A framework for adaptation of Australian households to heat waves

Final Report

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Cover image © Martin Belusko

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ABBREVIATIONS

ABCB	Australian Building Codes Board (ABCB)
ABS	Australian Bureau of Statistics
ADT	average daily temperature
AIRAH	Australian Institute for Refrigeration, Air Conditioning and Heating
ASHRAE	American Society for Heating, Refrigeration and Air Conditioning Engineers
BCA	Building Code of Australia
BMI	body mass index
BoM	Bureau of Meteorology
CAWCR	Centre for Australian Weather and Climate Research
CBD	central business district
CCF	cross-correlation function
CDB	corresponding dry bulb
CDFs	cumulative distribution functions
COAG	Council of Australian Governments
COP	coefficient of performance
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CWB	corresponding wet bulb
DB	dry bulb
DCCEE	Department of Climate Change and Energy Efficiency
DFC	Department of Families and Communities
DIT	Department of Infrastructure and Transport
dph	dwellings per hectare
DSEWPC	Department of Sustainability, Environment, Water, Population and Communities
EHF	excess heat factor
ESAA	Energy Supply Association of Australia
EU	European Union
GHG	greenhouse gases
IPCC	Intergovernmental Panel on Climate Change
low-e	low-emissivity
MEPS	Minimum Energy Performance Scheme
NatHERS	Nationwide House Energy Rating Scheme
NCC BCA	National Construction Code, Building Code of Australia

NCCARF	National Climate Change Adaptation Research Facility
NEM	National Electricity Market
NHSC	National Housing Supply Council
OECD	Organisation for Economic Co-operation and Development
PC	Productivity Commission
PV	photovoltaic
PWC	Price Waterhouse Coopers
SA	South Australia
SEQ	south-east Queensland
SES	State Emergency Service
SHGC	solar heat gain coefficient
SOG	slab-on-ground
SVD	saturated vapour density
TMY	typical meteorological year
TSR	total solar reflectance
UK	United Kingdom
US	United States of America
WB	wet bulb
WBCSD	World Business Council for Sustainable Development

ABSTRACT

Climate change is leading to an increased frequency and severity of heat waves. Spells of several consecutive days of unusually high temperatures have led to increased mortality rates for the more vulnerable in the community. The problem is compounded by the escalating energy costs and increasing peak electrical demand as people become more reliant on air conditioning. Domestic air conditioning is the primary determinant of peak power demand which has been a major driver of higher electricity costs.

This report presents the findings of multidisciplinary research which develops a national framework to evaluate the potential impacts of heat waves. It presents a technical, social and economic approach to adapt Australian residential buildings to ameliorate the impact of heat waves in the community and reduce the risk of its adverse outcomes.

Through the development of a methodology for estimating the impact of global warming on key weather parameters in 2030 and 2050, it is possible to re-evaluate the size and anticipated energy consumption of air conditioners in future years for various climate zones in Australia. Over the coming decades it is likely that mainland Australia will require more cooling than heating. While in some parts the total electricity usage for heating and cooling may remain unchanged, there is an overall significant increase in peak electricity demand, likely to further drive electricity prices.

Through monitoring groups of households in South Australia, New South Wales and Queensland, the impact of heat waves on both thermal comfort sensation and energy consumption for air conditioning has been evaluated. The results show that households are likely to be able to tolerate slightly increased temperature levels indoors during periods of high outside temperatures.

The research identified that household electricity costs are likely to rise above what is currently projected due to the impact of climate change. Through a number of regulatory changes to both household design and air conditioners, this impact can be minimised. A number of proposed retrofit and design measures are provided, which can readily reduce electricity usage for cooling at minimal cost to the household.

Using a number of social research instruments, it is evident that households are willing to change behaviour rather than to spend money. Those on lower income and elderly individuals are the least able to afford the use of air conditioning and should be a priority for interventions and assistance. Increasing community awareness of cost-effective strategies to manage comfort and health during heat waves is a high priority recommended action.

Overall, the research showed that a combined approach including behaviour change, dwelling modification and improved air conditioner selection can readily adapt Australian households to the impact of heat waves, reducing the risk of heat related deaths and household energy costs.

EXECUTIVE SUMMARY

Climate change is leading to an increased frequency and severity of heat waves. Spells of several consecutive days of unusually high temperatures have led to increased mortality rates for the more vulnerable in the community as well as increased levels of thermal discomfort. The problem is compounded by the escalating energy costs and increasing peak electrical demand, as people become more reliant on air conditioning. Domestic air conditioning during heat waves is the primary determinant of peak power demand which has been a major driver of higher electricity costs.

This report presents the findings of multidisciplinary research which develops a framework to evaluate the potential impacts of heat waves in Australia. It presents a technical, social and economic approach to adapt Australian residential buildings to ameliorate the impact of heat waves in the community and reduce the risk of its adverse outcomes in various climatic regions of Australia.

Through the development of a methodology for estimating the impact of global warming on key weather parameters in 2030 and 2050, the selection and anticipated energy consumption of air conditioners in future years was estimated by modelling future weather data within a building and air conditioning thermal model. By 2030 it is likely that all mainland cities will use more electricity for cooling than for heating. Adelaide, Melbourne, Perth and Darwin are likely to experience a small increase in heating and cooling costs, while dramatic increases are predicted in Sydney and Brisbane. Hobart can expect an overall reduction in heating and cooling costs.

Through the monitoring of groups of households in South Australia, New South Wales and Queensland, the impact of climate change and heat waves on both thermal comfort sensation and energy consumption for air conditioning has been evaluated. Air conditioning monitoring confirmed the importance of air conditioning in the total peak electricity demand. It is estimated that 38% of total peak demand is due to residential air conditioning. With climate change it is anticipated that peak demand in Adelaide, Melbourne, Darwin and Perth will have small increases in peak demand attributable to climate change; however Sydney and Brisbane can experience dramatic increases, well beyond current peak power demand growth. It is likely that this will further increase electricity costs above current projected increases.

Focussing on a 4 day hot spell in different Australian locations, 5 case study dwellings covering houses and apartments of various sizes were analysed to investigate the impact of implementing retrofitting measures and design modifications on the comfort and air conditioning needs. Both options demonstrated an increase of the number of hours of comfort without air conditioning and substantial reductions of air conditioning capacity and use in South Australia, Queensland and New South Wales locations.

For a current typical house in Adelaide, an increase of 18% of cooling system capacity and a 32% increase in electricity usage for cooling are anticipated in 2030. The use of suitable insulating materials and suitable roofing systems have been singled out as key feature for improving heat wave resistance and reducing air conditioning requirements. Other factors requiring consideration in the selection of air conditioning equipment are correctly sizing the system and preventing leakage of conditioned air in ducting.

The research identified a number of strategies capable of mitigating these expected impacts. Monitoring data have demonstrated that households are capable of tolerating higher indoor temperatures during hot weather.

A number of design and retrofit options were investigated for new and existing homes. These options range from adding no cost to the householder to a reasonable cost; however encompass existing designs and practices. One such peak demand reduction measure is changing the roof surface to achieve a high total solar reflectance. This represents a negligible additional cost for new houses or existing houses when upgrading the roof. The concept of a 'cool retreat' is also being proposed for new or retrofit house designs in which a dedicated zone specifically designed to cope with hot weather periods be incorporated into house designs. This zone can be applied at either negligible cost or involve a basement which represents a major additional cost. Overall, the philosophy presented is that future designs should focus on the peak cooling demand periods in addition to attempting to reduce the overall annual energy consumption for providing thermal comfort.

Current building and air conditioner regulations primarily focus on energy usage rather than peak cooling demand. A focus on peak cooling demand can have a dramatic and sustained impact on peak electricity demand and ultimately electricity prices. Rather than a prescriptive measure to adapting house designs to climate change, regulatory changes to the NatHERS energy rating tool are suggested. Furthermore, enhanced regulations of air conditioners are proposed. The cost impact of these changes need to be investigated, however, any increase in costs are likely to be offset by expected electricity price reductions.

Using a number of social research instruments, including interviews with key informants, households participating in the monitoring program and an on line survey of 500 individuals from Brisbane, Adelaide and Sydney, it was evident that there is a willingness of households to change behaviour rather than to spend money. This includes the correct use of external shades and curtains or moving to a cooler room during heat waves. Around half of the respondents were also willing to spend up to $2,000. However, 30% of respondents were not in a position to spend any money.

The research has demonstrated that a combination of responses are necessary to adapt to heat waves and to reduce its risks including behaviour change during heat waves as well as the need to reconfigure house design and the use of air conditioning. The need to reflect some of the proposed house design measures to enable people to cope better with heat waves in future building regulations is recommended.

Increasing community awareness of cost effective strategies to manage comfort and health during heat waves is high priority recommended action. The findings indicate that the current information and awareness campaigns regarding behavioural coping strategies and housing modifications to facilitate better coping with heatwaves are of limited effectiveness with regard to informing and influencing Australians' responses to heatwaves.

It is recommended that government educate the community on what a heatwave is, the signs of distress or negative health impacts that should be monitored in elderly people, babies and individuals with poor health and how to respond to these signs accordingly. This information should also include advice regarding how to plan for heatwaves. Technological advice could also be provided on how to make a dwelling more heat wave friendly and types and energy consumption of air conditioners.

Those on lower income and elderly individuals are the least able to afford the use of energy for air conditioning and should be a priority for interventions and assistance. Government grants and financial incentives to assist these groups to adapt their homes so that they can cope better during heat waves are also recommended.

Overall, an integrated approach is necessary to respond to heat waves. A combination of strategies including behaviour change, dwelling reconfiguration and the use of energy efficient air conditioning is required. These strategies can collectively reverse the current compounding health risks associated with climate change. In themselves each measure would achieve limited success due to the potential negative impact of other factors. However, the complementary nature of each component will deliver a framework for adapting households and diminish the risks associated with heat waves to individuals as well as reducing the need for augmenting the electricity infrastructure. On the basis of the research carried out in the project, the following actions are recommended for inclusion in a framework for adapting Australian households to heat waves:

- New TMY climatic data has been developed for 2030 and 2070. Climate data used in NATHERS and air conditioning design calculations must be adjusted to reflect a changing climate.
- Regulations for new buildings need to include a rating, through NATHERS, for the maximum peak power demand from building designs.
- The most effective methods for reducing the cooling demand for existing dwellings is to modify their roofs by increasing their total solar reflectance, adding reflective foils and increasing thermal insulation.
- Implement appropriate quality assurance measures of insulation installation in roofs consistent with other regulations in OECD countries.
- In addition to considering reducing annual energy and power demand for existing housing, special attention must be paid to minimise peak cooling demand in new buildings. The inclusion and use of cool retreats has been demonstrated to provide thermal comfort at dramatically reduced power consumption.
- Incorporate air conditioners within NATHERS considering the peak electrical demand.
- Regulate the sizing of air conditioners installed in dwellings.
- Incorporate the whole of air conditioning system in regulations, ensuring all regulations apply to all new systems rather than those installed in new buildings.
- Adopt quality assurance measures for installed air conditioners
- Adopt adaptive thermal comfort settings in air conditioning design guides and standards, and have these standards regularly updated.
- Educate public on the links between climate change and heat waves, likely impact on health and actions for reducing its impact
- Develop adaptation information which is currently lacking but welcomed within the community.
- Develop targeted interventions for specific vulnerable groups

1. OBJECTIVES OF THE RESEARCH

1.1 *Background*

Recent tragedies in Australia have demonstrated the need to adapt to the severe unusual weather events associated with climate change. Of all natural hazards, heat waves deliver the highest mortalities (Coates 1996). The increasing frequency and severity of heat waves (Alexander et al. 2007) have increased the mortality rates for the more vulnerable in the community who cannot afford air conditioning. The problem is compounded by the escalating energy costs and increasing peak electrical demand, as people become more reliant on air conditioning. Domestic air conditioning is the primary determinant of peak power demand (PC 2012b). An increase of peak demand for a few days results in increased electrical infrastructure which decreases the utilisation of the entire grid, driving up household electricity prices. As an example, in South Australia (SA), 50% of the electrical infrastructure is needed for only 5% of the time, resulting in SA having the highest electricity prices in the National Electricity Market (ESAA 2012). As a result, climate change can cause an upward spiralling effect of increasing electricity prices and increasing mortality rates over time. The proposed research aims to develop a framework to adapt Australian residential buildings to ameliorate this compounding affect and ultimately deliver a reduced risk of these adverse outcomes.

A major factor in adapting to heat waves involves the establishment of a suitable definition. Currently a variety of definitions are used by government authorities in different jurisdictions within Australia. For Adelaide, the current definition of a heat wave involves five consecutive days greater than or equal to 35^{o}C, or three days greater than or equal to 40^{o}C. In south-eastern Queensland, the definition is two consecutive days above an apparent temperature of 35^{o}C. The apparent temperature combines the effects of air temperature, humidity and other environmental conditions. Health authorities in Melbourne define a heat wave when the average of the daily maximum and minimum temperature is above 30^{o}C. To overcome the confusion presented by multiple definitions, the Bureau of Meteorology (BoM) in collaboration with the Commonwealth Scientific and Industrial Research Organisation (CSIRO), through the Centre for Australian Weather and Climate Research (CAWCR) has developed a more generic definition in terms of an excess heat factor (EHF) which focuses on the fundamental characteristic of a heat wave, a dramatically hot period (Nairn & Fawcett 2013). The EHF is used to define degrees of hot weather in terms of an excess heat event (a hot day), heat wave (three-day or more hot period), severe heat wave and extreme heat wave (Nairn 2012). Each degree is based on the EHF exceeding a locally derived threshold value, enabling local authorities to respond accordingly. This method is still under development and is yet to be formally adopted.

Once within a heat wave, the temperature conditions within a home are defined by the thermal characteristics of a building. Building energy regulations primarily focus on regulating the total maximum energy needed to heat and cool a building. Energy estimation in building rating and design relies on well-established thermal models which have been incorporated into the Nationwide House Energy Rating Scheme (NatHERS) and integrated into the Building Code of Australia (BCA) to establish minimum energy performance standards. The primary role of the regulatory framework associated with the thermal model is to reduce the annual energy needed to heat and cool the building. Consequently, the design and rating process gives no consideration to minimising peak power demand caused by heat waves. Research has shown that building occupants and building elements have a significant impact on the air conditioning energy use in comparison with the prediction of the building model (Saman & Mudge 2003; Belusko et al. 2011). Furthermore, Saman et al. (2008) have monitored cooling demand for residential buildings in Adelaide and showed that the difference between measured demand and predicted demand from the NatHERS increasingly diverged on peak cooling days. As a result, appropriate design principles need to be established for houses exposed to heat waves. Pullen (2008) highlighted the viability of a 'cool retreat' within current building designs, which would potentially successfully provide improved comfort for occupants. This builds on the concepts investigated by Torenio (2002) which showed that a well-designed space combined with air conditioning provides a more effective energy and comfort outcome.

