios to make the buildings future proof. A comfort-based climate analysis (Upadhyay 2018) was carried out on the NatHERS weather file (1976-2004) and the Ersatz Future Meteorological Year (EFMY) 2030 climate data (Lee 2011) (Figures 3 and 4). The EFMY for 2030 used the CSIRO Mk3.5 model which takes an A1B (medium CO_2 emissions peaking around 2030) from the IPCC's Special Report on Emissions Scenarios (SRES) with the assumption of a moderate rate of global warming (Gordon, O'Farrell et al. 2010, Clarke, Heady et al. 2014). Hourly temperature and humidity data determine comfort conditions for each hour, which are presented on a weekly basis to demonstrate the gradual change in weather outlook for a year. The current NatHERS weather file shows four weeks (weeks 3 to 6) of warm period, 30 weeks (weeks 15 to 44) of cool period and 18 weeks (weeks 45 to 2 and weeks 7 to 14) of the intermediate period, which are mostly comfortable (Figure 3).

The 2030 weather data for Richmond shows a 15 week long (weeks 50 to 12) warm period with consistently 'moderate to high' heat discomfort conditions. In 2030, Richmond would experience a cool period for 22 weeks (weeks 18 to 39) with relatively less 'severe' cold discomfort conditions (Figure 4).

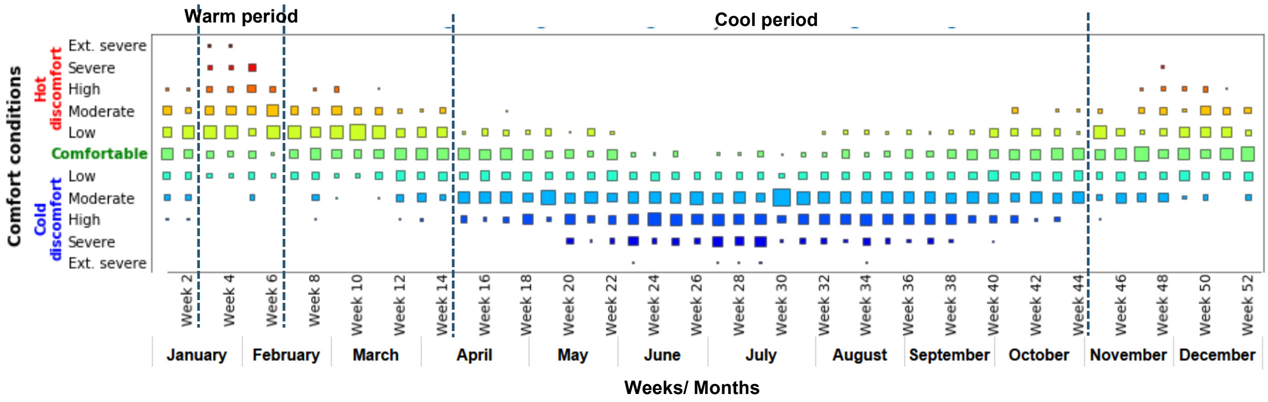

Figure 3: Analysis of the NatHERS weather file for Richmond using comfort conditions based on temperature and humidity

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*'K' denotes Kelvin to represent temperature difference

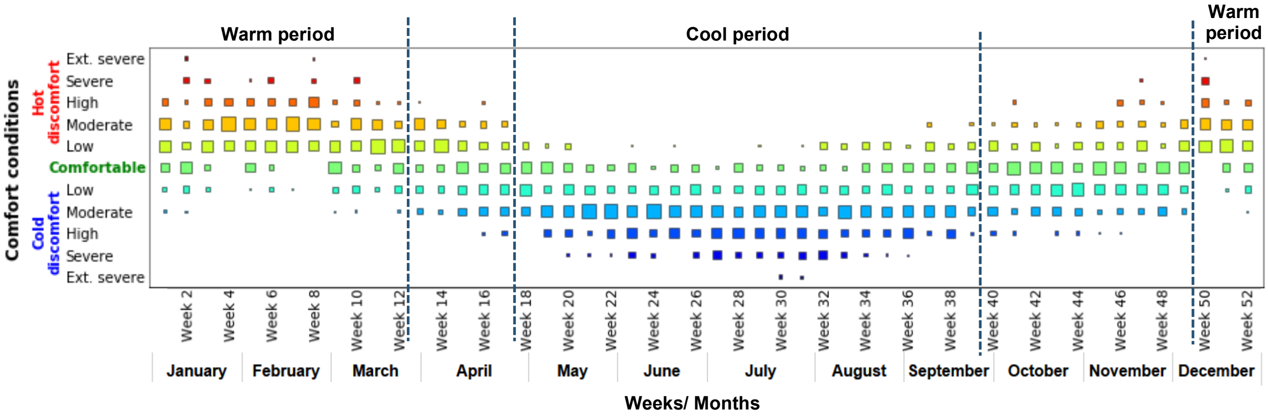


Figure 4: Analysis of the future weather file (2030) for Richmond using comfort conditions based on temperature and humidity

1.2. Thermal environmental conditions in Richmond

For building designers, it is necessary to understand the thermal environmental conditions that cause discomfort. Generally, temperature and humidity contribute to thermal discomfort. The role of humidity will be more prominent in higher temperature than in lower temperature bands. An analysis reveals that the discomfort conditions in the warm period in Richmond is primarily due to high humidity, and not to high temperature alone (Figures 5 and 6). However, during heatwaves, high temperature causes discomfort which usually lasts for a few hours in a day.

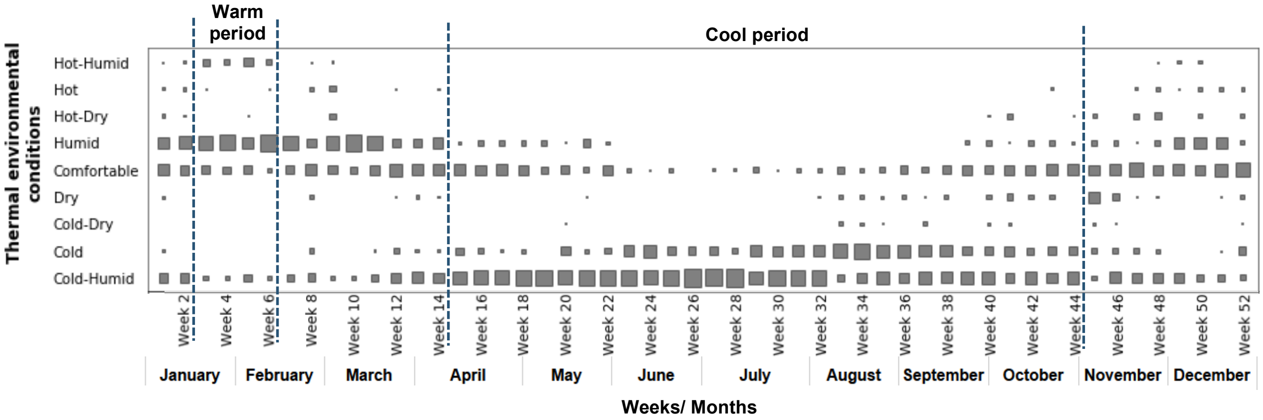


Figure 5: Analysis of thermal environmental conditions for NatHERS weather file based on temperature and humidity

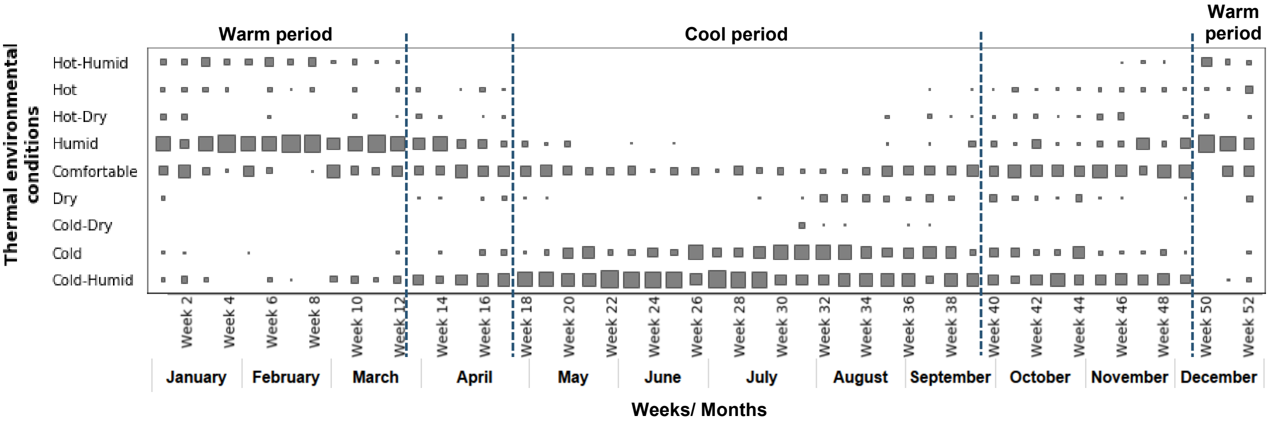


Figure 6. Analysis of thermal environmental conditions centred on the future weather data (2030) based on temperature and humidity comfort zones.

1.3. Solar exposure in Richmond

A passive solar design for a composite climate (such as Richmond) would need to utilise solar radiation in the cool period and avoid it during the warm period. Based on a 2030 climate outlook, a building in Richmond can benefit from solar exposure for 22 weeks (weeks 18 to 39) but should avoid it for the rest of the year, particularly during the warm period (weeks 50 to 12).

Figure 7 illustrates the solar exposure on a building during the cool and warm periods. The intensity of solar radiation from the north is the highest (4kWh/m²) in the cool period and can be incorporated to warm interiors by strategically placing the windows on the northern façade (within the NE to NW). The amount of solar radiation on the vertical surfaces (walls) drops significantly when moving away from the NE and NW (Figure 7). South orientation receives the least amount of radiation and mostly consists of diffuse radiation.

During the warm period, the west wall receives (within SW to NW) the highest amount of solar radiation (>3kWh/m²). This needs to be avoided through building design, placement of windows and window shading. The eastern (NE to E) faced also receives around 3kWh/m²; however, the amount of radiation drops significantly after moving away from the SE (Figure 7). The southern facade receives the least amount of radiation in the warm period too.

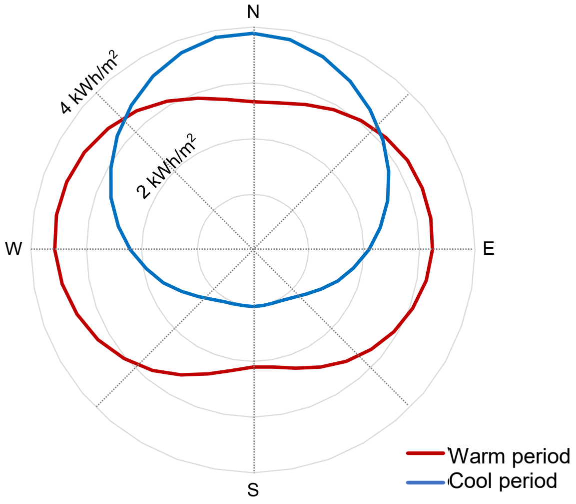


Figure 7. Solar radiation at different orientations in warm and cool periods in Richmond

1.4. Wind in Richmond

Wind is one of the highly unpredictable climatic elements, and 25 years of hourly wind data were analysed to prepare wind roses (Figures 8, 9 and 10). Wind direction in Richmond varies significantly during cool and warm periods. During the warm period, the wind primarily blows from the east and south with 21% calm period which mostly occurs at night-time.