A major determinant of cooling requirements is occupant thermal comfort defined partially by the indoor temperature. Thermal comfort is a perceived sense of thermal equilibrium between a person and their surroundings, and the definition with respect to temperature, humidity and other factors is well established (ASHRAE 2005). The current orthodox view is that during heat waves, people may tend to demand more cooling to reach comfort conditions. de Dear and others have determined that comfort temperatures, rather than being fixed, change with time and location according to the local outside weather conditions (de Dear et al. 1997; Nicol & Humphreys 2004; Peeters et al. 2009). This research has established the principle of adaptive comfort, which is now accepted in air conditioning standards in the United States (US), in which people adjust and tolerate higher temperatures with rises in outdoor temperatures. It is therefore hypothesised that as people are adapting to the warming environment, the upper limit of their thermal comfort will increase and people will become more forgiving of warmer conditions. However, the impact of a heat wave involves a sudden change in conditions, and comfort expectations may become more demanding. The adaptability of people during heat waves will potentially reduce electricity demand during heat waves, but will also affirm the potential for demand side management of air conditioners.

Convenience and cost are additional significant decisive influences on household behaviour in relation to temperature in the home (Shove 2003; Edwards & Pocock 2011). Based on Japanese studies, Iwashita and Akasaka (1997) showed that air conditioning usage was strongly influenced by cost during the day and by a concern that night-time usage would cause flu. Klineberg (2002) documented that low income and socially isolated aged people fail to use air conditioning, with adverse health outcomes. The way household members experience heat and their subsequent behaviour will vary by age and life-cycle stage, income, gender, home ownership, household composition and health status. Research by Liao and Chang (2002) in the US showed that the cooling thermostat settings set by the elderly were higher than those set by younger people. Current evidence documents significant differences between high and low income earners in the strategies used to cool their homes (Holloway & Bunker 2006; Brotherhood of St Laurence 2008; Dept of Sustainability and Environment 2008). This research identifies the variations in use and motivation that exist in different population groups; however, it does not yield information as to what active measures are most effective with households. Behavioural factors will affect which building design solutions are effective as well as which strategies are likely to reduce air conditioning demand during heat waves.

A critical input element for evaluating building cooling demand is the typical meteorological year (TMY) data used in building thermal models. The impact of climate change involves adjusting the TMY based on expected temperature changes. Guan (2006) developed new climate data and investigated the impact on building energy usage. The results confirmed an increase in peak cooling demand; however, the developed weather data did not include representative variations expected within weather data. Research work by Boland (2008) was a major part of the development of the TMY which is being used in the NatHERS. These data are constructed by incorporating a fixed stochastic component to climate variables such as temperature and solar radiation, as derived from actual weather data (Boland 2008; Magnano et al. 2008*)*. The impact of climate change is to impose a variable stochastic component as the climate changes, and currently no study has developed TMY data which includes this factor for Australian climatic regions.

The summer design temperature represents the extreme condition used for sizing cooling equipment. Current methods for determining these parameters are based on historical data (ASHRAE 2005; AIRAH 2007). However, with a changing climate, this approach is no longer valid: a new method needs to be developed which takes into consideration future climatic variation. The project will develop and use new TMY data for 2030 and 2050 to provide a set of new design temperatures covering all Australian climatic regions. These will form the basis for cooling load and cooling system design and selection calculations by air conditioning engineers, a critical factor which determines both occupant comfort and electricity usage during peak periods.

A report published by Price Waterhouse Coopers (PWC) confirmed the negative impacts of heat waves on people and infrastructure, and confirmed the high mortality rates which could be attributed to heat waves. The study focused on the increased risk of heat waves for each region over time with a specific focus on population trends. It was demonstrated that the risks of heat-related deaths are likely to increase (PWC 2011). The report identified those regions at risk with Adelaide, Melbourne and Brisbane rated as high. The study applied the EHF method developed by CAWCR, and projected that mortality rates in 2050 could double in these regions. This increase only considered population growth and ageing. The impact of climate change on Melbourne was also investigated, suggesting that the number of deaths could double again for extreme events. The report identified that there are multiple groups at risk of heat-related death. The report only focused on emergency response to heat waves, and to date no study has focused on strategic planning to reduce risks from heat waves.

1.2 *Conceptual Framework*

With climate change, the risk of adverse impacts due to heat waves increases. It is possible to mitigate these risks by identifying and addressing those factors that contribute to cooling demand. Specifically, these factors relate to the design of the building, type of air conditioning system, thermal comfort expectations and occupant behaviour. Consideration of these factors will result in an overall more resilient building stock and electricity grid as well as less heat wave vulnerability of the residents. No single factor will reliably reduce the risk of adverse effects; however, an integrated approach can reduce this risk. This study will focus on quantifying the comparative impact of individual factors: it will also provide a framework of how these factors interrelate. Each individual measure will have a level of associated uncertainty. However, collectively, the measures complement each other and, as a result, the likelihood of impacting on cooling demand is high; therefore, the framework should be viewed as a whole. Achieving a high reliability is critical to ensure a reduction of peak power demand, placing downward pressure on electricity prices and reducing associated health risks.

Developing new building design options initially relates to new residential buildings. However, given that building regulations are likely to also include energy-efficiency measures, any building design options must reduce total heating and cooling demands as well as reducing peak demand. These constraints need to be applied based on climatic conditions both today and in the future. In relation to existing homes, low-cost measures need to be readily implemented during renovation. All design variations will be considered using AccuRate, the NatHERS building model. Modelling will show the relative impact of design options on peak cooling demand.

Introducing the concept of adaptive comfort is an important consideration during heat waves. Given the limited actual monitoring data set, a qualitative determination of adaptive comfort is sufficient. A quantitative assessment can be achieved based on existing adaptive models, and the impact on peak cooling demand can be determined.

Cooling demand is met through air conditioning. Based on existing cooling technology, the electricity demand from cooling systems during peak times can be determined. Therefore, the relative impact of the cooling system, design options and adaptive comfort on peak electricity demand can be determined against projected electricity demand growth. Research is needed to investigate the understanding and attitudes and behaviour of people during heat waves and the associated nexus between air conditioning, electricity prices and heat-related deaths. This information is critical in order to establish appropriate strategies to support positive behaviour change.

1.3 *Aims*

The objective of the project is to develop a national framework for adapting Australian households to reduce the adverse risks associated with increased heat waves due to climate change. The project aims are to:

- develop a new typical meteorological year (TMY) for use in building simulation software, including NatHERS accredited software, and new summer design conditions for air conditioning design calculations for the years 2030 and 2070;
- establish new adaptive thermal comfort criteria for residential buildings for use within building simulation software and air conditioning design standards;
- evaluate the impact of climate change on annual household cooling energy use and peak power demand;
- examine current behaviour of householders during heat waves, and develop equitable design and policy options to achieve improved response to ensure safety and comfort during heat waves;
- develop affordable new design options for buildings and cooling equipment to avoid heat stress;
- identify suitable regulatory changes needed for the design of houses and air conditioning systems.

2. CLIMATE DATA

Critical to the design of buildings and cooling equipment is the impact of climate change on climatic data. Future yearly data in the form of the typical meteorological year (TMY) as well as extreme design temperature data have been developed for both 2030 and 2070. The 2007 CSIRO 'Climate change in Australia' report (referred to herein as the CSIRO report) on regional impacts vis-á-vis climate variables (Watterson et al. 2007) provides the basis for the climate change alterations implemented in this study. The projections are provided for 2030 and 2070. As a result, the TMY and design data will be developed for these projected years.

2.1 *Typical Meteorological Year*

Houses constructed in 2012 to five or six star energy rating standards will still be in use in 2030 and most likely in 2050. The energy efficiency and subsequent rating of a building are based on the thermal analysis provided by building thermal models such as AccuRate. The input for the analysis includes not only the house design but also a weather file containing a year's data for climate variables representing the expected typical conditions for the climate where the house will be built. This weather data file is referred to as a typical meteorological year (TMY). Once the TMY for 2030 and 2070 has been developed, a building energy analysis can be completed for 2030 and 2050, through interpolation.

2.1.1 Impact of Climate Change

In Appendix B of the CSIRO report, guidelines are provided for the projections of changes in the various climate variables at different probability levels. For instance, for Adelaide, there is a 90% chance that the mean temperature in summer will increase by at least 0.6^{o}C while only a 10% chance that it will increase by 1.4^{o}C or more. Three scenarios are provided for both 2030 and 2070. In the 2012 'State of the Climate Report' by the CSIRO and the Bureau of Meteorology, current trends in climate suggest that the more extreme scenario is more likely (CSIRO/BoM 2012). Therefore, for 2030 and 2070, the scenarios A1B (90p) and B1 (90p), respectively, from the CSIRO report are applied in this analysis.

The complicating feature that has to be taken into account is that the projected temperature increases are not expected to be uniform over time. Consequently, the changes to minimum and maximum temperatures are expected to vary. There is also an expectation of more frequent extreme temperature events. Previous work on altering climate data files (the TMY) includes that of Jentsch et al. (2008) and Guan (2009). The former relied on the method developed by Belcher et al. (2005), wherein the process called 'morphing' of data is used. This procedure involves a combination of shifting (translation) and stretching (dilation) of the separate climate variables to change their mean and variance. It does not take into account any differential translation or any cross-correlation between variables. The procedure described by Guan, on the other hand, is more sophisticated, having similar attributes but also taking into consideration differential changes for minimum and maximum temperatures. The drawback of the method used is that the representation of the variation of temperature over the day is represented by a single sinusoid, unchanging over the year. Herein, a more sophisticated Fourier model for both temperature and solar radiation is used. The solar radiation treatment is more sophisticated here as well, taking into account the three components of radiation, global, diffuse and direct.

2.1.2 Temperature

The data used in the development of a 2030 data set were based on the TMY data for Adelaide. This was constructed using the methodology of TMY2 as in Marion and Urban (1995). It has 8,760 hourly values. The year runs from 1 December as the year is split into seasons, with summer being December to February. The first step is to identify and model the seasonality which can be represented using discrete Fourier transforms which reveal periodicities in the data as well as the relative strengths of those periodic components (Boland 2008). Several significant cycles were identified using spectral analysis. The power spectrum in Figure 2.1 illustrates that the significant peaks are located at 1,365 and 730 cycles/year, these being the annual, daily and twice-daily cycles. From this analysis, the Fourier series for the seasonality in Adelaide is of the form given in Equation 2.1, with time, '*t*', in hours.

$$\begin{aligned} T(t) = \alpha_0 + \alpha_1 \cos \frac{2\pi t}{8760} + \beta_1 \sin \frac{2\pi t}{8760} \\ + \alpha_2 \cos \left(365 \frac{2\pi t}{8760} \right) + \beta_2 \sin \left(365 \frac{2\pi t}{8760} \right) \\ + \alpha_3 \cos \left(730 \frac{2\pi t}{8760} \right) + \beta_3 \sin \left(730 \frac{2\pi t}{8760} \right) \end{aligned} \tag{2.1}$$

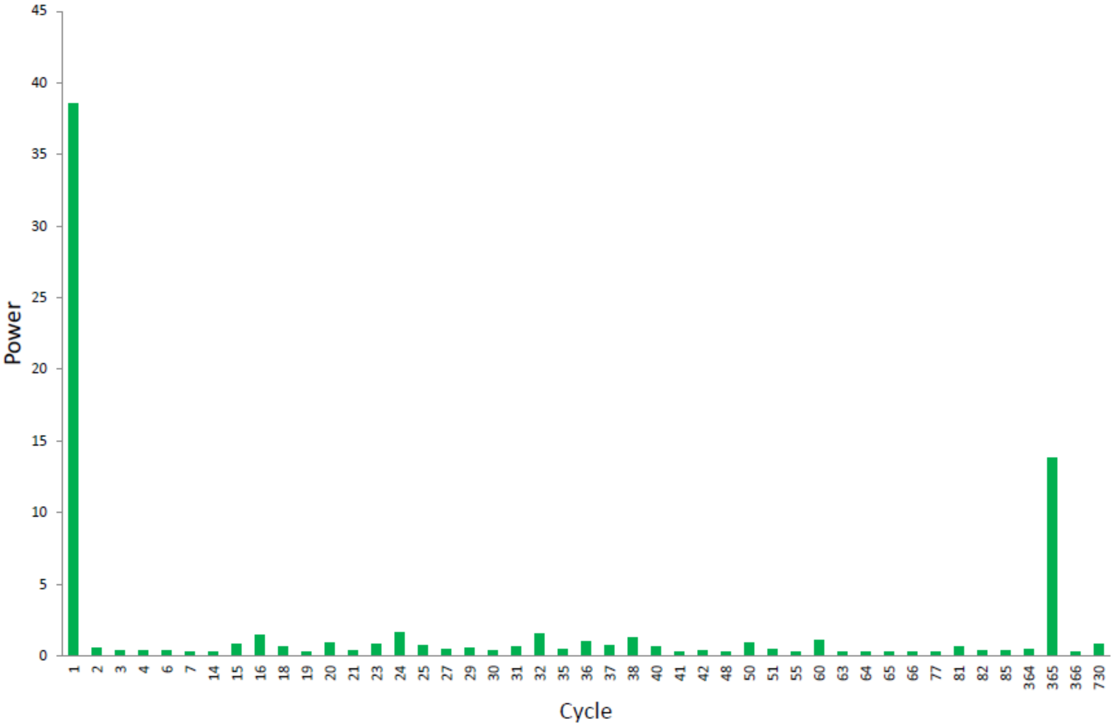


Figure 2.1: Power spectrum for temperature – the X-axis is in cycles/year

Here *T (t)* is the seasonal component which can be seen overlaid on the actual data in Figure 2.2. Subtracting the seasonal component from the original hourly time series gives what is called the de-seasoned data. From Figure 2.3, it can be seen that there is a higher variance in summer than winter. However, on examining only the summer data (Figure 2.4), it is apparent that the data are now homoscedastic (common variance) and thus the variance does not need to be considered in the context of climate change adaption. To enable the adjustment of the residuals to create a higher frequency of extreme events in 2030, an appropriate probability distribution is fitted to the frequency distribution of the summer residuals. One that is defined on a closed interval with no assumption of symmetry is the beta distribution, as given in Equation 2.2 where *B(a,f3)* is the beta function, *a* and *f3* are the shape parameters and the range is *a x b*.