During the cool period, westerly and southerly winds are prominent; however, calm periods apply 33% of the time, mostly during evenings and mornings. The westerly wind brings cold air from inland areas.

In the intermediate periods (in between warm and cool periods), the wind patterns almost resemble the warm period wind directions.

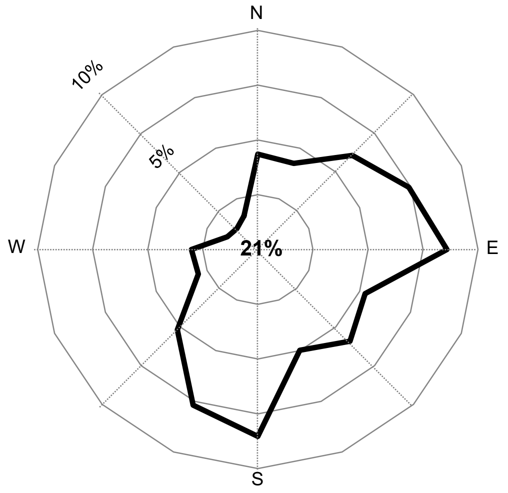


Figure 8. Wind rose for the warm period in Richmond

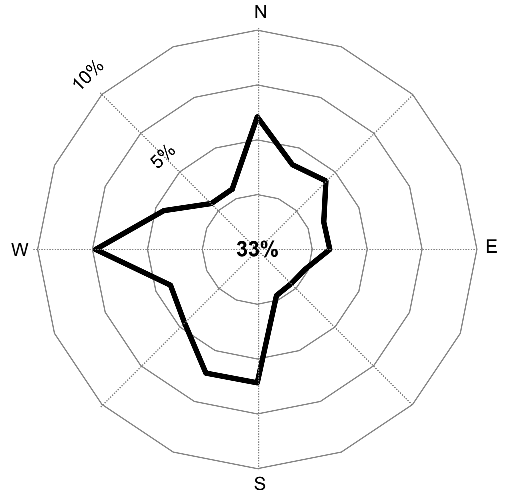


Figure 9. Wind rose for the cool period in Richmond

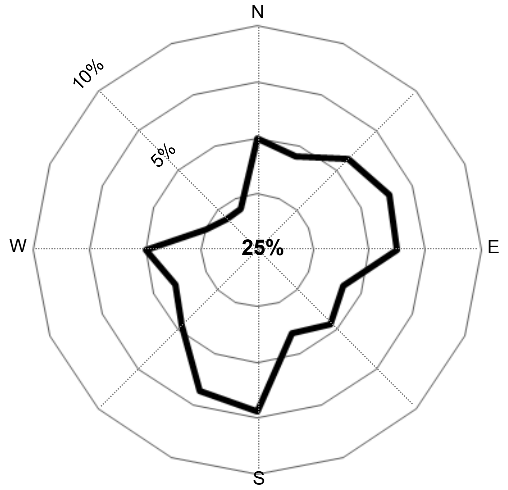


Figure 10. Wind rose for the intermediate periods (April, October and November) in Richmond

1.5. Rainfall in Richmond

Long term (23 years) rainfall data was analysed to understand the rainfall pattern in Richmond (Figure 11). On average, Richmond received 735 mm of rainfall annually. However, around half of the total precipitation was received in the warm period (four months). The intensity of rainfall was also the highest around February and March. The cool period in Richmond received the lowest amount of rainfall. The number of rainy days (>1 mm rainfall) in warmer months was 27% of the total days, whereas the number of rainy days in the cool period was 16% of the total. In the last 23 years, there were four occasions when Richmond received more than 100 mm of rainfall within a 24 hour period.

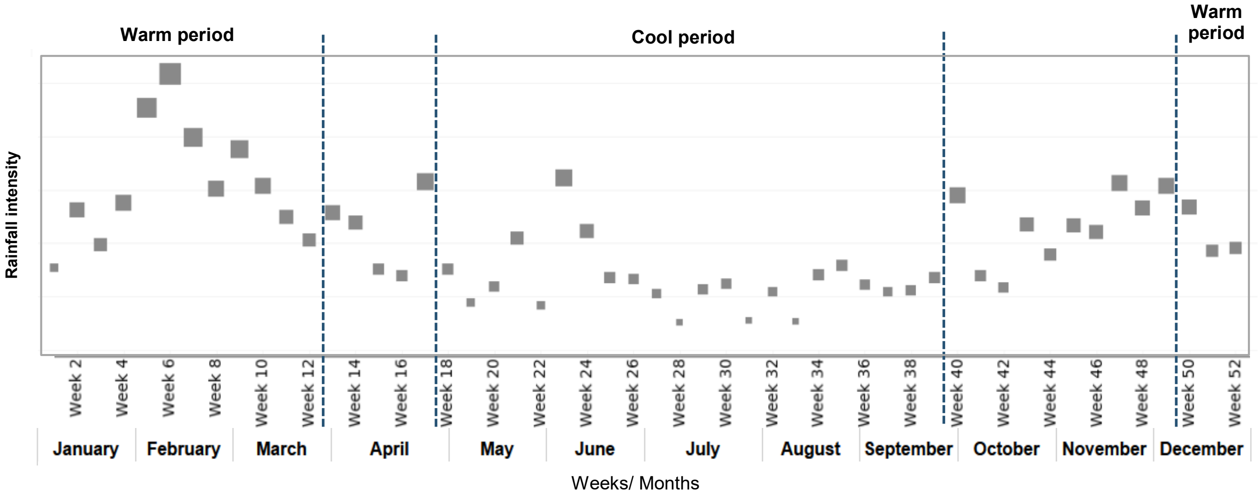


Figure 11. The annual rainfall pattern in Richmond

1.6. Summary

The future climate of Richmond presented here looks strikingly different than the climate currently portrayed by the NatHERS weather file. The NatHERS weather files are important, as this data is used for simulating dwellings to demonstrate compliance to the building code for thermal performance. In 2030, Richmond will experience a warm period almost four times longer than is informed by the NatHERS weather file. High humidity will be the major cause of discomfort, followed by hot-humid conditions in Richmond. The cool period will be shorter in 2030 with an extended comfort period in the afternoon and less severe discomfort at night and in the morning. Solar radiation from the east and the west will be most dominating in the warm period, whereas, the north façade will receive most radiation in the cool period. Wind is a less reliable option for ventilation as well as for purging heat from thermal mass within the buildings. Wind mostly blows from different directions with low speed (i.e. <5m/s). In urban areas, the effect of the wind will be significantly less, as the buildings are often grouped close to each other. Rainfall pattern in Richmond demonstrates a concentrated rainfall during the warm period and it is mostly dry during the cool period.

This information is important for designers and builders to produce resilient buildings for the future climatic conditions of Richmond. Part 2, ‘Design for the local climate’, outlines design strategies based on the future climate outlook of Richmond.

Part 2 - Design for the local climate

Based on the climate analysis presented in Part 1, it is clear that the buildings in Richmond need to respond to both warm and cool conditions. Figure 12 shows hourly temperature and humidity data plotted on a psychrometric chart for the future (2030) climate. The chart shows that, in general, April, October and November are thermally comfortable months. A period between December and March is humid and hot-humid which would result in heat discomfort, mostly experienced from late morning until evening.

The cool period extends for almost five months (May to September) and can be cold, especially at night and in the early morning. In the cool period, the daytime remains mostly clear and receives a fair amount of solar radiation for passive solar heating.

High humidity in the air is a dominating issue in Richmond and causes discomfort. In the cool period, high relative humidity indoors causes condensation in cold spots such as glazing and cold wall/ceiling surfaces. High humidity conditions are favourable for microorganisms that cause allergies and may be especially harmful for occupants with asthma.

Table 1 summarises outdoor thermal conditions, corresponding comfort conditions, design requirements and design strategies for Richmond considering 2030 climate outlook. Table 2 presents detailed climate design strategies for Richmond based on climatic variables discussed in Part 1.

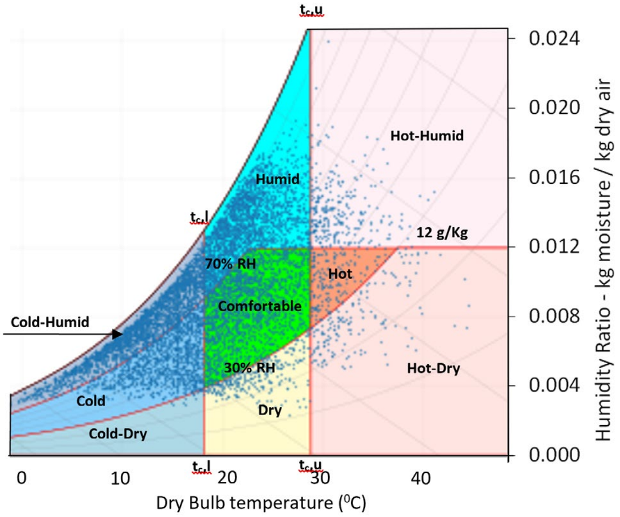


Figure 12. Hourly temperature and humidity data (2030) plotted on a psychrometric chart overlayed with various thermal environmental conditions

Table 1: Broad design strategies and recommendations for Richmond based on 2030 climate outlook

Outdoor thermal conditions	Comfort conditions	Dominant period	Design requirements	Design strategies and recommendations
Cold-Humid, Cold (46% of the time/yr.)	Cool	Late April to late September	Heating may be required.	Passive solar heating strategies • Maximise solar heat gain from northern facades; • Use thermal mass to retain warmth; • Well-insulate walls, floor and ceiling; • Reduce air-infiltration.
Humid and Hot-Humid (26% of the time/yr.)	Warm	December to March	Dehumidification required	• Use hygroscopic (moisture absorbing) building materials; • Reduce external/internal heat gain; • Minimise moisture generating activities indoors; • Minimise direct ventilation; • Reduce air-infiltration; • Install energy recovery ventilation (ERV) system (if necessary).
Comfortable (21% of the time/yr.)	Comfortable	Around 5 – 7 hours per day during daytime in April and October – November	Outdoor living spaces can be integrated with the indoors	• Maximise outdoor air for ventilation

Table 2: A summary of recommended architectural characteristics and physical attributes for Richmond