The model fit (Figure 2.5) is not as good as one would hope. One issue was identified that ultimately led to an improvement. The essential assumption about the residuals from the Fourier series model is that they should be independent of the original series. However, in plotting these residuals against the original data (Figure 2.6), there is an upward trend in the residuals with an increase in temperature. The dependence can be accounted for using simple linear regression. The frequency distribution of these residuals (data minus model) from this regression analysis is then fitted with a beta distribution. With these new residuals, the beta distribution fit is far more successful as seen in Figure 2.7. This is supported by Figure 2.8 for the first week in December. This is a comparison between the real data after the seasonality has been removed and the corresponding values from the beta model correlated to the frequency distribution of these residuals as depicted in Figure 2.7. Note that when going through this process, a time stamp is added to each data value so that after all adjustments are made to a specific data value, it can be put back into the final model at precisely the same time from which it was derived.

$$y = f\left(x|a,b,\alpha,\beta\right) = \frac{(x-a)^{\alpha-1}(b-x)^{\beta-1}}{B(\alpha,\beta)(b-a)^{\alpha+\beta-1}} \qquad (2.2)$$

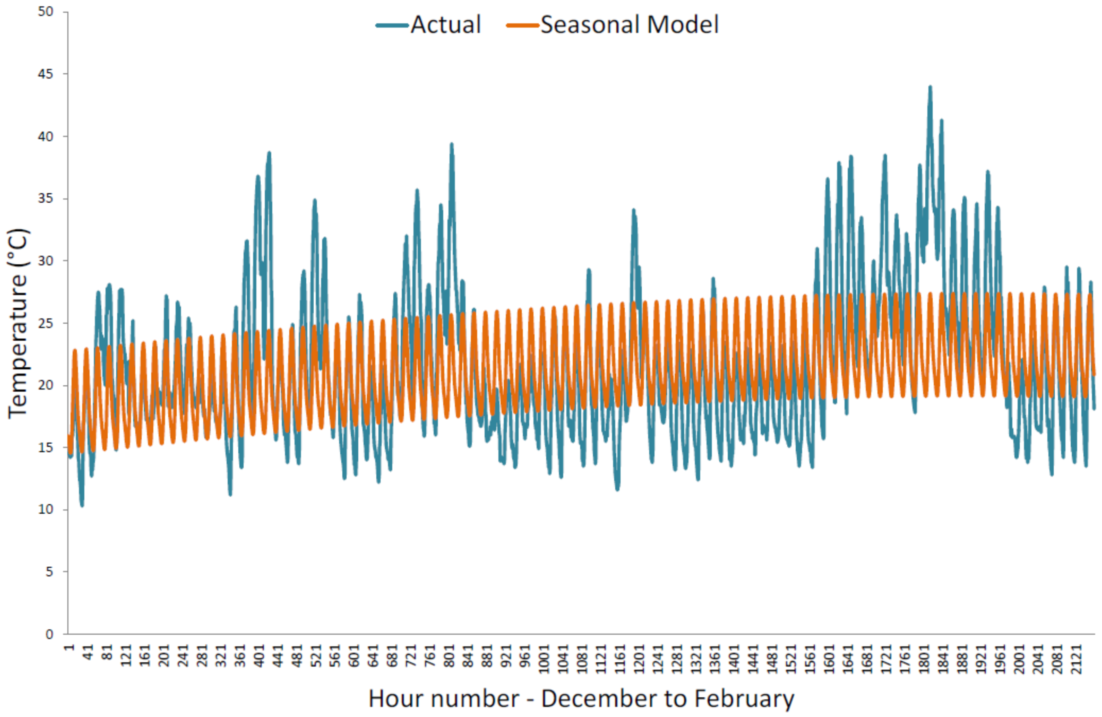


Figure 2.2: Adelaide seasonal model for temperature during the summer

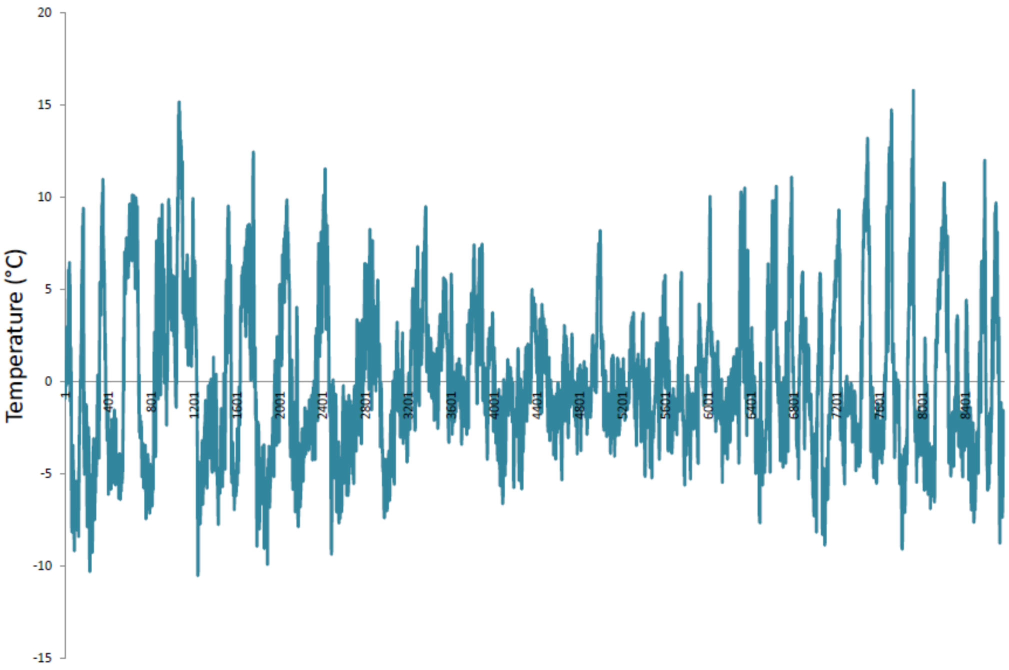


Figure 2.3: De-seasoned temperature

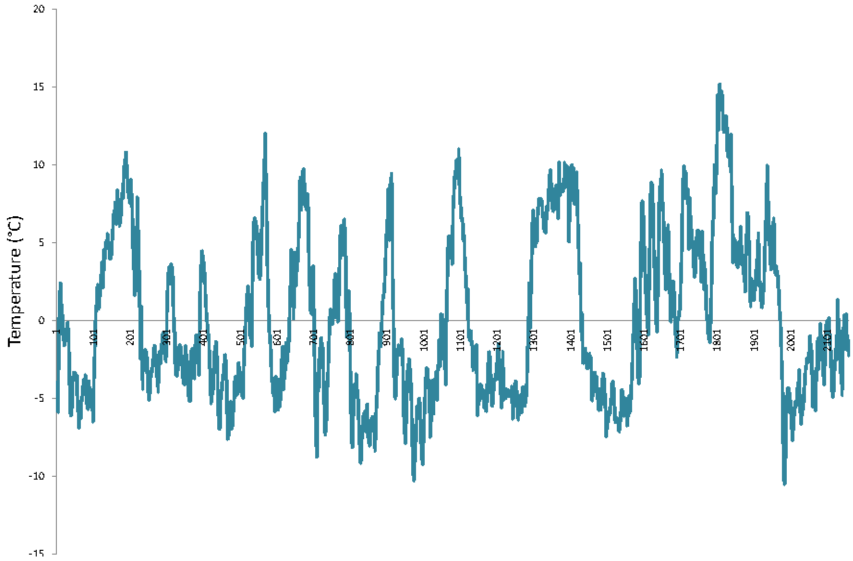


Figure 2.4: De-seasoned summer temperature

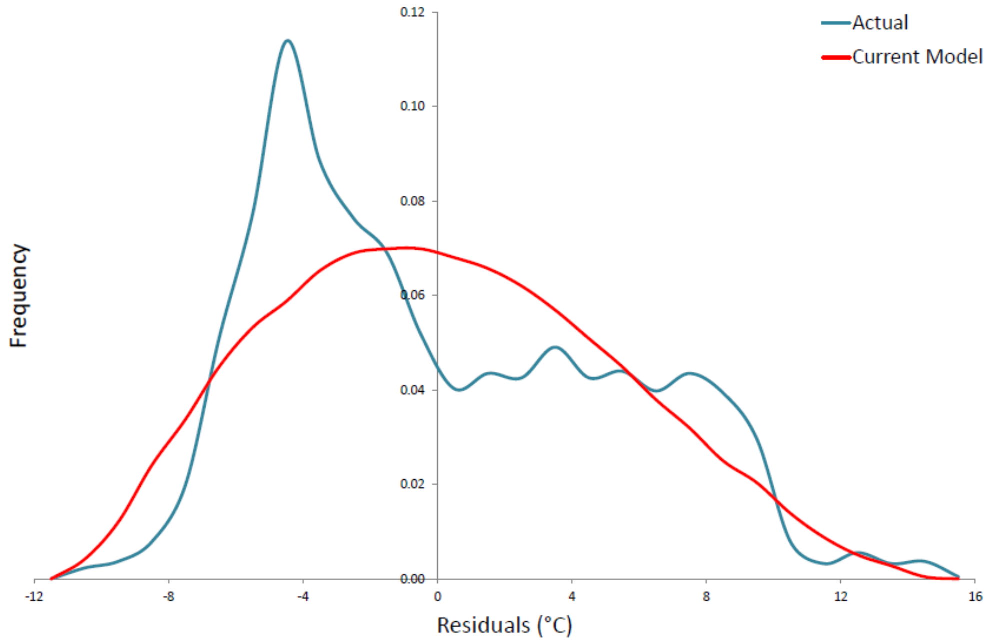


Figure 2.5: Summer standardised residuals and beta distribution

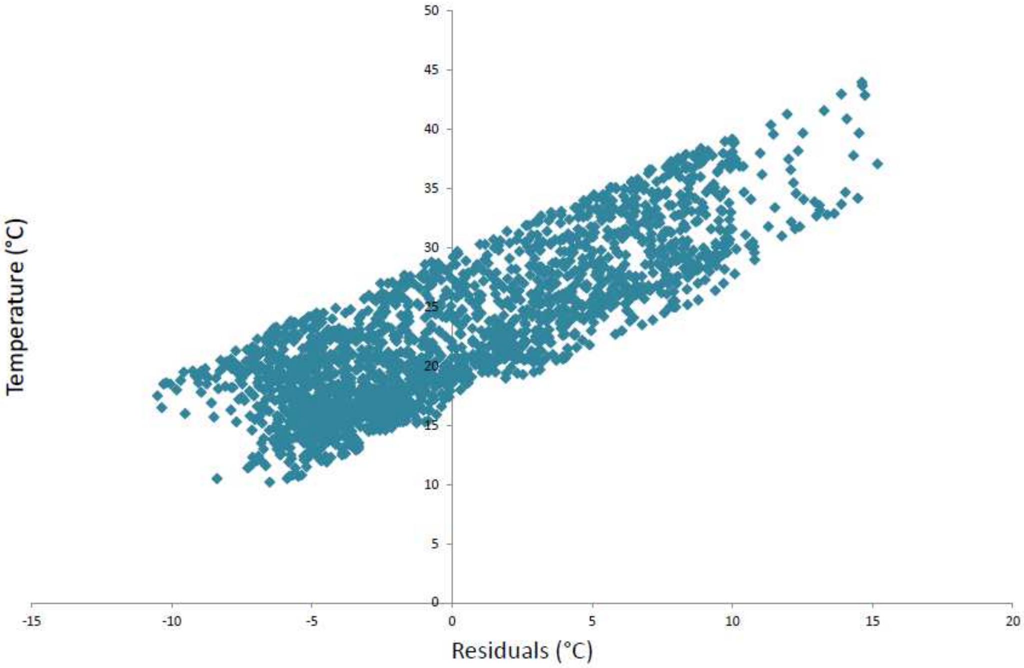


Figure 2.6: Summer temperature residuals against original data

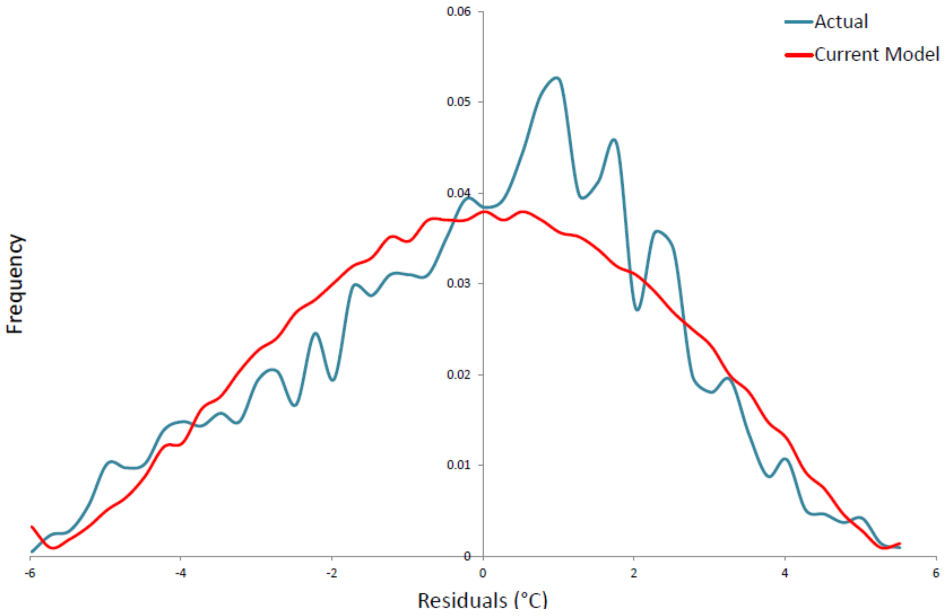


Figure 2.7: Summer standardised residuals and beta distribution

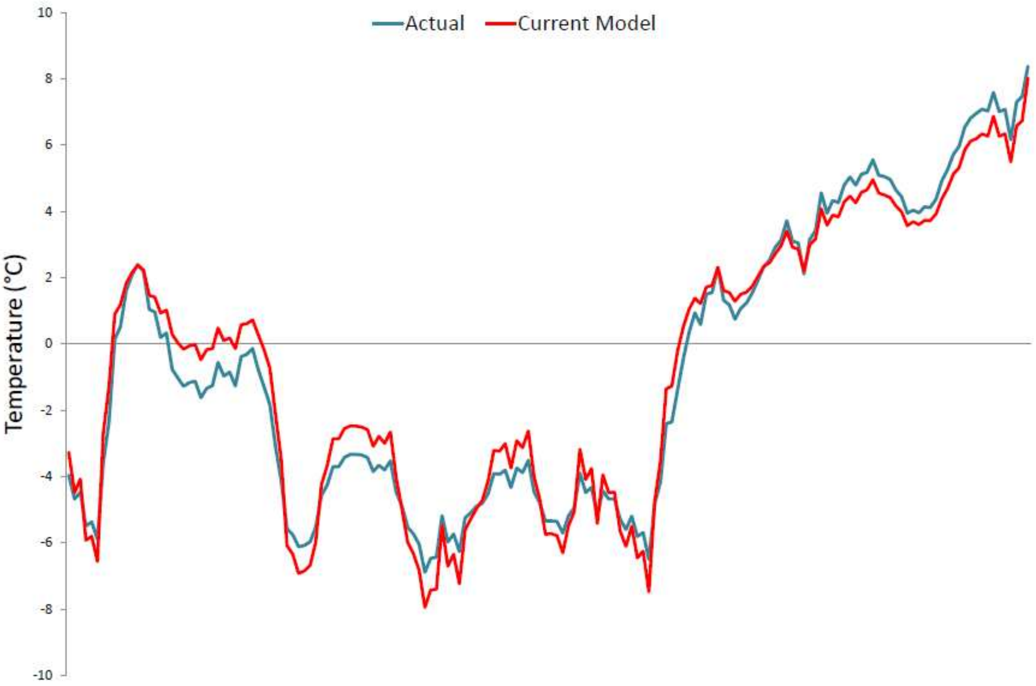


Figure 2.8: Summer residuals with beta model

The 'Climate Change in Australia' report (Watterson et al. 2007) states that during summer, the maximum temperature increases by up to 5% more than the mean in coastal locations. At the same time, the average increase in Australian minimum temperature is predicted to be approximately 10% higher than the average. This indicates that there needs to be a differential change in the temperature, the minimum is changing at a different rate to that of the maximum. Previous work in this area uses the technique of morphing whereby two transformations are applied to the present data sets (Belcher et al. 2005; Jentsch et al. 2008). With reference to the climate change projections, a climate variable, for example, temperature, is both translated and stretched, thus changing both the mean and the variance. There is no allowance for the differential change of minimum and maximum temperatures. In the present work, the Fourier series daily profile is altered more in the minimum than the maximum.