Climatic variables	**Layout** (Orientation, topography)	**Spatial configuration** (Room positioning, alfresco, pergolas, verandas, patios, courtyards, terraces and balconies)	**Fabric/ envelope** (Perimeter insulation, wall systems, ventilation, roof design and insulation, sun shading for windows and western façades)	**Form, structure, & materials** (Volume, height, roof, walls and floor)
Temperature and humidity: Moderate to high level of discomfort due to predominantly high humidity in the warm period Moderate to high level of discomfort in both the warm & cool periods	• Building layout should avoid heat gain in the warm period and allow solar penetration in the living areas in the cool period.	• Temperature controlling measures can be undertaken using room positioning, design variations and outdoor shading elements; • Daytime living spaces should be oriented towards the north and other non-daytime use spaces can be allocated to the east and the west; • Services can be located to the south; however, if living spaces need to be located there, design may utilise clerestory windows to the north and skylights can be incorporated to allow solar penetration in the cool period; • Moisture control is required in living areas. Kitchens, bathrooms and laundries need to be segregated from the living areas to avoid moisture flow to the living areas when necessary.	• Perimeter insulation is a key to avoid infiltration/ exfiltration, particularly in the air-conditioned spaces; • Based on outdoor environmental conditions, specific details need to be developed for walls orientated differently to avoid heat gain/ loss and moisture and water penetration; • Due to high humidity in the warm period, direct ventilation may not be suitable. In addition, Richmond only experiences a low wind speed (<5m/s); therefore, a dedicated low energy mechanical ventilation system may be required; • Metal/ Tile roof with roof insulation (sarking) can help to achieve air-tight attic space as well as it creates a thermal barrier. Further, ceiling insulation can help to thermally isolate living and attic spaces.	• Double storey dwellings are preferred as they have almost half the roof area and receive half the amount of solar radiation from the roof compared with single storey dwellings; • A balance between the north facing window area and the amount of thermal mass in internal walls can contribute towards building energy efficiency in Richmond; • A strategically placed internal thermal mass, i.e. thermal mass exposed to the sun for space heating and thermal mass protected from sunlight for space cooling, are effective in maintaining indoor thermal comfort in both cool and warm periods; • Similar to the roof, an air-tight floor is expected for thermal efficiency of a building. A solid floor (e.g. concrete or tile) is preferable to a timber subfloor; • Building height should be at least 2700 mm to accommodate ceiling fans to achieve thermal comfort in warm (humid) period.
Solar radiation and glare Warm period is often cloudy and therefore glary. Cool period is mostly sunny and pleasant.	• Building layout should maximise north facing walls for solar heat gain and roof for photovoltaic panels/ solar hot water system installations.	• Outdoor covered areas can be arranged in such a way that the northern exposure of rooms can still be maintained for solar heat gain; • Based on site opportunities and constraints, an outdoor semi-covered area to the eastern/ western sides of the building can help to control low angle sun penetrating into the living areas while also creating outdoor living spaces.	• Western walls should be shaded appropriately to avoid unnecessary heat gain in the warm periods; • Western walls should have higher R-value than the northern walls to withstand high heat gain if it is unshaded; • All windows should be appropriately shaded to avoid heat gain in the warm period; however, arrangements should be made to allow sun penetration in the cool period.	• The solar load on each façade should be carefully considered as well as the window types (frames, glazing and opening arrangement); • The western façade will benefit from using reflective glass, whereas double glazing will be appropriate for southern windows; • Thermally broken window frames are beneficial in both the warm and the cool periods.

Table 2: A summary of recommended architectural characteristics and physical attributes for Richmond (Contd…)

<table>
<tr><th>Climatic variables</th><th>Layout
(Orientation, topography)</th><th>Spatial configuration
(Room positioning, alfresco, pergolas, verandas, patios, courtyards, terraces and balconies)</th><th>Fabric/ envelope
(Perimeter insulation, wall systems, ventilation, roof design and insulation, sun shading for windows and western façades)</th><th>Form, structure, & materials
(Volume, height, roof, walls and floor)</th></tr>
<tr><td>Wind speed and direction
Mostly light winds (<5m/s) and scattered wind directions</td><td colspan="4">• Due to low wind speed and variable wind directions, direct ventilation may not be as effective and therefore its influence in design decision is considered to be insignificant. However, casement windows would be better than the top/bottom hung windows for catching breezes during the comfortable periods.</td></tr>
<tr><td>Rainfall
The warm period receives the most rainfall and cool period receives the lowest in Richmond</td><td colspan="4">• Building design should address gutter and drainage design given the high intensity rainfall that may occur in Richmond;
• Appropriate overhangs should be provided to protect the walls and the openings from rain.</td></tr>
</table>

2.1. Thermal performance evaluation at the design stage

The National Construction Code (NCC) requires new buildings to demonstrate an acceptable level of thermal performance at the design stage, either through deemed-to-satisfy (DTS) provisions or using a NatHERS accredited simulation tool. DTS is a prescriptive method which outlines the thermal properties of floors, walls, roof and glazing for different climate zones. In the simulation method, the designer will have greater flexibility and can demonstrate the overall thermal performance of the dwelling by star rating or cooling and heating loads based on the floor area.

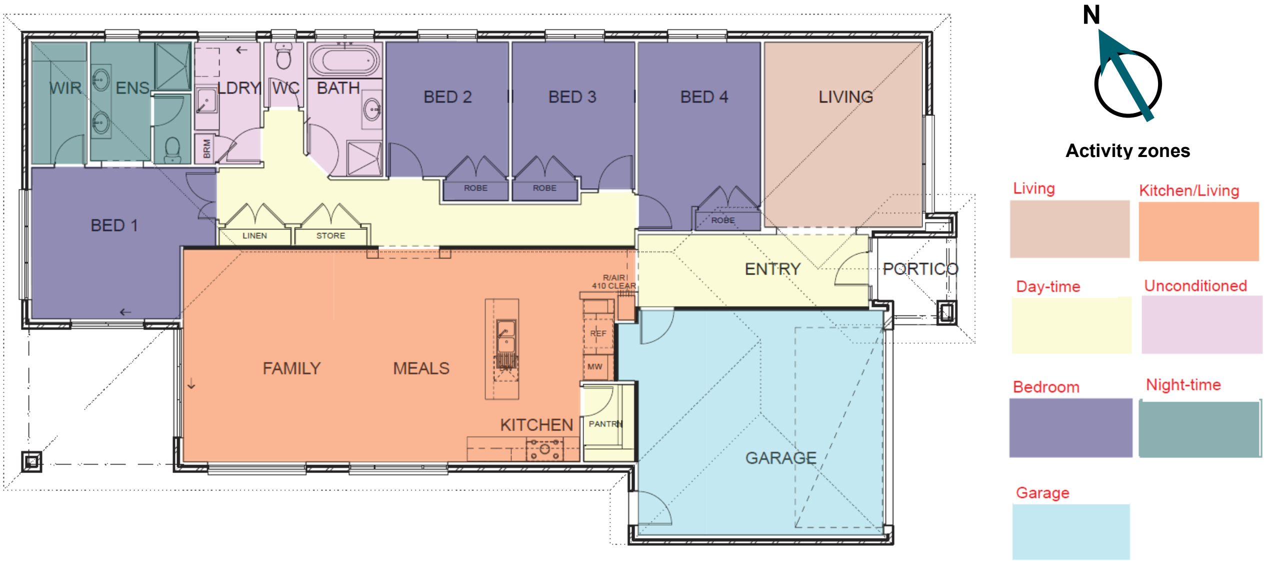


Figure 13. Plan of the NatHERS Demonstration House 1. The model of the house comes with the AccuRate software.

2.1.1. NatHERS thermal simulation of a house

A NatHERS Demonstration House, which comes with AccuRate software, has been used to simulate and compare the thermal performance of the dwelling using current NatHERS weather file, last ten years of actual weather conditions and EFMY for 2030 based on the CSIRO Mk3.5 model (Gordon, O'Farrell et al. 2010, Lee 2011). Figure 13 shows the building layout and an identification of different activity zones for the thermal performance simulation in AccuRate software.

The NatHERS Demonstration House 1 is a single storey brick veneer house with timber framed single glazed windows, R4.0 ceiling insulation, and R2.5 wall insulation with reflective air gap and a tiled roof. The building has 596mm eaves. A concrete waffle slab is used as the base floor and timber is used as the floor finishing in the living/meal/kitchen areas. The bedrooms, walk-in robes and living zone are carpeted. The laundry, bathroom and ensuite floors are all tiled. Internal walls to the garage have R2.5 insulation. The design of this house resembles a standard project home; however, it has used slightly higher construction specifications to achieve better thermal performance.

The model was simulated for four different orientations, i.e. N (original, as shown in Figure 12) and at 90° ani-clockwise rotations – W, S and E. All iterations complied with the current heating and cooling thresholds (i.e. 55.7 MJ/m^2 for heating and 56.2MJ/m^2 for cooling) prescribed under the BASIX protocol (NSW Government 2019) and demonstrated an acceptable star rating of ≥ 6 stars under the NCC. Table 3 shows the results with the star rating and heating and cooling loads. The overall thermal performance of this house is almost the same for all four rotations. All four orientations were modelled throughout the study; however, the results for the original orientation (as in Figure 13) are presented in this section.

Table 3: The simulation results of NatHERS Demonstration House 1

Orientations	Heating (MJ/m2)	Cooling (MJ/m2)	Total (MJ/m2)	Star rating	BASIX compliance
N	39.2	37.4	76.6	6.5	Yes
W	45.3	38.1	83.4	6.5	Yes
S	41.4	40.6	82.0	6.3	Yes
E	36.3	38.4	74.7	6.6	Yes

The NatHERS Demonstration House 1 was then simulated using yearly weather data from 2008 to 2017. The future climate scenario (EMFY – 2030) was compared with the average for 10 years (2008-2017) and a more recent 5-year period (2013-17). These simulations (Table 4) revealed a consistent reduction in heating loads compared to the current NatHERS weather file:

- 4% reduction for the 10-year average scenario
- 15% reduction for the 5-year average scenario
- 46% for the future scenario (2030).

However, cooling demand increased significantly in the more recent years as well as for the future climate scenario. The increase in the cooling load was:

- 21% for the10-year average scenario
- 41% for the 5-year average scenario
- 81% for the future scenario (2030).

The recent summer (i.e. 2018/19) was the hottest summer experienced in Australia (Commonwealth of Australia 2019). Due to the unavailability of the recent (2018/19) weather data file, it was not possible to calculate the actual cooling load for the most recent year. However, 2017 was also one of the hottest years recorded and the results revealed that the building required 89% more cooling energy than that of the current NatHERS weather file.

However, the different climate scenarios result in an almost similar total energy demand and therefore negligible difference in the star rating of the house. The cooling energy load for the 2030 future climate scenario requires 67.7 MJ/m^2 which exceeds the current BASIX cooling threshold of 56.2 MJ/m^2 and therefore, fails to meet the BASIX requirements.

Table 4: Thermal performance of the NatHERS Demonstration House 1 using different climate scenarios

Climate scenarios	Heating (MJ/m^2)	Cooling (MJ/m^2)	Total (MJ/m^2)	Star rating	BASIX compliance
Current NatHERS weather file (1976-2004)	39.2	37.4	76.6	6.5	Yes
10-year average (2008-17)	37.8	46.8	84.6	6.3	Yes
5-year average (2013-17)	33.3	52.8	86.1	6.2	Yes
EFMY - 2030 based on the CSIRO Mk3.5 model	21.0	67.7	88.7	5.9	No (exceeded cooling threshold of 56.2 MJ/m^2)

Further simulations were carried out to model the thermal performance of the house using the current typical build specifications, with R3.5 ceiling insulation, aluminium single glazing, concrete slab on ground, dark metal roof with an R1.3 anticondensation blanket and 450 mm eaves. These changes result in the increased heating and cooling loads as shown in Table 5.