The process for developing the adjusted data set for temperature is detailed in the following steps:

1. Using the current TMY data, the year is rearranged to flow from December to November to assist with seasonal flow.
2. A Fourier series for the annual, daily and twice-daily components is identified as per Equation 2.1. This analysis is performed for the whole year's data.
3. The data for the season of interest is extracted and the residuals from the Fourier series are regressed against the temperature data to obtain a linear model for the trend in the residuals. This trend is then subtracted to form the second stage residuals.
4. A beta model is fitted to the frequency distribution of the residuals.
5. The 'Climate Change in Australia' report's (Watterson et al. 2007) projections for climate change mean there will be an alteration in the distributional specifics of the temperature. The procedure in this example entails taking the beta model of the standardised residuals and, keeping the 10th percentile static, increasing the 50th percentile by a small amount and the 90th percentile by a greater amount to account for the increased number of days over 35°C. This was done by solving a simple optimisation problem wherein we perturbed the α and β, parameter estimates so that the distribution has these altered percentile values. The effects of the changes to the residuals are evident in the comparison between present and projected cumulative distribution functions as shown in Figure 2.9.
6. The Fourier series in Step 1 is now refitted to accommodate the amount of the seasonal increase in temperature as identified for the location less the amount already accounted for in Step 5.
7. The new Fourier series, the model for the residuals trend (Step 3) and the beta residuals from Step 4 are added together to form the new adjusted data set for the season. The effects of the alterations are shown in Figures 2.10 and 2.11.

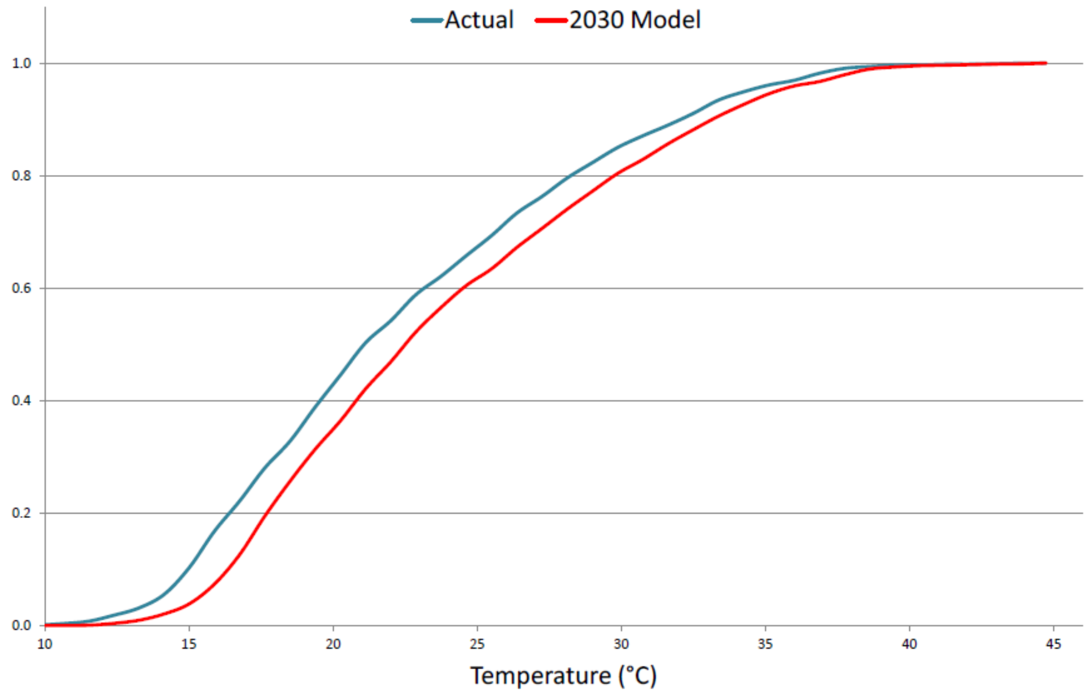


Figure 2.9: Comparison of cumulative distribution functions (CDFs) of original and altered residuals

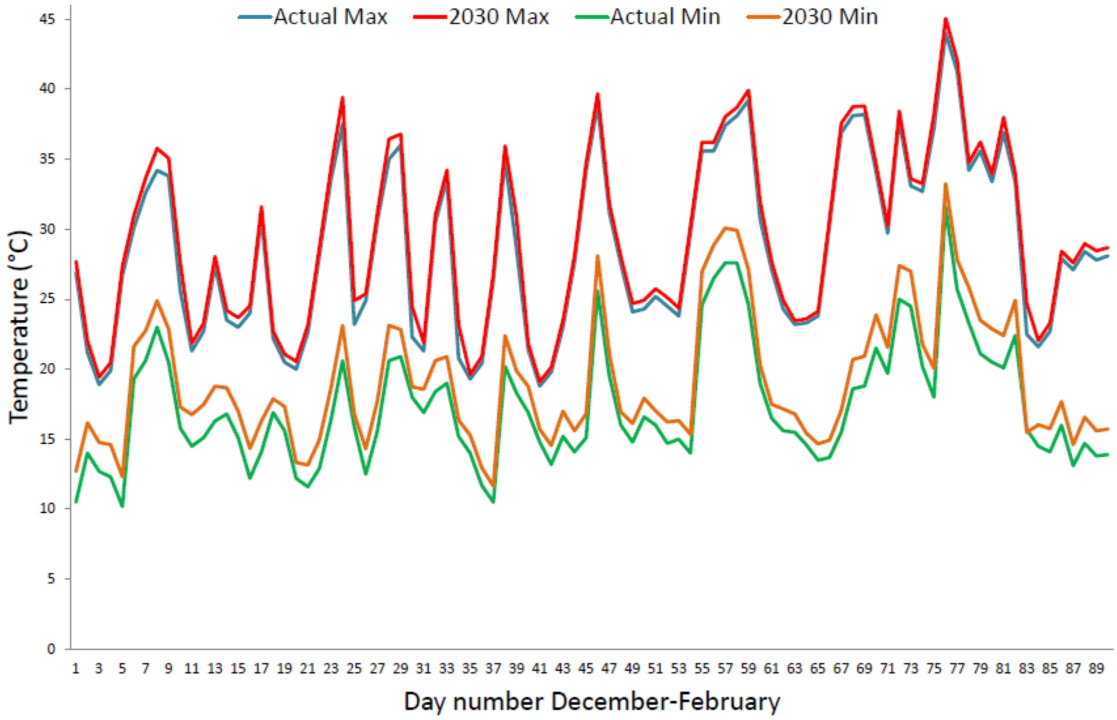


Figure 2.10: Comparison of maximum and minimum temperatures during the Adelaide summer

2.1.3 Radiation

A different approach is taken for solar radiation modelling. The Intergovernmental Panel on Climate Change (IPCC) ‘Report on Climate Change’ (Trenberth et al. 2007) states that "[t]he increase in surface solar radiation (brightening) agrees with satellite and surface observations of reduced cloud cover" (Wang et al. 2002; Rossow & Duenas 2004; Norris 2005; Pinker et al. 2005). This then suggests that with reduced cloud cover the increase in global radiation should be accounted for by an increase in only the direct radiation.

Again, using the Adelaide hourly values from the TMY, the annual increase for solar radiation in Adelaide in 2030 is projected to be 1.2% (Watterson et al. 2007). Global solar radiation is broken down into its constituent elements as shown below.

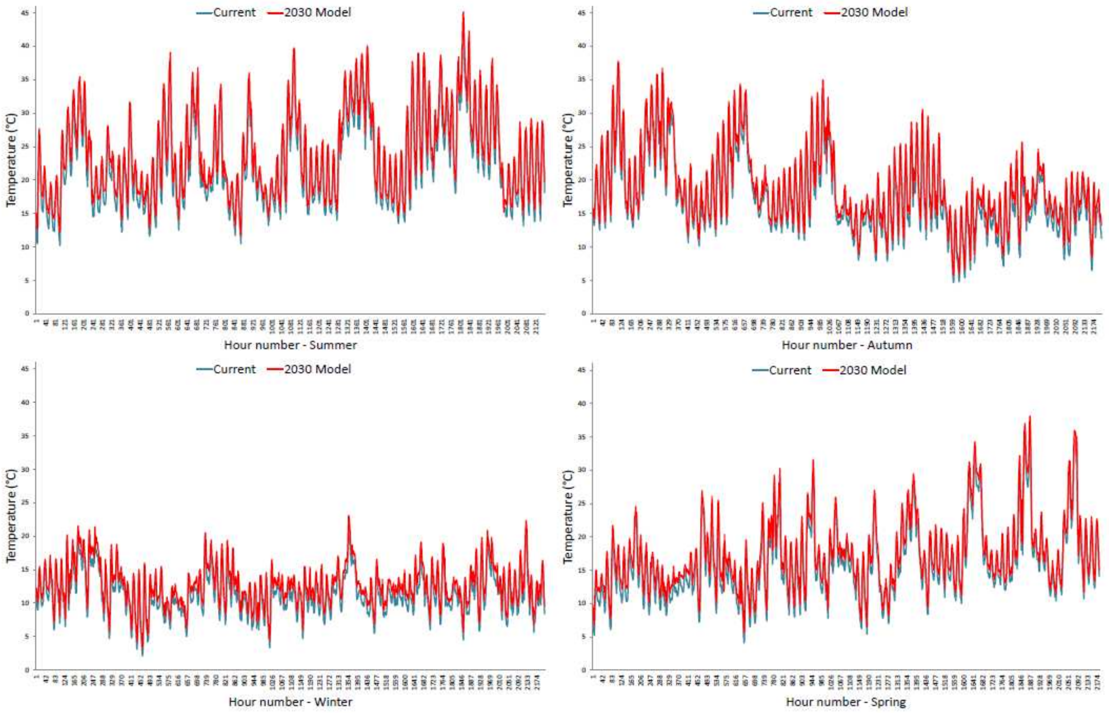


Figure 2.11: Seasonal models for temperature

$I_G = I_d + I_{DN} \sin \alpha$ (2.3)

where,

I_G = global radiation

I_d = diffuse radiation

I_{DN} = direct normal radiation

α is the solar altitude angle.

The global radiation is simply multiplied by 1 + 0.012 to obtain the desired increase. It is assumed that the increase will be only in the direct normal radiation, reflecting a clearer sky. To find the adjustment in the direct normal radiation, the fact is used that the global on the horizontal is the sum of the other two components on the horizontal plane. The calculation for the direct normal radiation is shown in the following equations, where the subscripts ^{C}, ^{A} stand for current values and adjusted values respectively. The diffuse radiation is then calculated using Equation 2.3. Figures 2.12 and 2.13 illustrate the quality of this methodology.

$$\begin{aligned} I_{\mathrm{G}}{}^{\mathrm{C}} &= I_{\mathrm{d}}{}^{\mathrm{C}} + I_{\mathrm{D}}{}^{\mathrm{C}} \\ &= I_{\mathrm{d}}{}^{\mathrm{C}} + \sin\alpha I_{\mathrm{DN}}{}^{\mathrm{C}} \\ I_{\mathrm{G}}{}^{\mathrm{A}} &= 1.012 I_{\mathrm{G}}{}^{\mathrm{C}} \\ &= I_{\mathrm{d}}{}^{\mathrm{C}} + I_{\mathrm{D}}{}^{\mathrm{A}} \\ &= I_{\mathrm{d}}{}^{\mathrm{C}} + \sin\alpha I_{\mathrm{DN}}{}^{\mathrm{A}} \end{aligned} \qquad (2.4)$$

$$I_{\mathrm{DN}}{}^{\mathrm{A}} = \frac{0.012 I_{\mathrm{G}}{}^{\mathrm{C}}}{\sin\alpha} + I_{\mathrm{DN}}{}^{\mathrm{C}} \qquad (2.5)$$

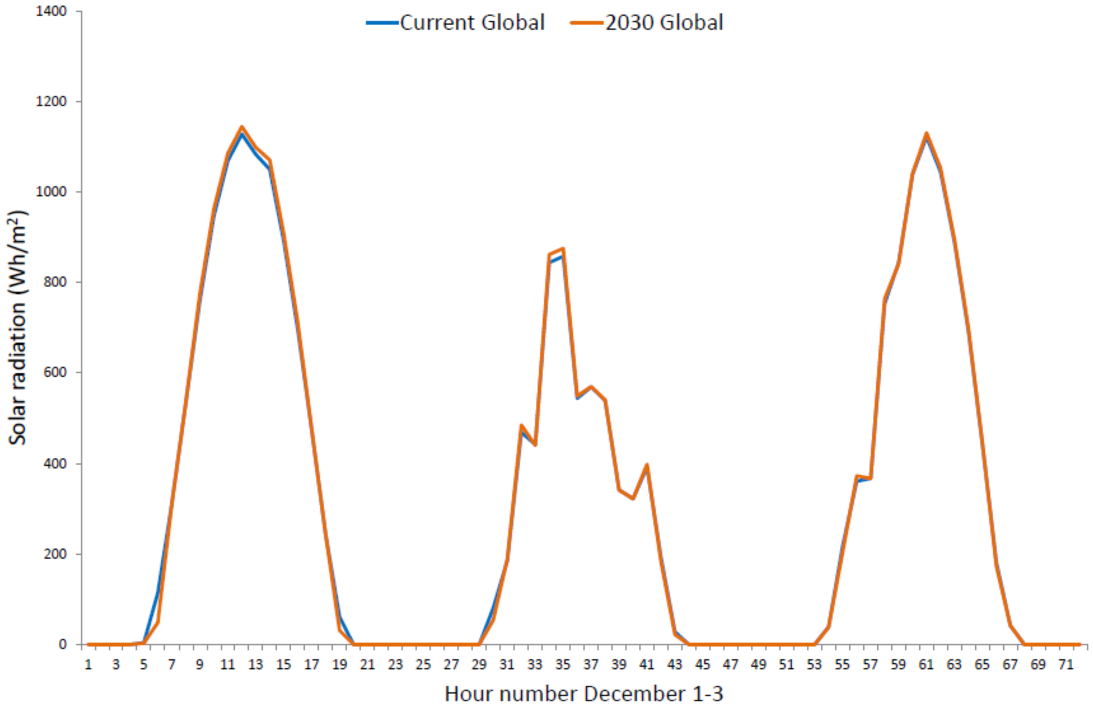


Figure 2.12: Original and 2030 summer global radiation

2.1.4 Cross Verification

As a method of verifying that the process is valid, it is necessary to inspect the cross-correlation between temperature and global radiation and to ensure that the same relationship exists within the current data and the 2030 data. The cross-correlation function (CCF) is a measure of the relationship between two time series at multiple lags. Ridley (2002) determined that temperature is dependent on the previous two days' solar radiation, but solar radiation is independent of temperature.

The temperature and radiation data used here are clearly not normally distributed so one cannot use a standard correlation measure. However, Spearman's rank correlation coefficient (p) is a non-parametric measure of statistical dependence between two variables. It assesses how well the relationship between two variables can be described using a monotonic function. Table 2.1 presents the statistical analysis summary of this test. Here we can see that the correlations for the current data and the 2030 data are almost the same.