Table 5: Thermal performance of the NatHERS Demonstration House 1 adapted for the future climate scenario (2030)

Climate scenario	Building details	Heating (MJ/m^2)	Cooling (MJ/m^2)	Total (MJ/m^2)	Star rating	BASIX compliance	Construction/ shading
EFMY - 2030 based on the CSIRO Mk3.5 model	NatHERS Demonstration House specification	21.0	67.7	88.7	5.9	No (Exceeded cooling threshold of 56.2 MJ/m^2)	• Walls: R2.5 • Ceiling: R4.0 • Glazing: timber/ single • Floors: waffle slab + carpet (in bedrooms) & timber (living area) • Roof: dark tile with 596mm eaves
	Current typical build	28.7	75.9	104.6	5.3	No (Exceeded cooling threshold of 56.2 MJ/m^2)	• Walls: R2.5 • Ceiling: R3.5 • Glazing: aluminium/ single • Floors: concrete slab + carpet (in bedrooms) & timber (living area) • Roof: dark metal with R1.3 anticondensation blanket / 450mm eaves
	Fully optimised for 2030	30.8	22.4	53.2	7.6	Yes	• Walls: reverse brick veneer (R2.5) • Ceiling: R4.0 • Glazing: timber/ Insulated glass unit (IGU) with low-e, high SHGC • Floors: concrete slab + carpet in bedrooms • Roof: light metal with R1.3 anticondensation blanket/ 750mm eaves

The third simulation used EFMY - 2030 as a basis for investigating strategies to reduce the increased cooling load. The construction upgrade was carried out on a step by step basis which included increased internal thermal mass, increased horizontal shading with 750mm eaves and the use of low-e and high Solar Hear Gain Coefficient (SHGC) double glazing in a timber frame and a light metal coloured roof with an R1.3 anticondensation blanket. With the above-mentioned changes, the cooling load was reduced by 70% with marginal increase in the heating load. Overall, this dwelling achieved 7.6 stars and satisfied the current BASIX cooling threshold too.

The construction variations carried out on the NatHERS benchmark house to suit a future climate scenario was again simulated using the current NatHERS weather file to investigate its applicability in the present context. Table 6 summarises the results. The current NatHERS weather file estimated significantly higher heating loads for both current typical build as well as for the fully optimised construction for 2030. Due to the current BASIX heating threshold, the modified building would not comply with the BASIX requirements.

Table 6: Thermal performance of the NatHERS Demonstration House 1 adapted for the future climate scenario (2030): modelled using the current NatHERS weather file

Climate scenario	Building details	Heating (MJ/m^2)	Cooling (MJ/m^2)	Total (MJ/m^2)	Star rating	BASIX compliance	Construction/ shading
Current NatHERS weather file (1976-2004)	NatHERS Demonstration House specification	39.2	37.4	76.6	6.5	Yes	• Walls: R2.5 • Ceiling: R4.0 • Glazing: timber/ single • Floors: waffle slab + carpet (in bedrooms) & timber(living) • Roof: dark tile with 596mm eaves
	Current typical build	58.8	25.1	83.9	6.2	No (Exceeded heating threshold of 55.7MJ/m)	• Walls: R2.5 • Ceiling: R3.5 • Glazing: aluminium/ single • Floors: concrete slab + carpet (in bedrooms) & timber(living) • Roof: dark metal with R1.3 anticondensation blanket and 450mm eaves
	Fully optimised for 2030	61.5	6.9	68.4	6.9	No (Exceeded heating threshold of 55.7MJ/m)	• Walls: reverse brick-veneer (R2.5) • Ceiling: R4.0 • Glazing: timber/insulated glass unit (IGU) with low-e, high SHGC • Floors: concrete slab + carpet in bedrooms • Roof: light metal with R1.3 anticondensation blanket and 750mm eaves

2.2. Summary

The results obtained in Tables 5 and 6 demonstrate the issues associated with the weather files used in the building thermal performance simulation tool. The design and construction solution which performs well for heating and cooling for the 2030 scenario failed to meet the BASIX heating threshold. It is, therefore, not enough to simply focus on a good design (ASBEC & ClimateWorks Autralia 2018), but also, to amend regulations to promote better design and construction for the specific climate zone based on future climate scenarios.

If one considers a lifespan of around 50 years for each new house, it is imperative that the current designs take into consideration a significantly warmer future climate. However, the BASIX heating threshold puts a restraint on designing buildings that are fully optimised to mitigate extreme heat events and may impose costs and discomfort on householders through increased cooling demand as well as the increased infrastructure costs needed to service the additional energy demand for cooling. The simulations carried out in this study highlight the role of up-to-date climate files in designing more efficient building designs. On the other hand, out-of-date climate files, coupled with the current regulatory environment, become a real barrier to developing energy efficient designs for a future warmer climate.

Once a design that takes into account local climate conditions is finalised, it is necessary to pay attention to the construction quality of the buildings. A performance gap is often observed between estimated energy consumption and actual energy consumption in dwellings. The next section will discuss some of the design/ construction issues which must be addressed in achieving energy efficient buildings.

Part 3 – Build to perform

Construction quality for thermal performance is vital for building energy efficiency. Ding et al. (2019) highlighted the importance of building construction quality and its impact on building energy consumption for space cooling and heating. Trade workmanship has been recognised as one of the major issues that contributes towards poor construction quality. The National Construction Code (NCC) outlines a series of measures to ensure building energy efficiency at the design stage, rather than at the post occupancy stage. For example, building energy efficiency is demonstrated using standard protocols (Deemed-to-Satisfy or simulation methods) at the design stage, and actual performance at the post-occupancy stage is often ignored. NCC mandates a minimum of 6 Stars NatHERS rating for residential buildings' energy efficiency in Australia. However, there is no measure to undertake and validate whether the actual construction achieved mandated energy efficiency standards at the occupancy stage. If a building at post-occupancy stage has not achieved the same level of energy performance provided by the design criteria, then it is likely to require additional energy to maintain thermal comfort at the operational stage. As a result, the household would use additional energy for space conditioning and emit higher GHG emissions to the environment.

This section presents some of the energy efficiency non-compliance issues at the construction stage taken from some of the dwellings from the case study area. These non-compliance issues contribute towards energy inefficiency at building operation stage. This part of the study explores issues related to building assemblies, building airtightness, insulation installation, air-conditioning ducting and ventilation arrangements in dwellings. The construction issues are general in nature and can be applied in other locations of Australia too.

3.1. Building assemblies

Building assemblies refer to building fabrics such as walls, the roof, windows and the floors in a building. One of the common issues that contribute to building energy inefficiency is the lack of detailing to address environmental issues such as solar radiation, temperature levels, moisture movement, water penetration and airtightness at the construction stage.

3.1.1. Walls

NCC specifies a minimum R-value for wall assemblies irrespective of building orientations. However, east and west walls receive low angle sun, contributing to higher thermal load on these walls than the walls facing north in the warm period. Generally, the southern wall does not receive direct solar radiation in Richmond.

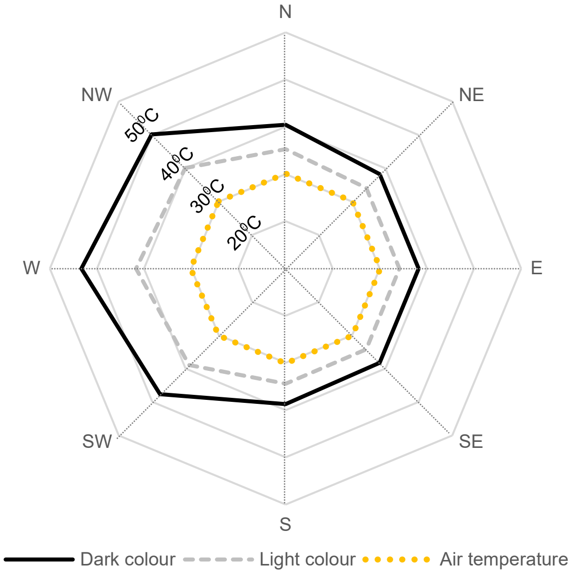


Figure 14. Average sol-air temperature on eight different wall surfaces for light colour (α=0.4) and dark colour (α=0.8). An afternoon hours period (2 PM - 6 PM) in January is taken for the sol-air temperature calculation.

Figure 14 demonstrates the sol-air temperature on light and dark coloured vertical walls facing different directions. To demonstrate the severity of heat gain in the afternoon, a four hours (2:00 PM – 6:00 PM) period in January was used for the calculation. The surface temperature of the walls facing NW, W and SW has at least 6K higher temperature than the light-coloured walls facing east. The temperature difference exceeds more than 12K for the dark coloured surfaces.

Table 7 illustrates heat flux through a standard brick veneer wall with a total of R2.4 wall insulation. THERM software (Lawrence Berkeley National Laboratory and University of California 2019) is used to determine the heat flux. In the afternoon, the western walls transmit almost the double the amount of heat flux to the interior compared with the eastern walls.

Table 7: Heat flux through eastern and western walls during afternoons in January (Outdoor temperature 30^0C and expected indoor temperature is 25^0C).

U-value of the wall = 0.41 W/m²K	East	West
Light colour	3.8 W/m^2	7.0 W/m^2
Dark colour	5.5 W/m^2	11.8 W/m^2

Recommendations:

1. The east and west walls should be protected from solar heat gain, particularly in the warm period. However, western walls are more vulnerable as they transmit additional heat when the room temperature is already higher than a comfortable temperature, due to at least 6 hours of solar exposure through the eastern walls and the roof.
2. The R-value of the western walls should be double that of northern walls to eliminate the impact of solar heat gain if the walls are unshaded.
3. Use of the dark colours on the western walls should be avoided.
4. Highly conductive materials (such as metal frames) should be well insulated to avoid thermal bridges within walls.

3.1.2. Roof

Most new dwellings have a gable and hip roof with unused attic spaces. The NCC allows a non-sarked roof (Figures 15 and 16) except in bushfire prone areas. For building energy efficiency, sealed roof spaces can be beneficial as they prevent the flow of uncontrolled hot and cool air between the attic and the outdoors. Sarking reflects radiative heat entering the roof space. Furthermore, sarking can reduce the possibility of condensation within the metal roof space. Condensation within the roof space can damage ceiling insulation.

Figure 15. Unsarked gable roof in a residential building in NSW (Source: Munsami 2018)

Figure 16. Gaps between tiles are clearly visible in an unsarked roof (Source: Munsami 2018)

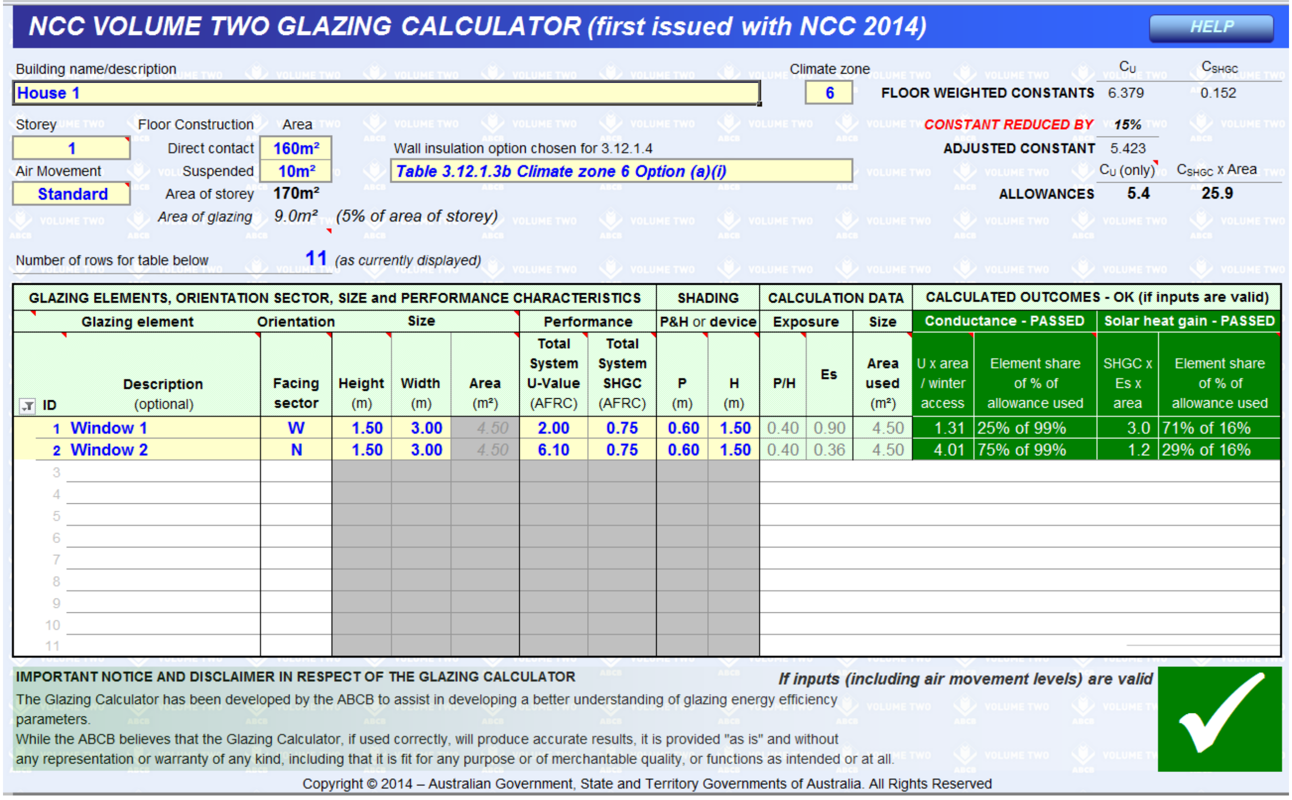
Recommendations:

1. The roof must have sarking to prevent unnecessary heat gain and loss in warm and cool periods, especially through infiltration.
2. A mechanical ventilation system installed in the roof space can help in removing hot air in the warm period and in rapidly cooling the roof space.
3. Wall/roof vents in the roof space can also regulate roof space temperature through cross air flow.

3.1.3. Windows

Low performance windows contribute to building energy inefficiency as they lose heat from indoors in the cool period and gain heat from the outdoors in warm periods through conduction. They also allow excessive solar heat gain when the sun is at a low angle. Compliance with the NCC for energy efficiency in a building using DTS requires a designer to demonstrate that each window meets conductance and solar heat gain criteria using a glazing calculator (Australian Building Code Boards 2019)(Figure 17).

However, if a simulation method is used to demonstrate building energy efficiency, it considers the whole house as one entity and allows the designer to compensate thermal performance of one element with the other, e.g. a highly insulated wall can allow for low performing glazing on the western façade. Even if a dwelling has achieved high energy efficiency using a simulation method, there could be situations where a room facing the west becomes unbearably hot during the afternoon and evening in the warm period and which is often uncomfortable to occupy. This may trigger the households to use air conditioning to cool the western room or the whole house (if a ducted air-conditioner is installed).


NCC VOLUME TWO GLAZING CALCULATOR (first issued with NCC 2014)

Building name/description: House 1

Climate zone: 6

	C_U	C_{SHGC}
FLOOR WEIGHTED CONSTANTS	6.379	0.152
CONSTANT REDUCED BY	15%	
ADJUSTED CONSTANT	5.423	
	C_U (only)	C_{SHGC} x Area
ALLOWANCES	5.4	25.9

Storey: 1

Air Movement: Standard

Floor Construction	Area
Direct contact	160m²
Suspended	10m²
Area of storey	170m²
Area of glazing	*9.0m²* *(5% of area of storey)*

Wall insulation option chosen for 3.12.1.4: *Table 3.12.1.3b Climate zone 6 Option (a)(i)*

Number of rows for table below: 11 *(as currently displayed)*

GLAZING ELEMENTS, ORIENTATION SECTOR, SIZE and PERFORMANCE CHARACTERISTICS								SHADING		CALCULATION DATA			CALCULATED OUTCOMES - OK (if inputs are valid)			
Glazing element		Orientation	Size			Performance		P&H or device		Exposure		Size	Conductance - PASSED		Solar heat gain - PASSED	
ID	Description (optional)	Facing sector	Height (m)	Width (m)	Area (m²)	Total System U-Value (AFRC)	Total System SHGC (AFRC)	P (m)	H (m)	P/H	Es	Area used (m²)	U x area / winter access	Element share of % of allowance used	SHGC x Es x area	Element share of % of allowance used
1	Window 1	W	1.50	3.00	4.50	2.00	0.75	0.60	1.50	0.40	0.90	4.50	1.31	25% of 99%	3.0	71% of 16%
2	Window 2	N	1.50	3.00	4.50	6.10	0.75	0.60	1.50	0.40	0.36	4.50	4.01	75% of 99%	1.2	29% of 16%
3																
4																
5																
6																
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8																
9																
10																
11																

IMPORTANT NOTICE AND DISCLAIMER IN RESPECT OF THE GLAZING CALCULATOR

The Glazing Calculator has been developed by the ABCB to assist in developing a better understanding of glazing energy efficiency parameters.

While the ABCB believes that the Glazing Calculator, if used correctly, will produce accurate results, it is provided "as is" and without any representation or warranty of any kind, including that it is fit for any purpose or of merchantable quality, or functions as intended or at all.

If inputs (including air movement levels) are valid ✓

Figure 17. Glazing calculator to check each window for its conductance and solar heat gain performance for energy efficiency (Source: Australian Building Code Boards 2019)

Recommendations:

1. A glazing calculator should be used even if using simulation methods to ensure each glazing element has complied with conductance and solar heat gain requirements. However, the designers can exceed the minimum performance recommended by the glazing calculator.

3.1.4. Floor

Newly constructed dwellings often have a slab-on-ground floor system which has multiple benefits such as durability, thermal mass coupling to the ground and low maintenance. North facing living rooms with large northern windows benefit from the exposed concrete floors which can store daytime heat and re-radiate it in the evening and at night to maintain a comfortable temperature in the cool period (Figure 18). The amount of heat stored in the slab exposed to the sun is significantly higher than a slab which receives indirect solar radiation. However, the benefit of thermal mass becomes redundant once the concrete floor is covered with carpet (Alterman, Page et al. 2017).

On the other hand, rooms facing south can experience uncomfortable conditions in the cool period due to exposed concrete floors as the rooms do not receive solar exposure and thermal mass proves to be unhelpful if intermittent heating is in use.

A timber sub-floor can contribute to infiltration and exfiltration, especially in tongue and groove flooring. This contributes to heat loss in winter.

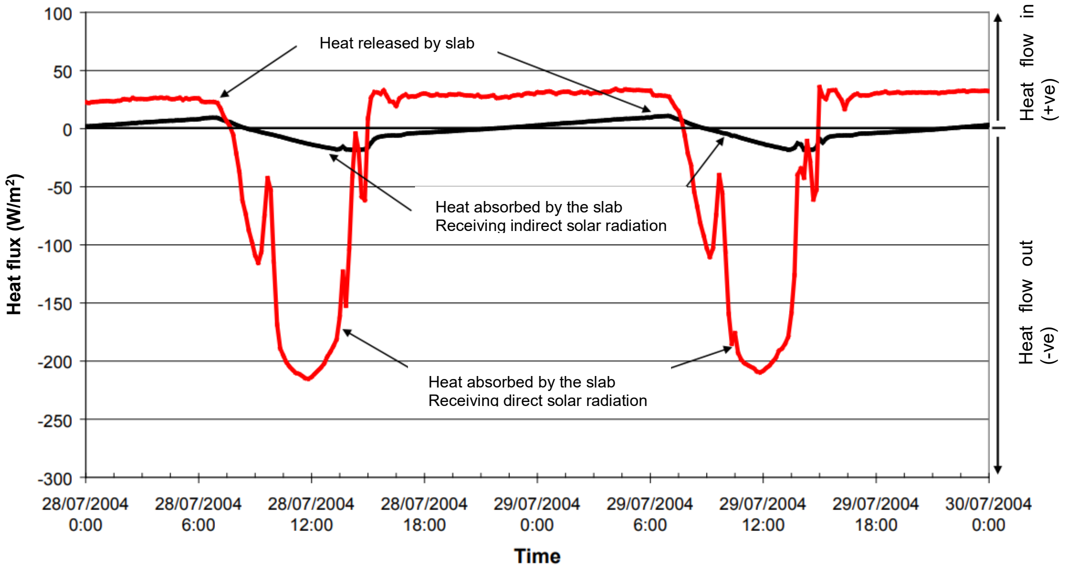


Figure 18. Heat absorption and release by a slab in winter conditions. The red line refers to the slab which is exposed to direct sunlight and the black line refers to the slab which is away from the sun, receiving indirect solar radiation. (Source: Moghtaderi, Alterman et al. 2011)

Recommendations:

1. The designer needs to specify floor finishing considering its impact on indoor thermal comfort. A band of exposed concrete near north facing windows can be beneficial for capturing solar radiation in the cool period.
2. One of the essential requirements is to have perimeter insulation in concrete floors if underfloor heating is incorporated.
3. In cases of sub-floor construction, radiant or air barriers to reduce infiltration and exfiltration should be provided in the subfloor framework. An air or radiant barrier can be placed on the joist prior to the placement of tongue and groove flooring or particle flooring.

3.2. Building airtightness

Infiltration is not a designed attribute but an uncontrolled form of air flow within the building envelope. Leakages in buildings contribute to unwanted heat gain and loss in the warm and cool periods respectively. The phenomena can be exaggerated especially during the use of mechanical heating and cooling. Furthermore, heat loss can be expected during the heating season due to the stack effect in two storey buildings. Cold air is drawn in from the lower parts of the building creating an uncomfortable feeling from draughts.

The NCC is yet to consider building airtightness in dwellings. In the absence of measured infiltration rates in dwellings, it is impossible to determine optimum energy efficiency strategies and therefore, energy efficiency performance cannot be appropriately managed. Ambrose and Syme (2017) identified that there were 15 air changes per hour at 50 Pascal (ACH_{50}) for Australian dwellings, whereas international standards averaged around 3.5 ACH_{50} (Ding, Upadhyay et al. 2019).