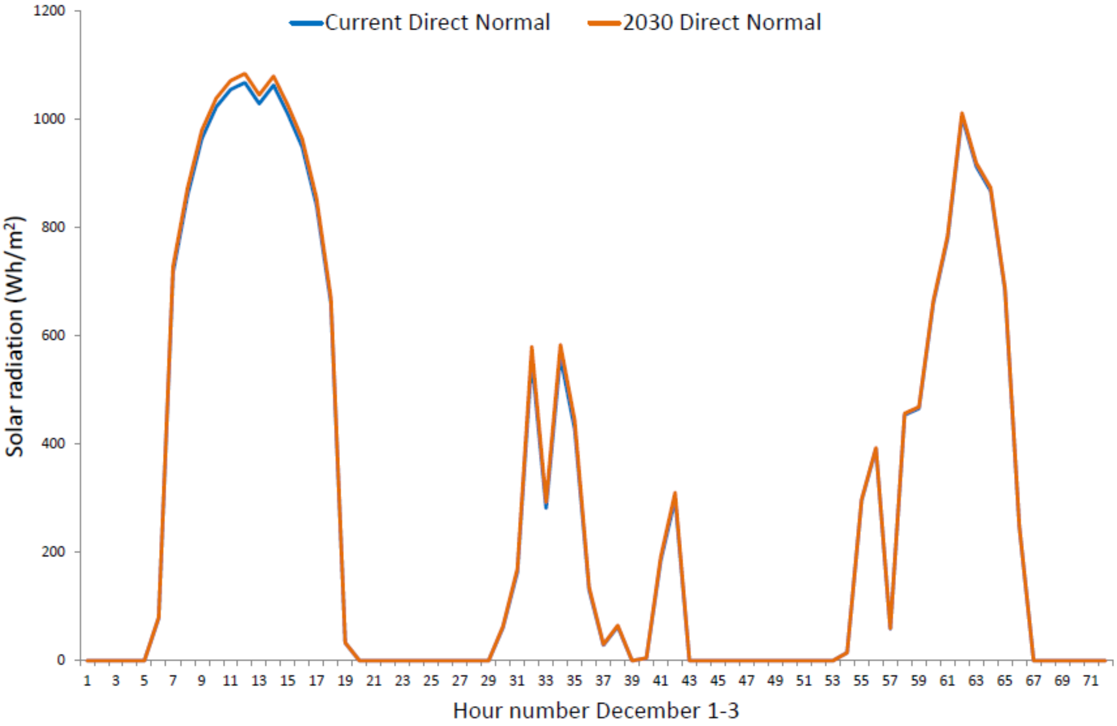


Figure 2.13: Original and 2030 summer direct normal radiation

Table 2.1: Pearson cross-correlations

	Temperature	
	Current	2030
Global	0.201	0.198
Global (t-1)	0.368	0.367
Global (t-2)	0.250	0.253

2.1.5 Relative Humidity

The amount of water vapour in the air at any given time is usually less than that required to saturate the air. The relative humidity defines this fraction of saturation. The following formulation for relative humidity was obtained from the website for Hyperphysics (Nave 2005) which is hosted by the Georgia State University. Relative humidity is the ratio of the actual vapour density and the saturation vapour density for a given temperature. The saturated vapour density (SVD) is given by Equation 2.6 and is a function of the dry bulb temperature.

$$SVD = 5.018 + 0.32321T + 8.1847 \times 10^{-3}T^{2} + 3.12473 \times 10^{-4}T^{3} \qquad 2.6$$

In a TMY, the corresponding variable is moisture content, which is equal to actual vapour density. So, by taking into consideration the CSIRO projections for changing the relative humidity, one can solve this equation to obtain the projected moisture content in consideration of the new temperatures as obtained in Section 2.1.2.

2.1.6 Baseline Data Selection

The work reported in this chapter is based on baseline TMY climatic data for all Australian capital cities. Newly developed TMY data were anticipated to be the basis of the development of future data for this project. Only some of this baseline data was supplied, and this occurred in the second half of the project, with the rest provided at the conclusion of the project. In addition to the lack of data, uncertainty surrounding the basis for this data has prevented its use.

Table 2.2 summarises this new TMY data for Adelaide, showing how data for all of summer and half of spring are chosen from 2004. The long-term averages for Adelaide are presented in Tables 2.3 and 2.4. An inspection of them shows that the mean minimum and maximum temperatures for 2004 versus the long term are substantially different. The purpose of these weather data is to represent the ‘typical’ year. To investigate the impact of climate change, future weather was alternatively developed from the best available existing TMY data.

Table 2.2: Description of newly supplied TMY for Adelaide

Location	Year	Month	Season
AD	2004	12	Summer
AD	2004	1	
AD	2004	2	
AD	1998	3	Autumn
AD	2000	4	
AD	2001	5	
AD	2005	6	Winter
AD	1999	7	
AD	2000	8	
AD	2004	9	Spring
AD	1999	10	
AD	2004	11	

Table 2.3: Long-term minima for Adelaide

Year	Jan	Feb	Mar	Oct	Nov	Dec
2002	15.3	15	14	11.1	14.2	16.1
2003	18	17.4	13.2	9.4	14.9	16.9
2004	14.9	17.8	14.1	12	14.1	15.4
2005	16.8	15.1	14.3	12.1	14	16
2006	19.9	15.5	16.5	11.8	14.1	15.6
2007	18.2	19	16.1	11.7	14.9	16.4
2008	17.5	16.4	17.9	12	14.3	15.4
2009	17.9	18.7	15.1	11.5	18	15.9
2010	18.1	19	16.2	11.7	14.1	16
2011	18.3	18.6	15.2	13	14.7	16.3
2012	19.1	17.2	15.1			

Summary of statistics for period 1961–1990

Statistic	Jan	Feb	Mar	Oct	Nov	Dec
Mean	17.1	17.2	15.2	11.5	14	15.6
Lowest	14.1	15	13.1	9.4	12.3	12.8
5th %ile	14.6	15.2	13.3	10	12.4	14.1
10th %ile	14.8	15.5	13.9	10.6	12.6	14.5
Median	17.4	17.1	15.1	11.7	14.1	15.8
90th %ile	19.3	19	16.6	12.2	14.9	16.5
95th %ile	19.9	19.9	17.1	12.5	15.6	16.7
Highest	20.3	20.3	18	13	18	16.9

Table 2.4: Long-term maxima for Adelaide

Year	Jan	Feb	Mar	Oct	Nov	Dec	Annual
2002	27.2	26.4	25.8	21.6	26.4	27.8	22.4
2003	31.4	29.2	24.8	19	27.6	29	22.5
2004	25.9	32.2	27.7	23.8	24.7	27.3	22.6
2005	29.1	27	26.2	22	25.2	27.3	22.8
2006	31.9	27.2	28.6	24.4	27.1	28.5	23.1
2007	29.6	32.9	27.3	23.2	28	28.9	23.7
2008	31	27.6	30.9	24.1	24.7	25.5	22.8
2009	32	31.4	26.3	21.9	30.8	28.5	23.5
2010	31.4	31.4	27.7	21.4	24.3	26.7	22.5
2011	30.6	29.1	24.6	22.1	26.8	27.9	22.7
2012	31.1	28.1	26.2				

Summary of statistics for period 1961–1990

Statistic	Jan	Feb	Mar	Oct	Nov	Dec	Annual
Mean	29.3	29.4	26.3	21.8	25.1	27	22.3
Lowest	25.1	26.4	23.1	18.8	21.5	23.3	21
5th %ile	26.2	27.1	23.8	19.6	22.6	24.8	21.4
10th	26.3	27.3	24.4	20.6	22.7	25.1	21.6
Median	29.1	29.1	26.2	21.9	24.7	27.3	22.3
90th	31.9	32.1	28.2	23.4	27.6	28.8	22.9
95th	32	32.3	28.7	23.9	28	28.9	23.2
Highest	33.7	32.9	30.9	24.4	30.8	29	23.7

2.1.7 Future TMY Generation

Development of the TMY involves identifying both the changes in direct and diffuse radiation. The CSIRO report (Watterson et al. 2007) is unclear about the levels of change in the variables and some informed extrapolation has been required. The report provides information on the increase in global radiation. With knowledge of the Adelaide climate along with the CSIRO reporting reduced cloud coverage, it was deduced that the increase should be accounted for in the direct radiation with no change in the diffuse component. The report is less clear with regards to the changes in other cities where the relationship between the maximum and the minimum temperatures is different.

The TMY data for all capital cities were generated for the years 2030 and 2070. Tables 2.5 and 2.6 summarise the key changes of the TMY. Table 2.5 shows the increase in warm/hot days. Adelaide, Melbourne and Perth show a 13%, 24% and 22% increase respectively in the number of days above 35°C in 2030. Darwin experiences a dramatic increase in the number of days above 35°C; however, this reflects some warm days above 30°C which shift category, and the total increase in warm/hot days is not significant. Sydney and Melbourne experience a dramatic increase, with the number of warm/hot days doubling in 2030. In Hobart, the number of warm/hot days does increase; however, the total number is still small. Table 2.6 presents the change in cold/cool days for each city in the TMY. Across all cities where heating is required, there is a significant decrease in the number of cold and very cold days. Overall, these results will have a significant impact on heating and cooling costs.

Table 2.5: Change in the number of warm and hot days in the TMY

Location	No. days, daily max ≥ 35°C			No. days, daily max ≥ 30°C		
	Current	2030	2070	Current	2030	2070
Sydney	1	4	7	13	25	29
Adelaide	23	26	36	63	69	74
Melbourne	7	8	12	27	34	38
Brisbane	0	0	1	21	46	69
Perth	23	28	40	72	84	91
Darwin	4	35	68	303	344	354
Hobart	1	2	2	4	6	7

Table 2.6: Change in the number of cold and very cold days in the TMY

Location	No. days, daily min ≤ 10°C			No. days, daily min ≤ 5°C		
	Current	2030	2070	Current	2030	2070
Sydney	55	36	20	0	0	0
Adelaide	126	92	65	12	4	1
Melbourne	155	100	80	14	7	4
Brisbane	55	35	24	9	6	2
Perth	116	85	53	15	4	1
Darwin	0	0	0	0	0	0
Hobart	220	184	162	56	30	24

2.2 *Design Data*

The American Society for Heating, Refrigeration and Air Conditioning Engineers (ASHRAE 2005) gives a standard set of guidelines for setting dry bulb temperature with coincident wet bulb temperature (or the other way around) to provide thermal comfort in particular locations. The summer design conditions are set based on historical maximum temperatures and coincident humidity measurements after discounting the extreme values (0.4%, 1% and 2% levels of exceedance of both dry and wet bulb temperatures and the coincident values of the other variable). On the other hand, the summer design conditions is set by the Australian Institute for Refrigeration, Air Conditioning and Heating (AIRAH 2007) by investigating the dry and wet bulb temperature values recorded at 3 p.m.

We have temperature data for the major capital cities in Australia, but not exactly in the correct format for our needs. As an example, the data for Adelaide was gathered at one location until 1977 with this location then changing. The most difficult aspect to deal with though is the fact that the wet bulb temperature is not recorded, only the dry bulb temperature and relative humidity. The standard method of estimating wet bulb temperature has been to use psychometric tables or charts. However, Stull (2011) derived an empirical formula for the estimation based on the dry bulb temperature and relative humidity, using a technique called gene expression programming. It is given as:

$$\begin{aligned} T_W &= T\tan^{-1}[0.151977(R_H+8.313659)^{\frac{1}{2}}] \\ &\quad +\tan^{-1}(T+R_H)-\tan^{-1}(R_H-1.676331) \\ &\quad +0.00391838{R_H}^{\frac{3}{2}}\tan^{-1}(0.023101R_H)-4.686035 \end{aligned} \tag{2.7}$$

2.2.1 *The ASHRAE Approach*

Table 2.7 presents the data for all capital cities. Data for these cities ranged from 1993–2012 to 1997–2012. For this approach, the 0.4%, 1% and 2% levels of seasonal temperature are calculated from the cumulative distribution function for the whole season. The second and third columns list the values of the dry bulb temperature and corresponding wet bulb temperature. These values are normally used to represent the outside summer conditions in the selection and sizing of comfort air conditioning equipment for buildings. The last two columns are the design conditions used when the humidity level is more significant than the temperature in equipment selection such as cooling towers. The different exceedance level choice depends on how critical is the particular situation in maintaining the indoor temperature when the outside conditions exceed the design conditions.

Table 2.7: ASHRAE summer design temperatures at different levels of exceedance for all cities

City	Percentage	DB	CWB	WB	CDB
Adelaide	0.4	39.8	17.4	23	27.1
	1	38.2	21.5	22.3	30.6
	2	36.6	19.4	21.5	42.6
Perth	0.4	38.9	18.8	24.2	35.2
	1	37.3	22.5	23.3	37.3
	2	35.7	23.2	22.6	26
Darwin	0.4	33.9	23.8	27.6	33.2
	1	33.4	25	27.3	33.1
	2	32.9	27.5	27.1	31.6
Brisbane	0.4	33.7	20.4	25.9	31
	1	32.4	22.2	25.3	32.2
	2	31.4	24.4	24.8	30
Melbourne	0.4	37.8	18.6	22.7	36.5
	1	35.6	19.4	21.8	23.9
	2	33.8	19.1	21	27.6
Sydney	0.4	33.2	23.3	24	28.9
	1	31	18.4	23.4	28.3
	2	29.1	24.8	22.9	23.9
Hobart	0.4	32.7	18.3	20.1	32.3
	1	29.8	17.8	19.2	25.3
	2	27.2	15.8	18.4	22.6

Note: DB = dry bulb; CWB = corresponding wet bulb; WB = wet bulb; CDB = corresponding dry bulb

2.2.2 The AIRAH Approach

The traditional method used by AIRAH relied on the temperatures at 3 p.m. every day of the summer for the years in which records were gathered. The design temperatures are those which are exceeded 10 times per annum. Table 2.8 shows the results for all capital cities. However, these data contradict currently presented data within the AIRAH standard. The dry bulb (DB) design condition for the AIRAH standard delivers similar results to the ASHRAE method at the 2% level, and the design wet bulb (WB) condition is consistent with the 0.4% level from the ASHRAE method.

Table 2.8: AIRAH summer design temperatures for all capital cities

City	DB	CWB	WB	CDB
Adelaide	36	16.6	20.4	35.3
Perth	35.7	21.6	22	41.9
Darwin	33.2	22.4	27	32.6
Brisbane	30.9	23.8	24.4	31.6
Melbourne	33	17.3	20.2	32.7
Sydney	28.1	21.2	22.2	25.6
Hobart	25.4	16.7	17.6	24

Note: DB = dry bulb; CWB = corresponding wet bulb; WB = wet bulb; CDB = corresponding dry bulb

In the AIRAH handbook, there is another criterion that should be calculated. This is the critical process design temperature, defined as the DB and WB temperatures that are individually exceeded 0.25% of the hours of plant operation. For continuous operation, values are given for all capital cities in Table 2.9.

Table 2.9: AIRAH summer design temperatures for critical processes

City	DB	CWB
Adelaide	40.4	23.4
Perth	39.6	24.6
Darwin	34.1	27.7
Brisbane	34.5	26.3
Melbourne	38.9	23.1
Sydney	34.9	24.2
Hobart	34.1	20.6

Note: DB = dry bulb; CWB = corresponding wet bulb

2.2.3 Adjusting Design Temperatures to Suit Climate Change Projections for 2030/2070

Due to the lack of availability of baseline data, accurate projections for design data could not be determined. However, indicative values are provided.

The suggested changes in the annual maximum and minimum temperature are presented in Table 2.10. These changes are based on the methods used to determine future temperature projections for the TMY.