If mechanical ventilation systems are installed, the infiltration rates can be lowered around 0.5 ACH_{50} which is similar to the *Passive house* standard. In the absence of a mechanical ventilation system, an acceptable ventilation rate for indoor air quality needs to be maintained.

The ASHRAE Standard 62.2-2016 (Ventilation for Acceptable Indoor Air Quality in Residential Buildings) considers whole house ventilation with the required air flow based on floor area and the numbers of bedrooms. The standard is based on the inclusion of mechanical ventilation with infiltration credit.

Once the infiltration rate is known, it is easier to determine the energy saving potential from a dwelling. Often, the reduction in energy demand due to infiltration is proportional to the reduction in infiltration rate. For example, if a dwelling consumes 3 kWh energy per hour for heating with 15 ACH_{50}, the reduction in energy consumption would be 66.6% by tightening the building and maintaining infiltration to 5 ACH_{50}.

Recommendations:

1. Perform a blower door test before the Occupation Certificate for the building is issued. A blower door test is repeatable with accurate results and is able to pinpoint leaky areas with additional equipment such as thermal imaging and ultrasonic sound devices.
2. A tracer gas test can also be performed using CO_2. However, tracer gas test results would differ in relation to the wind pressure around the building envelope as it is based on the natural air flow.
3. A simple monitoring of CO_2 of the internal space of the dwelling can verify the leakiness of the building. Low CO_2 levels or ‘close to outdoors’ (around 450 ppm) indicate a high ventilation/ infiltration rate, whereas a high concentration of CO_2 levels indicates air tightness or a low ventilation rate.

3.3. Insulation installation

To meet the minimum thermal performance of building elements, NCC mandates walls, roofs and floors to achieve a minimum R-value. Often walls and roofs use insulating materials together with structural or infill building elements to comply with the NCC standards. Insulation is one of the key building materials which can help to balance the indoor thermal environment. There are many types of insulating materials used in the buildings, the most commonly used being fiberglass or polyester batts. Fiberglass is easy to install and offers great flexibility. However, due to its flexible nature, it is more likely that the insulation is moved or displaced when services are being installed in the buildings.

Ding et al. (2019) found that the insulation was either moved or displaced from the walls and ceilings of a number of dwellings the researchers investigated. Displacement of insulation will significantly reduce the thermal performance of the buildings. Figure 19 shows the displacement of roof insulation. The homeowner was unaware of this and it could have been moved when air conditioning ducts were installed after the ceiling insulation was laid.

Figure 19. Missing ceiling insulation in roof space (Source: Munsami 2018)

Missing and displaced insulation in buildings is not noticeable to the occupants as shown in Figure 20. However, thermal imaging of the same ceiling (Figure 21) can show thermal anomalies in the ceiling space due to the missing and displaced insulation. In Figure 20, the spots with missing insulation show higher temperature (bright yellow colour) than the spots with insulation (dull orange colour). Cold air coming through the AC duct is purple in colour.

Figure 20. Digital image of a ceiling space (Source: Munsami 2018)

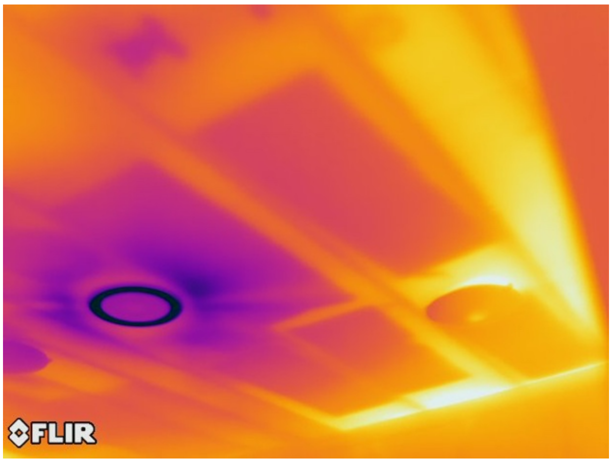


Figure 21. Thermal image of the same ceiling space as shown in Figure 20 (Source: Munsami 2018)

Further to the displaced insulation in the ceilings, a case study home (Figure 22 and 23) also revealed sub-standard practices in the placement of insulation in the area adjacent to the walls and the ceilings. Due to the narrow strip at wall plate level (in between the rafter and the top plate), insulation is often not placed along the wall plate. As the wall plate is close to the roof and without insulation, a high amount of heat flux is transmitted to the wall from the wall plate area.

In Figure 22, the digital image presents no signs of thermal irregularities at the ceiling and the cornice level, which rests on the wall plate. However, the Figure 23 illustrates the thermal anomalies and pinpoints the location of the missing insulation.

Figure 22. Digital image of a room which shows walls and ceiling (Source: Munsami 2018)

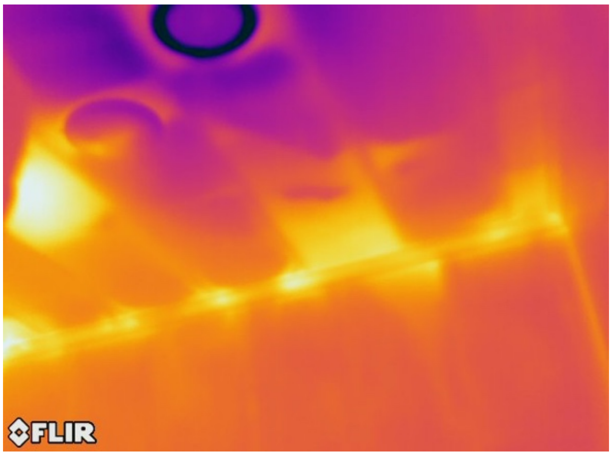


Figure 23. Thermal image of the same room as in Figure 22 which shows missing insulation in the ceiling and on the wall plate (Source: Munsami 2018)

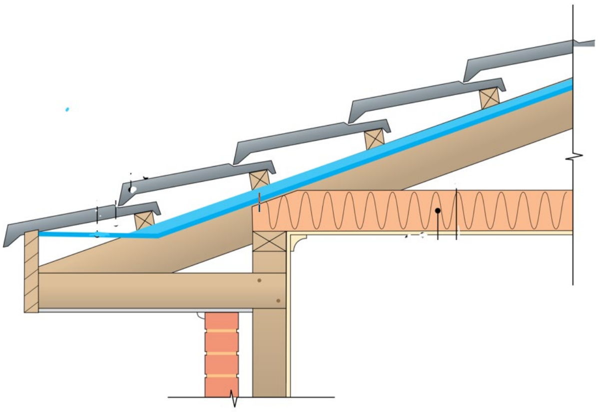


Figure 24. Correct method of ceiling insulation placement at the edge of the roof (Source: Insulation Council of Australia and New Zealand 2010)

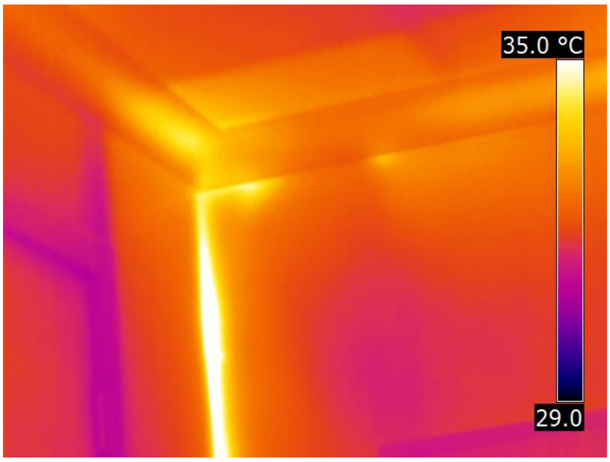


Figure 25. Thermal image of a wall corner facing to the east at 10 am (Source: Munsami 2018)

Figure 24 shows the correct method of installing insulation at the wall plate level. The insulation needs to be tucked in between wall plate and roof joists.

Walls also can have insulation displacement. However, due to complexities associated with the wall orientation, diurnal cycle and furniture placed against walls or other non-structural furnishings, it is difficult to locate missing insulation. Figure 25 shows thermal anomalies at the corner which may be caused by a steel column and thermal bridging at that point. The spot temperature was 35^{0}C at 10 am as the wall was facing east.

Recommendations:

1. Missing or displaced insulation is often caused due to the negligence of the tradesmen working in the buildings. It is important to re-iterate the value of insulation in building thermal performance through ongoing training when appropriate.
2. Documentation of the insulation which has been installed using a thermal imaging camera can be useful.
3. Prior to installing the internal lining, insulation should be checked by the supervisor and thermal images should be taken as the proof of satisfactory workmanship.
4. If a ducted air-conditioning system is installed by a third party at a later date, the owner should be aware of a possible insulation displacement. Owners can be sure that the insulation is intact in the roof space after the installation of air-conditioning ducting by requesting proofs, such as the photos of the roof space.
5. If metal frames are used in the walls, they should be properly wrapped with insulating materials to avoid unnecessary heat flow through thermal bridging.

3.4. Air-conditioning ducting

In the past, households often used a split air-conditioning system to cool a small area of a house in extremely warm weather conditions. However, with advanced air-conditioning technology and affordability, air-conditioners are now an integral part of a dwelling. In western Sydney, most of the dwellings are fitted with some kind of air conditioning units and the majority of the new dwellings are fitted with ducted air-conditioners. Ducted air conditioners rely on ducts to move air to various parts of a dwelling. In most applications, the ducts are installed in an unconditioned space such as the ceiling or sub- floor.

If the supply ducts are not sealed properly, unconditioned air would be drawn in from the ceiling into the supply register and conditioned air would also be lost into the unconditioned space. Moreover, leaky ducts can be a serious health hazard. The return ducts suck dust from the ceiling or sub-floor space and deposit it in the supply stream with high particulate levels, especially insulation dust.

Ducted air-conditioners can work efficiently when the building is air-tight and supply and return air are correctly balanced. The efficiency of air-conditioners drops significantly if a building is leaky as it pushes or draws air directly from outside (through leaks) which is often at a significantly higher temperature (in the warm period) and at a low temperature in the cool period.

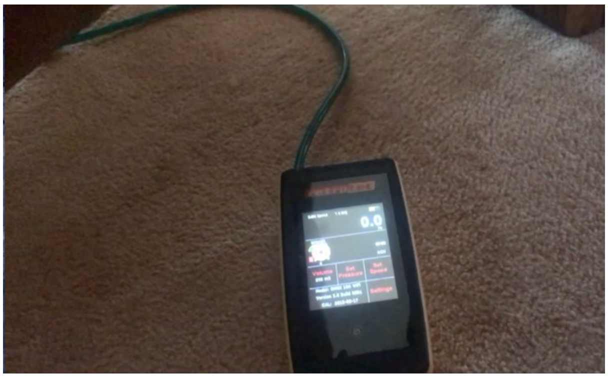


Figure 26. The manometer reading was 0 Pa when the door was opened and return air flow was not blocked (Source: Munsami 2018)

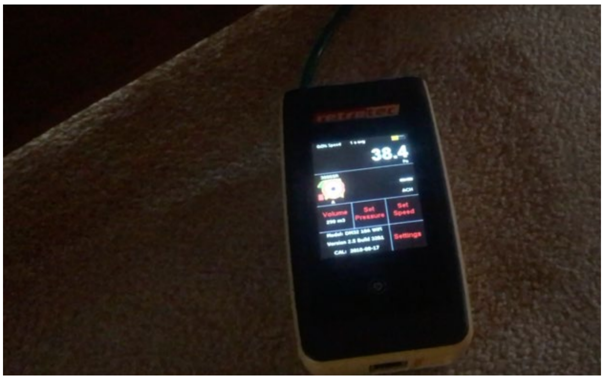


Figure 27. The manometer reading was 38.4 Pa when the door was closed and return air flow was blocked (Source: Munsami 2018)

An experiment was carried out to investigate the pressure difference when an air-conditioner is turned on (see Figure 26). The door to the bedroom was ajar and the manometer was placed in the passage. The ceiling in the passage had the return air register. The manometer recorded the pressure difference between the room and the passage at that time and indicated 0 Pascals pressure difference. This indicates that the amount of air flow leaving the bedroom register is balanced with the return air.