Table 2.10: Increases in annual maximum and minimum temperatures due to climate change

	Minimum Temperature		Maximum Temperature	
	2030	2070	2030	2070
Adelaide	1.3	2.2	0.8	1.5
Brisbane	1	2.1	1.6	2.3
Darwin	1.4	2.5	1.5	2.3
Hobart	0.7	1.2	1.2	1.6
Melbourne	1	1.8	0.7	1.6
Perth	0.7	1.6	1.2	2.1
Sydney	0.9	1.8	1.6	1.7

Accurately determining future design temperatures involves using the same historical data on which the TMY is based. With a suitable data set, the appropriate method to develop future design temperatures involves firstly taking the summer dry bulb temperatures and fitting a beta distribution. This distribution is defined by Equation 2.8.

$$f(x;\alpha,\beta,a,b)=\frac{1}{(b-a)}\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\frac{(x-a)^{\alpha-1}(b-x)^{\beta-1}}{(b-a)^{\alpha+\beta-2}} \tag{2.8}$$

This distribution is appropriate since it is bounded above and below and allows for skew. Boundary conditions could be determined by applying a heuristic and simply adding and subtracting a certain percentage of the range of known temperatures to the historical minimum and maximum. There are also more systematic methods using extreme value theory. Once the parameters *α* and *β,* are estimated, the corresponding quantiles of 0.4%, 1% and 2% probabilities of exceedance can then be determined in line with the ASHRAE method. A relatively simple method to estimate these quantiles for 2030 and 2070 would be to assume that the parameters, *α* and *β,* do not alter but only the minima and maxima, as per Table 2.10. Therefore, the new quantiles could be estimated from the probability density function.

A more systematic method would be to perform the alterations to all the historical data that had been performed on the TMYs, and to then construct a frequency distribution of temperatures as was completed for the present design data estimation. This type of alteration would be performed on both dry bulb and wet bulb temperatures, and a similar procedure to what was done to construct present design data would be performed.

To demonstrate this approach, an analysis was conducted on the current and future TMY data. Table 2.11 shows the current and future design data based on the TMY with the increases in maximum DB temperature applied to 2030 and 2070 data. Comparing the current DB temperatures to the ASHRAE values confirms how the TMY represents a typical year rather than encompassing the extreme periods.

Due to the delays and concerns related to the baseline data, the correct approach to determining future design data was not possible. In the absence of this approach, indicative future design temperatures can be determined by simply adding the predicted maximum temperature increases to all DB conditions determined by using the ASHRAE method only. Table 2.12 presents these approximate values.

Table 2.11: Examples of current and future design data determined from the TMY

City	Percentage	Current	2030	2070
Adelaide	0.4	39.3	40.1	40.9
	1	37.8	38.7	39.4
	2	36.4	37.3	38
Perth	0.4	37.5	38.7	39.6
	1	36.4	37.6	38.5
	2	35.3	36.5	37.4
Darwin	0.4	34.1	35.6	36.4
	1	33.6	35.1	36
	2	33.2	34.7	35.5
Brisbane	0.4	31.2	32.8	33.5
	1	30.7	32.2	33
	2	30.1	31.7	32.4
Melbourne	0.4	33.9	34.6	35.5
	1	32.6	33.4	34.3
	2	31.4	32.2	33
Sydney	0.4	32.7	34	34.4
	1	31.5	32.8	33.2
	2	30.4	31.8	32.2
Hobart	0.4	27.6	28.6	29
	1	26.1	27.1	27.6
	2	24.8	25.8	26.3

The CSIRO report provides a single value for the change in relative humidity for each location. This change is very small on average equating to +0.2% for 2030 and +0.6% for 2070, across all cities presented. This change has an almost negligible impact on the WB temperature. Given the uncertainty relating to the predicted DB design temperature, the corresponding WB temperature was found, assuming a constant relative humidity. Furthermore, the CSIRO report does not provide sufficient data to predict future design WB temperatures. Table 2.12 presents the corresponding WB temperatures for future years on this basis.

It should be emphasised that the data presented in this section are insufficiently developed and further work is needed to determine correct design data for the future. However, in the absence of other data, this information can be used as a guide in air conditioning design.

Table 2.12: Indicative ASHRAE 2030 and 2070 summer design temperatures at different levels of exceedance for all cities

City	Percentage	2030		2070	
		DB	CWB	DB	CWB
Adelaide	0.4	40.6	17.8	41.3	18.1
	1	39	22	39.7	22.5
	2	37.4	19.9	38.1	20.3
Perth	0.4	40.1	19.5	41	20
	1	38.5	23.3	39.4	24
	2	36.9	24.1	37.8	24.8
Darwin	0.4	35.4	25	36.2	25.6
	1	34.9	26.2	35.7	26.9
	2	34.4	28.8	35.2	29.6
Brisbane	0.4	35.3	21.5	36	22
	1	34	23.4	34.7	24
	2	33	25.8	33.7	26.4
Melbourne	0.4	38.5	19	39.4	19.5
	1	36.3	19.8	37.2	20.4
	2	34.5	19.6	35.4	20.2
Sydney	0.4	34.8	24.6	34.9	24.7
	1	32.6	19.5	32.7	19.6
	2	30.7	26.3	30.8	26.4
Hobart	0.4	33.9	19.1	34.3	19.4
	1	31	18.6	31.4	18.9
	2	28.4	16.6	28.8	16.9

Note: DB = dry bulb; CWB = corresponding wet bulb

2.3 *Prediction of Future Heat Waves and Mortality Rates*

Mortality rates have been demonstrated to be related to the excess heat factor (EHF) developed by Nairn and Fawcett (2013). This EHF is a function of the running average over a number of months and identifies temperature spikes. Mortality rates have been correlated to threshold values of the EHF. During the project, it was established that the determination of future EHF values requires the development of future synthetic weather data. This work is no trivial matter, is incompatible with the process of developing the TMY and is therefore beyond the scope of this project.

A potential approach for developing future synthetic data suitable for identifying the increase in mortality rates could involve the developed future TMY. Since the TMY represents the average year, it may be possible to develop synthetic weather data from the future TMY which gives the appropriate distribution of weather years. Alternatively, if a set of future years was developed from the present historical data, with alterations to suit climate change forecasts, comprehensive statistical analysis on that set of years would allow synthetic weather data to be produced. To establish the appropriate parameters which define the distribution of data, current synthetic weather data could be produced which deliver the same EHF values as currently measured. Applying these calibrated parameters to the future distribution would then enable future EHF and, subsequently, mortality rates to be estimated.

2.4 *Conclusions*

The future TMYs for 2030 and 2070 that have been developed are suitable for use in building thermal modelling tools. The TMY was altered based on the climate change projections detailed in the 2007 CSIRO climate change report (Watterson et al. 2007). The most complex part of this operation relates to temperature projections which must cater for both the local differential increase in maxima and minima as well as the increased frequency of extreme events. Changes to solar radiation specified in the CSIRO report could be directly applied; however, judgments as to the change in direct and diffuse radiation were required. The only other relevant climate variable was relative humidity which was adjusted as per the CSIRO report, and accommodated into the TMY as a change in the WB temperature.

Current design data were determined using existing weather data and the ASHRAE and AIRAH methods. Future indicative design temperatures are provided based on increases in the TMY. Further work is required to establish correct design data as the predicted values only represent a guide.

3. ADAPTIVE THERMAL COMFORT

3.1 *Introduction*

Having established the outdoor design conditions for 2030 and 2050, this part of the research aims to establish new adaptive thermal comfort criteria for buildings as well as indoor comfort temperature settings to be used in air conditioning design calculations and energy rating tools. The study was conducted by investigating household responses during hot weather through: a questionnaire, comfort survey and the monitoring of indoor temperatures and humidity, in 60 houses in Adelaide, Brisbane and Sydney.

The adaptive comfort model is based on the observation that the room temperature that people find comfortable is related to the outdoor climatic context; indoor comfort temperatures are warmer in hot weather and climates, and cooler in cold climatic contexts. In 2004, the American Society for Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) adopted de Dear and Bragers' adaptive comfort model (1998) as part of ASHRAE Standards 55–2004 and 55–2010 Thermal Environmental Conditions for Human Occupancy (2004, 2010). The adaptive standard was based on over 21,000 building occupants' responses on a comfort questionnaire with accompanying concurrent indoor thermal environmental conditions (air temperature, radiant temperature, humidity, air speed, clothing insulation and metabolic rate estimates). The adaptive model presents two ranges of indoor temperatures that would be acceptable to either 90% or 80% of occupants, as a function of outdoor climate. Outdoor climate is parameterised in the model as either a monthly mean outdoor temperature, or an exponentially weighted, running mean over at least a week leading up to the point in the time of interest, with the most recent days having the heaviest weighting (ASHRAE Standard 55-2010R – Addendum D 2012). As large as it is, the database used in defining ASHRAE's adaptive comfort standard was mostly restricted to occupants of 160 office buildings scattered across various climate zones on four continents (scant residential thermal comfort studies).

It should be noted that, in 2012, heat waves were not experienced in Adelaide, Brisbane or Sydney. In the case of Sydney, the 2011/12 summer was anomalously cool and the 2012/13 summer was anomalously hot, yet still no prolonged heat wave occurred. According to the Australian Bureau of Meteorology (BoM), a heat wave is defined as three consecutive days with daily maximum temperature of 40^0C or above, or five consecutive days of 35^0C or above. The comfort study in Adelaide captured more data during the 2011/12 summer because the household sample was in existence before the NCCARF contract was executed, whereas the Sydney and Brisbane sub-studies experienced delays in recruiting households to the sample. Data during the 2012/2013 summer season (December 2012–March 2013) were collected for Sydney and Brisbane.

These data were used to investigate the applicability of the adaptive comfort model (ASHRAE 2010) in the residential context. Testing the applicability of the adaptive comfort model/standard requires simultaneous observations of internal room temperatures and the comfort reactions of house occupants to those temperatures, along with concurrent outdoor meteorological temperatures and trends. These data can then be assessed for compliance with the range of acceptable temperatures prescribed by ASHRAE Standard 55–2010. In this study, apart from the objective (i.e. indoor and outdoor thermal environmental conditions) and subjective data (i.e. the comfort questionnaire), we also collected background information on the householders, house construction type and comfort equipment ([air conditioner] A/C details, fans, etc.).

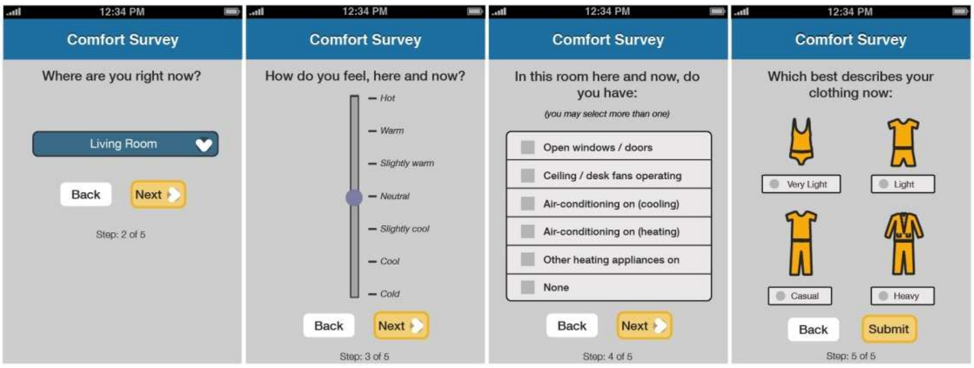
3.2 *Measurements*

Small autonomous temperature/humidity monitoring devices the size of a 5c piece (called iButtons) were installed in the sample householders' homes to record environmental conditions every 15 minutes. These were discreetly placed in the occupied zone of the main rooms throughout the sample houses, including the living room, bedroom, kitchen, dining room, study and any other rooms that featured air conditioner (A/C) units. The iButtons were typically attached to the underside of furniture, while maintaining thermal isolation from any thermal mass. In addition, an iButton was also placed directly into the supply-air pathway of the A/C or fan-coil unit of each room where air conditioning was installed. Data from the iButtons were uploaded every three months for the duration of the study. Significant divergence (> 4^0C) between simultaneous room and A/C supply-air temperatures enabled identification of when and where the A/C unit or units were being used. It should be noted that the indoor temperatures and humidity of eight houses in the Adelaide study were monitored by an in-built environmental system at 1-minute intervals, hence no iButtons were used in these houses.

Daily minimum and maximum outdoor air temperatures observed by the BOM were collected for the duration of the study. The selection of weather stations was based on their proximity to the houses in our samples. The association between each house and its corresponding weather station can be seen in Figures 3.2, 3.3 and 3.4 for the Sydney, Adelaide and Brisbane samples respectively. It should be noted that as the houses for the Adelaide study were located in Campbelltown SA about eight kilometres away from Kent Town, BOM gridded satellite data for Campbelltown SA developed by Energy Partners were also used to check if there were any significant differences with the data from the BOM in Kent Town. From these data, it was possible to calculate the daily mean outdoor temperature as well as an exponentially weighted running mean of the previous seven days (with yesterday's temperature most heavily weighted) which would be used in the ASHRAE adaptive comfort standard (ASHRAE 2010).

The installation of the iButtons was completed during the first site visit to the participant's residence. At this time, the participants were also asked to complete the background surveys. These surveys were used to gather general demographic information about the study sample, such as age, gender, income and education level, as well as detailed information regarding the participant's house, for example, building materials, shading quality, types of air conditioners, fans or heaters being used and how they operated these devices.

Throughout the monitoring period, participants were asked to respond to a comfort survey on a regular basis at least twice a week during mild weather, and more frequently when it was warmer. These questionnaires were used to record the participants' comfort perceptions of their thermal environment on a 'right-here-right-now' basis. For the Sydney study, the researchers periodically sent SMS messages directly to the householder's smartphone directing them to an online comfort questionnaire accessible on their smartphones (Figure 3.1). For the Adelaide study, as not all participants owned smartphones, two other options were available: paper-based and internet-based forms. In Adelaide's paper-based format questionnaire, participants were required to note the date and time each time a response was written (the smartphone and internet-based forms would automatically date- and time-stamp responses). The internet-based form had the same format as the smartphone version, except it asked if the respondents were in the same room in the last 15 minutes to determine if they had moved to a different room to log their response on the computer. In Brisbane, a combination of smartphone and paper-based questionnaires was used.



Where are you right now?

Living Room

Step: 2 of 5

How do you feel, here and now?

- Hot
- Warm
- Slightly warm
- Neutral
- Slightly cool
- Cool
- Cold

Step: 3 of 5

In this room here and now, do you have:

(you may select more than one)

☐ Open windows / doors
☐ Ceiling / desk fans operating
☐ Air-conditioning on (cooling)
☐ Air-conditioning on (heating)
☐ Other heating appliances on
☐ None

Step: 4 of 5

Which best describes your clothing now:

○ Very Light
○ Light
○ Casual
○ Heavy

Step: 5 of 5

Figure 3.1: The University of Sydney's smartphone 'right-here-right-now' comfort questionnaire

Note: This was initiated by an SMS text delivered to the householder's smartphone. If the householder was home at the time of the SMS, they were directed to this 4-screen, 60-second comfort questionnaire.

The comfort questionnaires asked four simple questions which identified: (1) whether the participant was at home; (2) the kinds of cooling strategies in use at that time, including A/C; (3) a simple classification of the clothing type and any thermal insulation being worn; and (4) the respondent's thermal comfort rating (i.e. thermal sensation on the universally accepted ASHRAE 7-point scale from cold (-3) through neutral (0), to hot (+3). Participants in Adelaide were asked an additional question about whether they would prefer to be warmer, cooler or to have no change. Each response was later matched to the corresponding room's physical indoor thermal environmental data recorded by the iButtons based on the time-stamp on the questionnaire.

3.3 *Survey Introduction*

All of the 30 households recruited for the Sydney sample had a smartphone (to complete the online comfort questionnaire) and at least one A/C unit installed in their home. The map in Figure 3.2 shows the location of participating households within the Greater Sydney region (33°51'S, 151°12'E). The Sydney Basin is large enough to contain several distinct climatic zones, and so 10 different BOM weather stations were used to maximise the relevance of the outdoor weather data to each house in the sample.

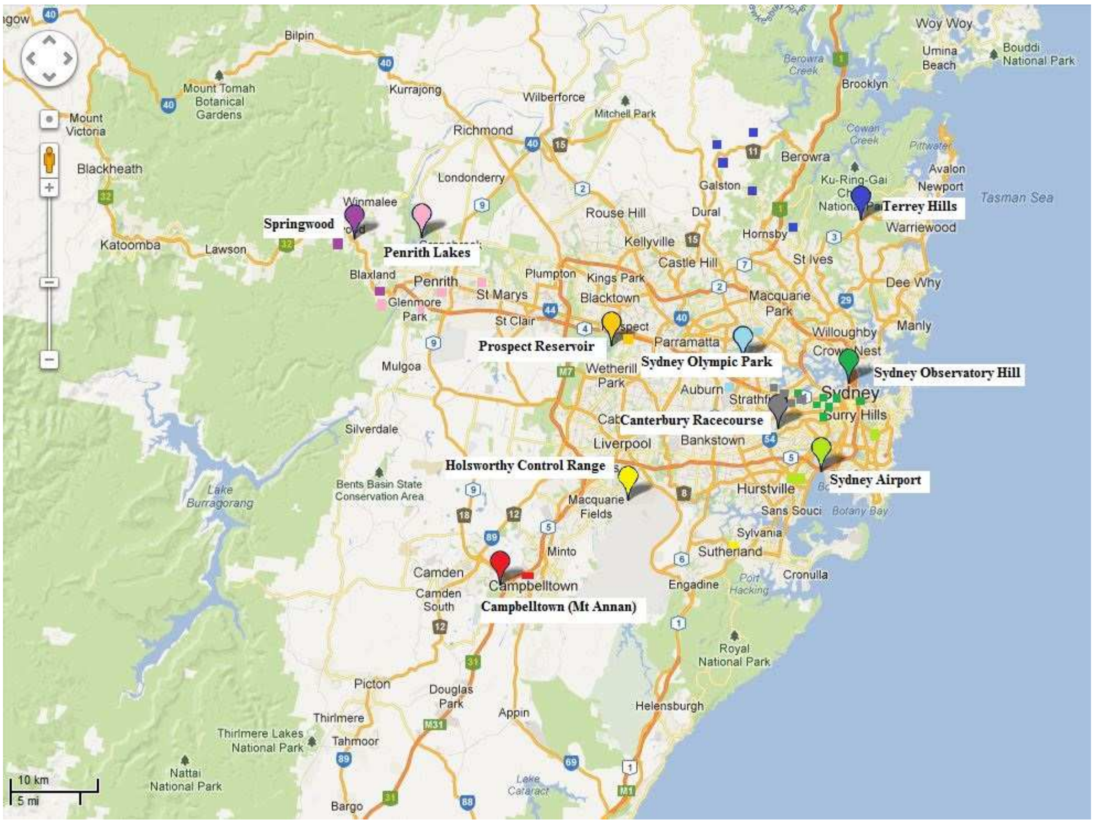
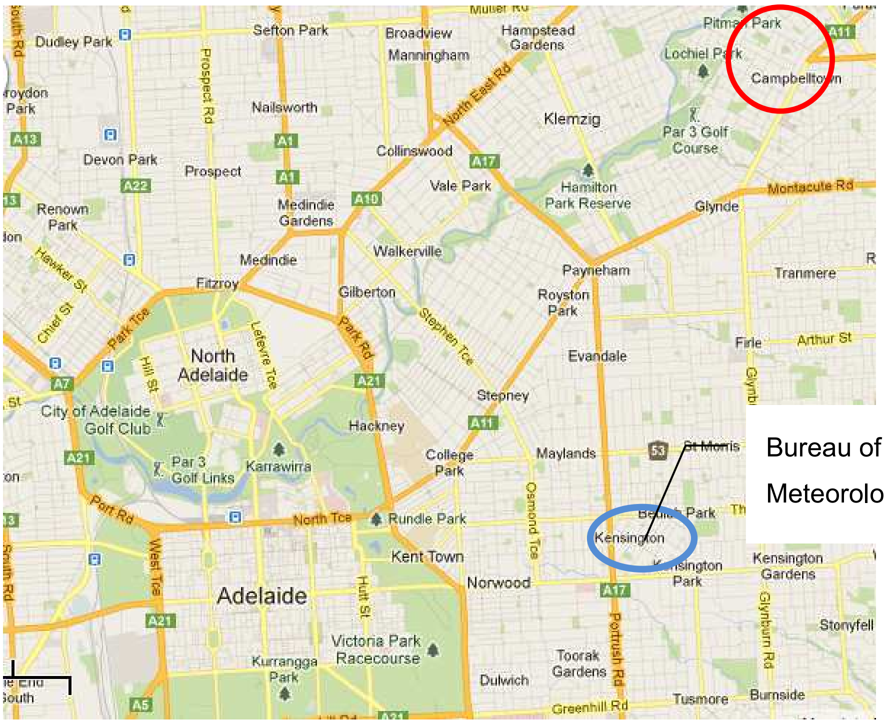


Figure 3.2: Map of Greater Sydney showing the location of recruited households and corresponding BoM weather stations

Note: This map shows the location of the 30 households recruited for the study and their corresponding Bureau of Meteorology weather stations which have been colour-matched (Modified from Google 2013).

Eighteen of the Adelaide households were located in Lochiel Park, Campbelltown with two other households being in the area just outside this housing development (Figure 3.3). This housing development is part of the CSIRO Intelligent Grid Cluster (www.igrid.net.au), established as a model "green village" with large landscaped areas, wetlands, energy-efficient housing and a recycled water system. Strict guidelines cover site planning and the design of the buildings. The majority of houses in this development are single, detached, owner-occupied homes. The development also has two-storey blocks of apartments built for low income families: these were also included in this study.



Bureau of Meteorology

Figure 3.3: Map of Adelaide and the location of households (red) recruited for the Adelaide study (modified from Google 2012)

Twenty households were recruited in south-east Queensland, as described in Table 3.4. The selection criteria consisted of dwellings constructed since 2005 (or which had had major renovations since that period) and dwellings equal to, or less than, the median house size for new Queensland homes (230 m^2). The targeted geographic area for recruitment was Brisbane's western suburbs (BERS Pro climate zone 9) as these inland suburbs do not experience cooling sea breezes, resulting in hotter summer temperatures and colder winter conditions compared to suburbs closer to the Pacific Ocean. They are also the main growth areas for new residential development in Brisbane.

Recruitment in the Springfield area of Brisbane was assisted by the estate developer, Lend Lease, which provided a list of preselected houses that met the construction and size criteria, and advertised the project in the community newsletter. A letterbox drop was conducted specifically to these pre-identified houses. Additional households within the general 'western Brisbane' suburbs were recruited by further direct mail campaigns, network emails and word-of-mouth.

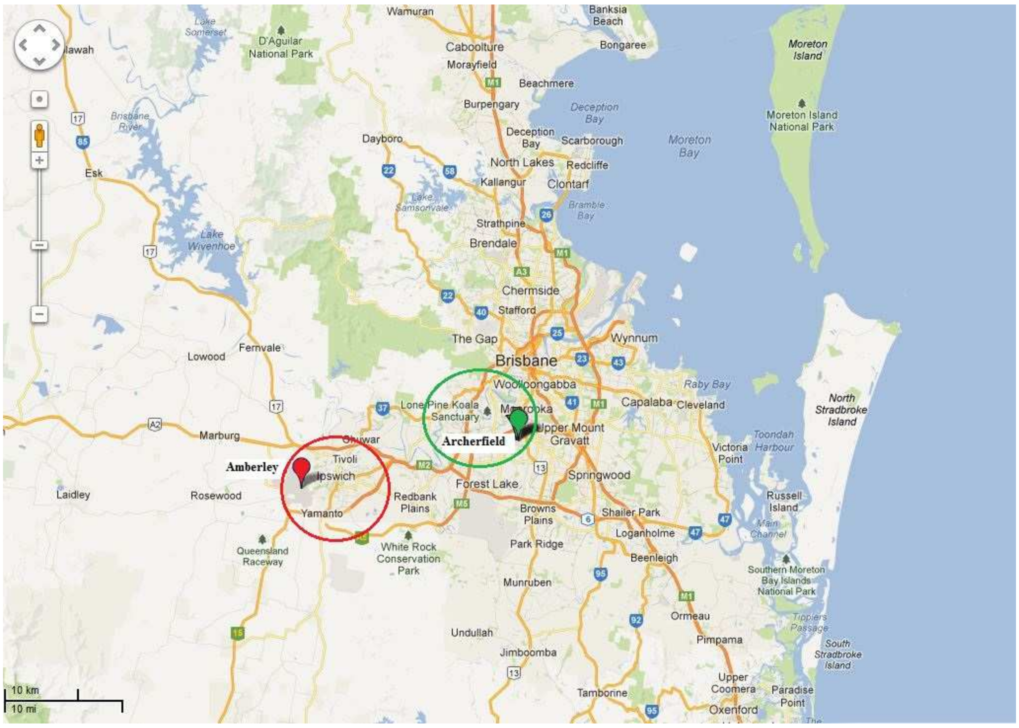


Figure 3.4: Location of the Brisbane household sample (in circle) and the corresponding BoM weather stations (Modified from Google 2013)

3.4 *Demographics*

Table 3.1 provides a descriptive summary of the demographic variables for each participating household in Sydney. Both genders were fairly equally represented with 18 females (60% of the sample) and 12 males (40%). According to the latest 2011 Census data from the Australian Bureau of Statistics (ABS), Sydney's population consists of 51% females and 49% males (ABS 2012). The participants' ages ranged between 30 and 60+ years old with 58% of the sample aged between 30 and 39, which is comparable to Greater Sydney's median age of 36 (ABS 2012). The majority of participants resided in Sydney's inner-western (five houses) and outer-western (seven houses) suburbs which, when combined, represented 41% of the sample. The next most populous location in terms of participants was the south-western suburbs, such as Newtown, Ashfield and Camperdown (five houses, 17%). The number of occupants in each house ranged between one and six with 12 houses having two occupants (41%). The sample can be considered highly educated with the majority of participants (18 houses, 62%) having achieved a postgraduate, Master's or PhD degree. Given the above average levels of education and that most participants worked full-time, it was not unexpected that 16 houses (55%) reported having a combined income over $110,000.

Table 3.2 provides a descriptive summary of the demographic variables for the participants in Adelaide. Not all occupants responded to the thermal comfort survey; however, of those who responded, both genders were fairly equally represented. The sample consisted of six households with a combined income of up to $50,000 per year, six households with a combined income of $50,000–$90,000 per year, and eight households with a combined income of more than $110,000 per year. The education levels varied from having completed high school to having PhD degrees. There were more participants who worked full-time than part-time.

Key demographics of the Queensland households are summarised below:

- They represent a range of family types from single adults, households of adults only, and households of adults and children. A quarter of participating households had children under school age. The breakdown is shown in Figure 3.5.
- Fifty per cent of the households were single-income households (i.e. only one adult working full time).
- No households had an annual gross income of less than $50,000. Half of the households had an annual gross income of greater than $110,000 (usually represented by more than one full-time working adult).

3.5 *House Construction and Other Design Features*

Table 3.3 provides detailed information for the Sydney sample regarding the participants' house typology and construction. The sample consisted of a mixture of one- and two-storey dwellings (accounting for over 70% of the sample) and apartments (six houses, 21%). Out of these 29 participating households, 17 were located on suburban terrain (59%), six were in urban areas and five were in rural areas.

House construction materials were analysed according to the most common responses. According to Table 3.3, the most common outer wall material was double brick (11, 38%) followed by brick veneer (10, 34%). A few houses featured lightweight cladding, timber and concrete. The most common roof material was tiles (15, 52%) and corrugated steel (10, 34%). In terms of floor, ceiling and inner wall materials, many households had combinations of different materials. Most households had a concrete slab or suspended timber floors (accounting for almost 50% of houses). The majority of households also had plasterboard ceilings with either timber-framed or plastered brick internal walls. It was noted that 66% of houses were insulated.

Table 3.1: Descriptive summary of participant demographic variables in Sydney based on background surveys

ID	Gender	Age	Location	Occupants	Education	Combined Income	Employment	
							Full-Time	Part-Time
1	M	30-39	SW	4	Postgraduate	NP	2	0
2	M	50-59	W	1	PhD/Masters	$110,000+	1	0
3	F	40-49	NW	3	University	$110,000+	1	1
4	F	50-59	NW	3	University	$110,000+	2	0
5	F	50-59	NW	3	TAFE	$50,000 to $70,000	3	0
6	M	60+	N	2	Postgraduate	$50,000 to $70,000	0	1
7	F	50-59	NW	4	University	$110,000+	1	3
8	M	30-39	N	2	University	$110,000+	2	0
9	F	40-49	N	4	University	$110,000+	3	1
10	M	30-39	SW	2	Postgraduate	$110,000+	2	0
11	F	30-39	SW	2	PhD/Masters	$30,000 to $50,000	1	1
12	M	30-39	SW	4	PhD/Masters	$110,000+	3	1
13	F	NP	W	NP	NP	NP	NP	NP
14	M	30-39	W	4	Postgraduate	$110,000+	3	0
15	M	30-39	W	6	Postgraduate	$50,000 to $70,000	0	2
16	F	50-59	W	2	PhD/Masters	$110,000+	2	0
17	F	30-39	SW	2	PhD/Masters	$110,000+	2	0
18	F	30-39	W	2	PhD/Masters	$90,000 to $110,000	1	1
19	F	30-39	SE	2	PhD/Masters	$70,000 to $90,000	1	1
20	M	50-59	W	4	Postgraduate	$110,000+	2	0
21	F	50-59	S	5	TAFE	$50,000 to $70,000	1	0
22	F	30-39	E	2	TAFE	$110,000+	1	1
23	M	30-39	W	6	University	$110,000+	4	1
24	M	40-49	W	4	PhD/Masters	$110,000+	1	1
25	F	40-49	S	3	University	$50,000 to $70,000	0	2
26	F	50-59	NP	2	PhD/Masters	$110,000+	2	0
27	F	30-39	S	3	Postgraduate	$70,000 to $90,000	1	0
28	F	40-49	W	5	Postgraduate	$90,000 to $110,000	1	1
29	F	30-39	W	2	Postgraduate	$110,000+	2	0
30	M	30-39	W	2	University	$90,000 to $110,000	2	0

Note: NP = response was not provided by the participant

Table 3.2: Descriptive summary of participant demographic variables in Adelaide based on background surveys