The manometer reading in Figure 27 was recorded with the bedroom door closed when the air-conditioner was still running. This is a common practice in most homes as rooms are closed to keep the warmth or coolth within the small enclosed space to save energy. However, in this instant, the pressure in the room ramps up to approximately 38.4 Pascals. This indicates that the bedroom is under intense positive pressure which would exert pressure on the gaps and cracks and push warm or cool air to the outside. This phenomenon impacts on air-conditioners' efficiency as well as wastes energy.

Figure 28 illustrates various methods of providing return pathways for air to escape from the bedroom to the hallway where a return air duct is often located.

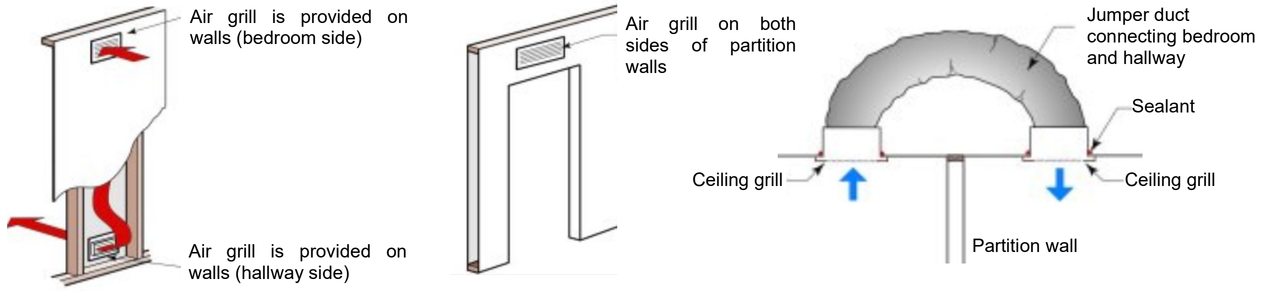


Figure 28. Various methods of providing return pathways for air to reduce pressure build-up in bedrooms (Source: Building Science Corportion 2019)

Another issue related to air-conditioning ducts is the quality of the ducts and their joints. Poor quality ducts (without or bare minimum insulation) and poor workmanship in joining ducts lead to reduced efficiency of the air-conditioning system. It is a common practice to use PVC duct tape in joining ducts together. In some cases, due to constricted roof space, the ducts are not properly taped around joints. On a hot day, the tape cannot withstand high temperatures (>70^{0}C) and is stretched, causing the joint's separation and resulting in a leaky duct.

Figure 29 shows a disjointed duct in an attic of a Sydney home. The household complained of the poor performance of the air-conditioner. A thorough investigation found this disjoint resulted from over-stretched PVC tape. This disjointed duct was responsible for not supplying cool air to the rooms. The quality of the duct tape is important in assuring a proper seal, that is able to withstand the forces within the ducts and the high considerable range of temperatures within the roof space. Aluminium foil tape can be a better choice for taping ducts as it can withstand extreme temperatures.

Figure 29. Disjointed duct in the attic of a house in Sydney (Source: Munsami 2018)

Recommendations:

1. Ducted air-conditioning systems must be balanced by allowing appropriate air flow between the closed supply areas (e.g. rooms) and the return area (e.g. hallways).
2. A manometer can be used to measure the pressure difference between rooms and the return area. A slight positive pressure in the supply area (room) would be advisable as it would not allow pollutants to be drawn into the room, thus creating a less healthy environment.
3. Duct sealing is critical and appropriate duct tape should be used based on the location of ducts. If air-conditioner ducting is located in an un-conditioned roof space, high heat resistance tapes should be used.
4. At building commissioning stage, a duct test should be performed to identify any leaks. For example, a Duct Blaster® can be used to directly pressure test the duct system for air leaks.

3.5. Ventilation arrangements

Ventilation is essential for health requirements and it also affects thermal comfort and productivity. In general, dwellings mostly rely on natural ventilation to achieve a comfortable indoor environment and natural ventilation is solely dependent on outdoor environmental conditions. However, outdoor conditions fluctuate continuously, and it would be impossible to achieve a desired indoor environmental condition through natural ventilation alone. Whilst designers often argue that naturally ventilated buildings are an advantage as they offer ventilation without using mechanical appliances, due to security and noise issues in urban areas, windows are opened less than might be expected.

In composite climate conditions such as Richmond, a building should work well in both warm as well as cold periods. In both periods, direct ventilation through wall openings can be problematic as it brings outdoor noise, pollution and hot/cold air depending on the season. Moreover, Richmond receives relatively low wind speeds (<5m/s) for the majority of the time and wind directions are often variable which limits the potential for cooling indoors when the outdoor environment is comfortable.

Energy recovery ventilation (ERV) is often regarded as a solution to maintain indoor thermal comfort as well as to supply filtered air without using too much energy. The filtration system can be specified based on external conditions such as a busy road with high traffic volumes.

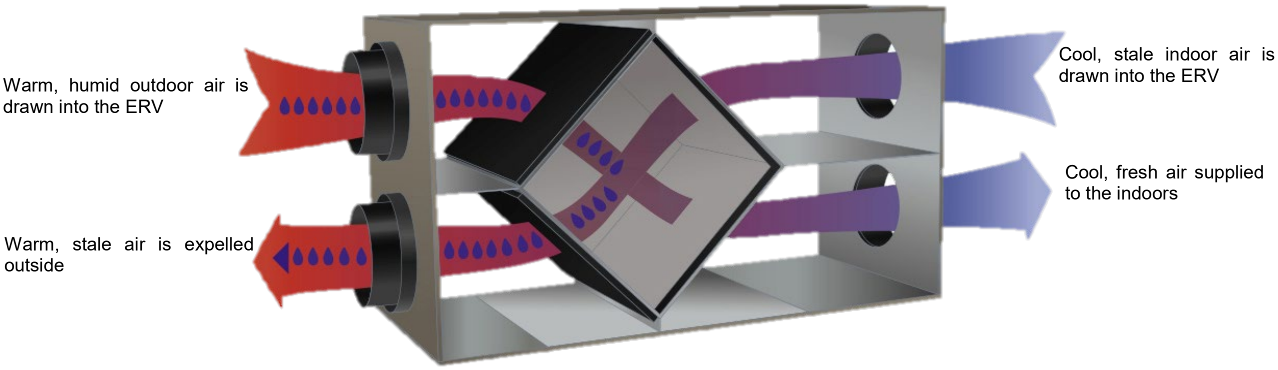


Figure 30. Incoming moisture is transferred to the outgoing air stream. Incoming warm air is cooled at the ERV core before it enters inside the building (Source: Lennox 2019)

Figure 30 shows the operation of an ERV system in warm and humid environmental conditions. At the heat exchanger unit, warm and humid outside air is crossed with cold inside air. In this process, the outdoor air gets cooled which is then supplied indoors.

Figure 31 illustrates the operation of ERV in a cool season. Cool, fresh outdoor air is crossed with warm inside air and the temperature of fresh outdoor air is elevated and supplied indoors.

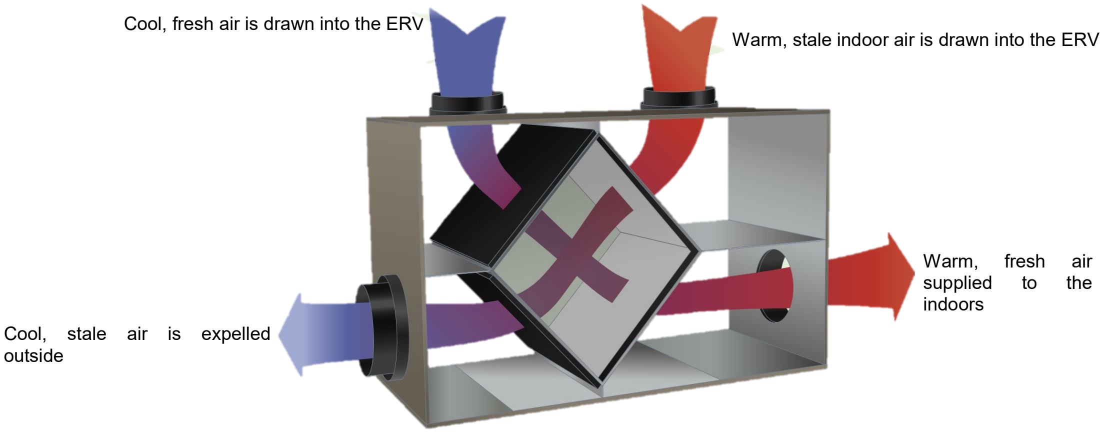


Figure 31. Heat from the stale indoor air is transferred through the unit's core to warm the old fresh air before it enters into the indoors (Source: Energyseal 2019)

Recommendations:

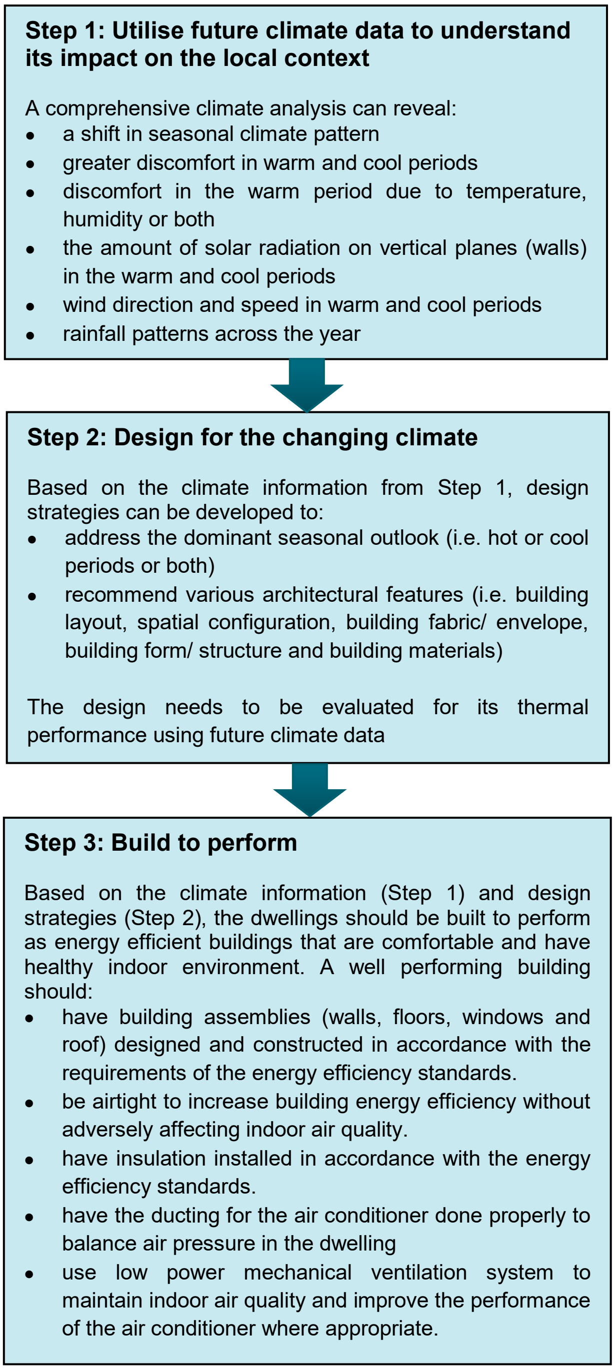
1. Install energy recovery ventilation. It can be coupled with air-conditioners to increase the efficiency of the air conditioning system.

Discussions

This study presents a framework to assist building designers and builders to design and build energy efficient and healthy homes to suit future climate conditions (Figure 32). It takes the case of Richmond in western Sydney to highlight changing climate and outlines the building design strategies which would suit the future climate context. The study demonstrates that Richmond will experience heat discomfort for 15 weeks in 2030 as opposed to just four weeks as portrayed in the NatHERS weather file. The increased temperature trend has been observed in recent years too. In 2030, the cool period will be reduced by 8 weeks (to 22 weeks from 30 weeks) when compared to the current NatHERS weather file. Therefore, the design and construction of dwellings should focus on addressing increasingly warm environmental conditions, as well as observing the cooler period.

The findings of this study highlights that the design strategy for buildings in Richmond should focus on well shaded and insulated buildings to avoid any heat gain in the warm period, but should harness solar exposure to warm up the indoors in the cool period. This study has presented a range of design recommendations for appropriate building layout, spatial configuration, building fabric and envelope, and materials to suit the climatic context of Richmond.

Furthermore, thermal performance evaluation also revealed a significant increase (almost 200% more) in cooling energy consumption in 2030 when compared with the energy simulations in the current NatHERS weather file. Therefore, the design needs to incorporate construction systems to reduce the amount of energy needed for cooling in future. In this study, the NatHERS Demonstration House 1 was simulated with upgraded building elements, and materials which respond to warm conditions such as, reverse brick-veneer (R2.5) external walls; R4.0 ceiling insulation; timber framed windows with insulated glass unit, low-e and high SHGC; exposed concrete slab flooring (throughout) except carpet in bedrooms; light coloured metal roof with R1.3 anticondensation blanket and 750mm eaves all around the house. The dwelling if built with the amended building specifications would require 40% less cooling energy than the current typical construction specification. However, this optimised dwelling for 2030 fails to comply with the current BASIX heating threshold when modelled with the current NatHERS weather file, thus preventing a designer from creating a more efficient design for future climate scenarios.



Step 1: Utilise future climate data to understand its impact on the local context

A comprehensive climate analysis can reveal:

- a shift in seasonal climate pattern
- greater discomfort in warm and cool periods
- discomfort in the warm period due to temperature, humidity or both
- the amount of solar radiation on vertical planes (walls) in the warm and cool periods
- wind direction and speed in warm and cool periods
- rainfall patterns across the year

Step 2: Design for the changing climate

Based on the climate information from Step 1, design strategies can be developed to:

- address the dominant seasonal outlook (i.e. hot or cool periods or both)
- recommend various architectural features (i.e. building layout, spatial configuration, building fabric/ envelope, building form/ structure and building materials)

The design needs to be evaluated for its thermal performance using future climate data

Step 3: Build to perform

Based on the climate information (Step 1) and design strategies (Step 2), the dwellings should be built to perform as energy efficient buildings that are comfortable and have healthy indoor environment. A well performing building should:

- have building assemblies (walls, floors, windows and roof) designed and constructed in accordance with the requirements of the energy efficiency standards.
- be airtight to increase building energy efficiency without adversely affecting indoor air quality.
- have insulation installed in accordance with the energy efficiency standards.
- have the ducting for the air conditioner done properly to balance air pressure in the dwelling
- use low power mechanical ventilation system to maintain indoor air quality and improve the performance of the air conditioner where appropriate.

Figure 32. Framework to develop an energy efficient and healthy homes to suit the future climate

Nevertheless, design and highly energy efficient construction systems alone, are not enough to achieve high performance at the post-occupancy stage. A dwelling which is rated well by NatHERS software may end up using more energy or occupants may experience discomfort because the software limitations allow trade-offs on the thermal performance of one building component against another. For example, NatHERS software provides an aggregated score for house (i.e. a star rating, heating and cooling loads) to demonstrate its energy efficiency merit. However, a room facing west receives almost the double amount of heat flux from the western wall than the northern or eastern walls in an afternoon during the warm period which makes the western room uncomfortable. As a result, the household may have to use an air-conditioner to maintain thermal comfort while occupying the room. Similarly, a window on the western façade, without shading, is acceptable in a NatHERS simulation, whereas, the NCC glazing calculator would not allow such a window if the DTS method were used to demonstrate the thermal performance of a house.

Other issues that influence thermal comfort in a dwelling relate to trade workmanship, such as building airtightness and insulation installations. Building airtightness has been ignored in Australian dwellings until recently and this study reports proportional savings on energy demand if the dwelling is airtight. Another benefit of maintaining airtighteness in a building is to reduce discomfort due to draughts in the cool period.

Similarly, missing or displaced insulation from the ceiling cause significant discomfort and additional heating and cooling energy demands. Therefore, there needs to be an awareness among homeowners and tradespeople that insulation cannot be displaced or moved, in order to prevent inefficiencies developing in a well designed building.

Windows are considered as the primary mechanism to fulfil ventilation requirements in dwellings. However, due to various reasons such as low wind speed, pollution and noise, it may not always be possible to open windows to ventilate the house. Consequently, households may not be getting enough fresh air to maintain a healthy indoor environment. A low energy ventilation system such as energy recovery ventilation (ERV) can ensure an acceptable level of ventilation in a dwelling. If the ERV system is used together with an air-conditioner, the efficiency of the air-conditioning system will substantially increase.

Conclusions

Overall, this report presents an approach to understanding the nature of our future climate, designing to suit that local climate and constructing dwellings that would perform in an energy efficient manner and have a healthy indoor environment. The measures discussed in this report would help to design a high performing building shell that would require significantly less energy to maintain thermal comfort in the future. This report also highlights the issues associated with heating energy threshold in BASIX when modelling the optimised design for the future climate using the current NatHERS weather file for Richmond. The weather file considers a much cooler scenario than has been experienced in recent years and also in the future (2030).

Research limitations

The findings on the outlook for future climate conditions and corresponding design strategies are specific to Richmond, NSW and may not be applicable to other locations, even in the same NatHERS climate zone (i.e. 28). However, the building construction issues are more general and can be applied in other locations with some adjustments.

Future research directions

Further research on exploring a future climate scenario of the major population centres of Australia can provide a comprehensive overview on the changing climate outlook and help designers and builders to develop energy efficient and healthy dwellings for the future.

References

- Alterman, D., A. W. Page and B. Moghtaderi (2017). A study of the thermal performance of Australian housing - Volume II. Newcastle, NSW, University of Newcastle.

- Ambrose, M. and M. Syme (2017). "Air Tightness of New Australian Residential Buildings." Procedia Engineering **180**: 33-40.

- Australian Building Code Boards. (2019). "Glazing Calculator." Retrieved 10th April, 2019, from https://www.abcb.gov.au/Resources/Tools-Calculators/Glazing-Calculator-NCC-2014-Volume-Two.

- Australian Sustainable Built Environment Council and ClimateWorks Australia (2018). Build to Perform: An industry led pathway to a zero carbon ready building code. Melbourne, Victoria, ClimateWorks Australia.

- Beyond Zero Emissions and Melbourne Energy Institute (The University of Melbourne) (2013). Zero carbon Australia: Buildings plan. Melbourne, Victoria, Beyond Zero Emissions

- Building Science Corportion. (2019). "Info-604: Transfer Ducts and Grilles." Retrieved 10th May, 2019, from https://www.buildingscience.com/documents/information-sheets/information-sheet-transfer-grilles-and-ducts.

- Clarke, J. M., C. Heady and L. Webb (2014). Future climate data for 100 prospective Australian solar energy sites, CSIRO Marine and Atmospheric Research.

- Commonwealth of Australia (2017). Australian Energy Update 2017. Canberra, Department of the Environment and Energy.

- Commonwealth of Australia. (2019). "2018–19 was Australia's hottest summer on record, with a warm Autumn likely too." Retrieved 10th May, 2019, from http://www.bom.gov.au/climate/updates/articles/a032.shtml.

- Ding, L., A. K. Upadhyay, W. Craft, K. Yenneti, M. Samaratunga, K. Munsami and D. Prasad (2019). Validating and Improving the BASIX Assessment Tool for Low Carbon Dwellings. Sydney, Australia, Cooperative Research Centre for Low Carbon Living.

- Energyseal. (2019). "Energy Recovery Ventilation (ERV)." Retrieved 28th May, 2019, from http://www.energyseal.net/products/ventilators.html.

- Gordon, H. B., S. P. O'Farrell, M. A. Collier, M. R. Dix, L. D. Rotstayn, E. A. Kowalczyk, A. C. Hirst and I. G. Watterson (2010). The CSIRO Mk3.5 Climate Model. Aspendale, CSIRO Marine and Atmospheric Research.

- Insulation Council of Australia and New Zealand. (2010). "Insulation handbook (Part 1: Thermal performance)." Retrieved 5th May, 2019, from http://icanz.org.au/wp-content/uploads/2013/04/17132_ICANZ_ThermalPerformance.pdf.

- International Energy Agency (2014). Energy efficiency indicators: Fundamental on statistics. France, International Energy Agency (IEA).

- Lawrence Berkeley National Laboratory and University of California (2019). THERM. Windows and Daylighting US Department of Energy.

- Lee, T. (2011). Changing climate: Ersatz future weather data for lifelong system evaluation. 12th Conference of International Building Performance Simulation Association. Sydney, Australia.

- Lennox. (2019). "Energy Recovery Ventilation (ERV)." Retrieved 28th May, 2019, from https://www.lennox.com/products/indoor-air-quality/ventilation/erv.

- Moghtaderi, B., D. Alterman, A. W. Page and S. Hands (2011). A study of the thermal performance of Australian housing - Volume I. Newcastle, NSW, University of Newcastle.

- NSW Government. (2019). "The BASIX thermal comfort protocol." Retrieved 15th May, 2019, from https://www.basix.nsw.gov.au/iframe/component/content/article.html?id=210.

- Pipkorn, J. (2019). Carbon Zero, Carbon positive in Your Home. Your Home. Department of the Environment and Energy. Australia, Commonwealth of Australia.

- Upadhyay, A. K. (2018). "Climate information for building designers: a graphical approach." Architectural Science Review **61**(1-2): 58-67.