House ID	Gender	Age	Occupants	Education	Combined Income	Employment	
						Full-Time	Part-Time
1	F	50-59	1	Postgraduate	$50,000 to $70,000	1	0
2	F	60+	1	Postgraduate	$30,000 to $50,000	1	0
3	F + M	30-39	2	Postgraduate	$50,000 to $70,000	1	1
4	F + M	50-59	2	University - Postgraduate	$110,000+	1	1
5	M	21-29 50-59	2	High school	$10,000 to $30,000	0	0
6	F + M	21-29	2	TAFE	$50,000 to $70,000	1	1
7	F + M	18-20 30-39 40-49	3	High school - TAFE	$50,000 to $70,000	1	0
8	F + M	60+	2	PhD	$30,000 to $50,000	0	0
9	F	21-29 50-59	2	University	$10,000 to $30,000	0	1
10	M	21-29	1	High school	$10,000 to $30,000	0	1
11	F + M	< 5 5-17 21-29 30-39	5	High school	$70,000 to $90,000	1	0
12	F + M	< 5 5-17 30-39	4	Bachelor - Postgraduate	$110,000+	2	0
13	F + M	50-59	2	TAFE	$110,000+	0	0
14	F + M	60+	2	TAFE - Postgraduate	$70,000 to $90,000	0	1
15	F + M	< 5 21-29	2	Bachelor	$10,000 to $30,000	1	0
16	F + M	21-29 50-59 60+	4	Bachelors PhD	$110,000+	4	0
17	F + M	50-59	2	TAFE	$110,000+	1	1
18	F + M	50-59	2	High school Postgraduate	$110,000+	2	0
19	F + M	30-39	2	Bachelor PhD	$110,000+	1	0
20	F + M	50-59	3	Postgraduate PhD	$110,000+	2	1

Table 3.3: Detailed summary of house type and construction in Sydney

Type	**One-Storey**	**Two-Storey**	**Split Level**	**Unit/ Apartment**		
Count	11	10	2	6		
Terrain	**Urban**	**Suburban**	**Rural, Flat**	**Rural, Undulating**	**Exposed**	
Count	6	17	1	4	0	
House Materials						
Outer Wall	**Double Brick**	**Brick Veneer**	**Timber**	**Lightweight Cladding**	**Concrete**	**Polystyrene**
Count	11	10	1	4	4	1
Roof	**Tile**	**Corrugated Steel**	**Concrete Slab**			
Count	15	10	5			
Floor	**Concrete Slab**	**Suspended Timber**	**Suspended Concrete**	**Carpet**		
Count	14	14	7	2		
Ceiling	**Plasterboard**	**Timber**	**Other**			
Count	25	3	3			
Internal Wall	**Timber framed**	**Plastered Brick/Block**	**Exposed Brick/Block**	**Concrete**		
Count	17	14	0	3		
Is your house insulated?						
Insulated	**Yes**	**No**				
Count	19	9				

In the Adelaide sample, those whose annual combined incomes were more than $110,000 mostly lived in detached houses. The others lived in the two-storey blocks of apartments. All houses in the Lochiel Park housing development were designed following passive design principles. The 10 apartments or units were on an east–west elongated site and they all had a north-facing orientation. The units were either single or double-storey and all except one had two bedrooms. The exception, the largest unit, had three bedrooms. All one-storey units, whether they were on the ground floor or first floor, had a similar layout with a combined living, dining and kitchen space facing north, two bedrooms with south-facing windows, and a combined bathroom and laundry in the centre of the unit. In the two-storey units, the ground floor usually consisted of the combined living, dining and kitchen space with openings facing north and south, the bathroom and laundry to the south and bedrooms on the first floor. The detached houses, except the ones outside the Lochiel Park housing, were all double-storey with three bedrooms, one of which was on the ground floor. All of them had north-facing windows with much smaller openings towards the east and west, even though the main entry to the house faced east or west.

The external walls of all of the houses were constructed of a combination of either double (cavity) concrete blocks or insulated reverse masonry veneer construction. Concrete slabs were used for both the ground and first floors. Ceilings and roof were in general insulated with R2.5 and R2 insulation respectively. Solar photovoltaic (PV) cells were installed on the north-facing roof. The windows were aluminium-framed with low-e (emissivity) glazing, and most were able to be opened, to allow for cross-ventilation; however, many of these windows could be opened only as wide as 100 mm. To block direct solar radiation and provide some privacy, internal blinds were provided to all dwellings.

The recruited Queensland homes represented the diversity of housing that makes up the Queensland housing market:

- One-third of the homes were of elevated construction while the remainder were slab-on-ground (SOG).
- One-third of the homes were of lightweight construction, with the remainder being of heavyweight construction (brick veneer or cement block).
- Most homes were single storey (the two-storey homes are highlighted in Table 3.4).
- All homes were designed to meet 5–6 star building code requirements.

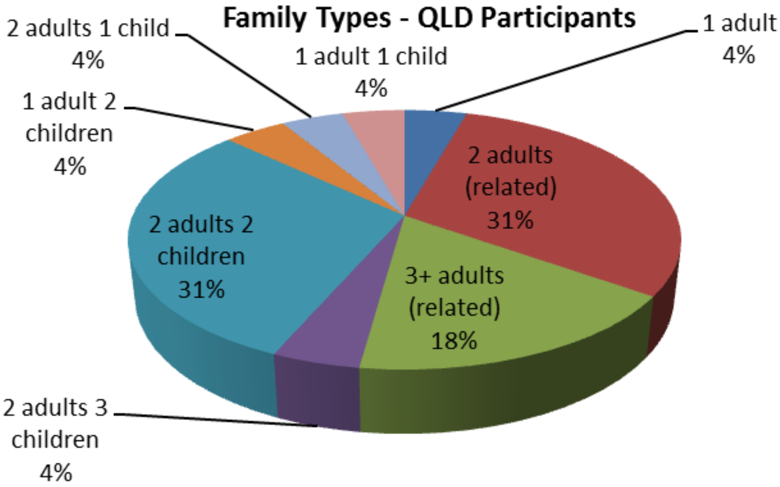


Figure 3.5: Breakdown of family types of Queensland comfort survey participants

Table 3.4: Summary of Queensland houses under study

ID	Location	Family (Adults, Children)	House Construction Type	Construction Year (Renovation)
QLD 1	Springfield Lakes	1A	SOG, brick veneer	2003 (2007)
QLD 2	Springfield Lakes	2A, 2C	SOG, brick veneer	2008
QLD 3	Springfield Lakes	2A, 3C	SOG, brick veneer	2009
QLD 4	Springfield Lakes	3A	SOG, mixed	2007
QLD 5	Springfield Lakes	2A, 2C	SOG, brick veneer [SOG, lightweight, 2-storey townhouse]	2008 [2012]
QLD 6	Springfield Lakes	1A, 1C	SOG, brick veneer	2009
QLD 7	Brisbane south-west	5A	Elevated, lightweight	2008
QLD 8	Springfield Lakes	1A, 2C	SOG, brick veneer	2009
QLD 9	Springfield Lakes	2A, 2C	Elevated, lightweight	2006 (2010)
QLD 10	Brisbane south-west	2A, 1C	SOG, brick veneer	2009
QLD 11*	Brisbane south-west	2A, 2C	Elevated, lightweight	2011
QLD 12*	Brisbane south-west	2A, 2C	Elevated, lightweight	(2009)
QLD 13	Brisbane south-west	2A, 1C	SOG, brick veneer	2005
QLD 14	Brisbane south-west	2A	SOG, brick veneer	c. 2006
QLD 15	Brisbane south-west	3A	SOG, brick veneer	Pre 2006
QLD 16	Brisbane south-west	2A	SOG, brick veneer	c. 2006
QLD 17	NOT IN USE			
QLD 18*	Gold Coast – inland	2A	Elevated, lightweight	2009
QLD 19*	Gold Coast – inland	2A	Elevated, lightweight	2008
QLD 20*	Gold Coast – inland	2A	Elevated, mixed weight	2008
QLD 21*	Brisbane north-west	2A, 2C	SOG, lightweight	2011

*No air conditioning

3.6 *Passive Comfort Options and A/C Behaviour*

The participants were asked to express what strategies they employed to achieve thermal comfort before resorting to using their air conditioner unit. As illustrated in Figure 3.6, many participants in the Sydney study used common passive cooling strategies, for example, opening their windows (24%), changing clothes (21%) or opening their doors (16%). These results corresponded well with the fact that most participants (72%) stated that their comfort could mostly be achieved through natural ventilation, that is, opening windows and doors. The next most common cooling strategy was to turn on fans (17%). These results also related well to the most common strategies that participants used when the occupied room was stuffy, with opening windows, opening doors and turning on fans representing 38%, 28% and 22% of responses respectively.

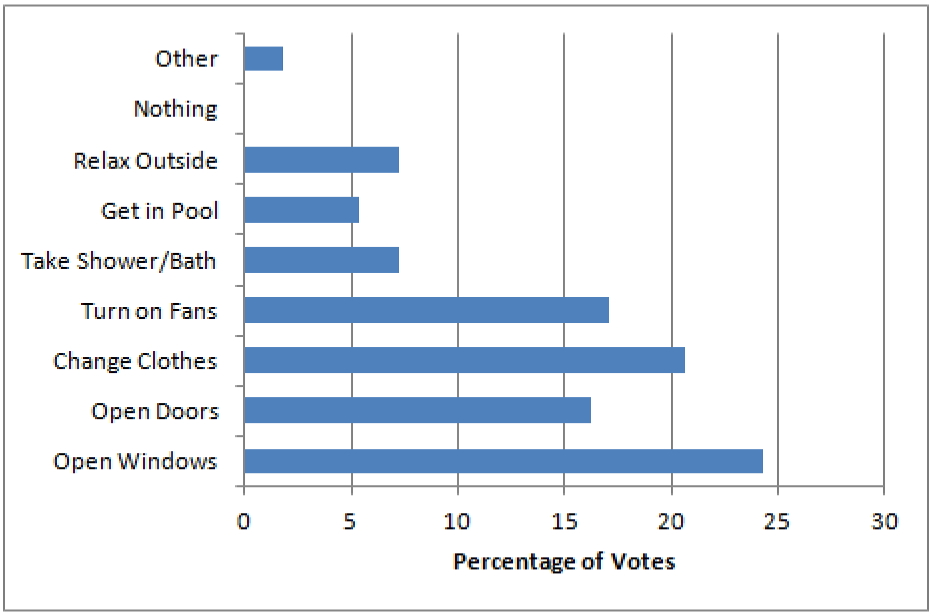


Figure 3.6: Percentage of Sydney participants' passive cooling strategies prior to using air conditioning (based on the householder background surveys)

The results in Adelaide were similar to those in Sydney, although turning on fans (21%) was the strategy most frequently employed to achieve thermal comfort in the house (Figure 3.7). The next most popular strategy was closing the windows, doors and curtains (17% each) when it was hot outside, or opening them when outside temperatures were acceptable. Only 3% stated that they would pre-emptively turn on air conditioning during forecasted warm periods. Figure 3.8 shows that when the house was considered too stuffy, most participants would open the windows first (32%), followed by opening the doors (28%) and then turning on the fans (23%).

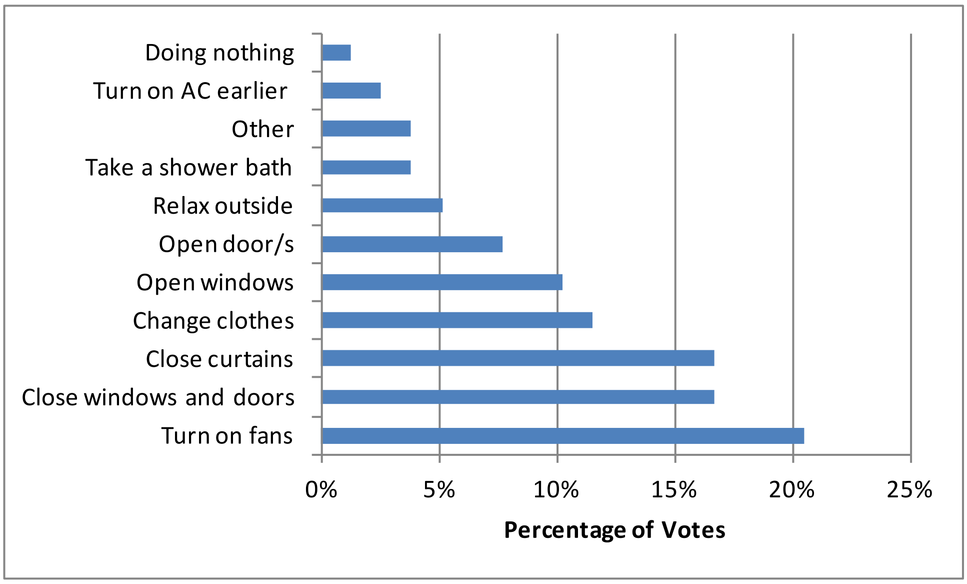


Figure 3.7: Percentage of Adelaide participants' passive cooling strategies

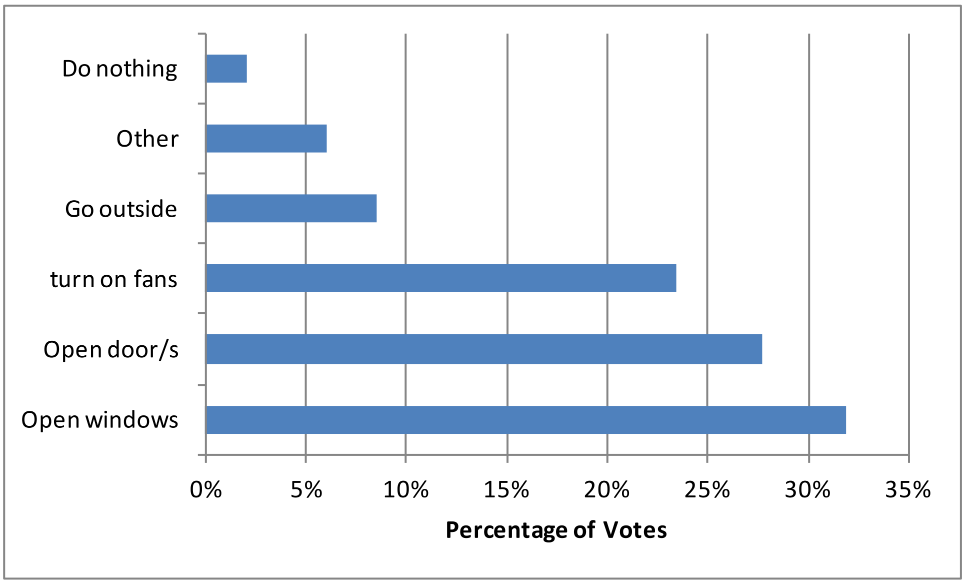


Figure 3.8: Percentage of Adelaide participants' strategies when house felt too stuffy

In terms of residential air conditioning systems, 16 houses in Sydney had fixed split air conditioner units representing 61% of the sample. The next most popular air conditioner unit type was ducted (seven houses, 25%) followed by portable units (four houses, 14%). Only one house had a wall/window unit. Figure 3.9 is a breakdown of the most common rooms where each type of air conditioner system was located. Across all households, the living room had the highest number of air conditioner units (34). The majority of air conditioner units within these rooms were fixed split systems (16), followed by ducted systems (five). All types of rooms featured ducted air conditioner units, with the majority located in the bedroom (seven). Only one house had a wall/window air conditioner unit, which was located in their living room. Some houses also had portable air conditioner units operating in their living rooms and bedrooms. In addition to air conditioner units, 78% of households also had a variety of fans within their home. Of the fans in participants' households, 53% were ceiling fans with the majority located in the living room.

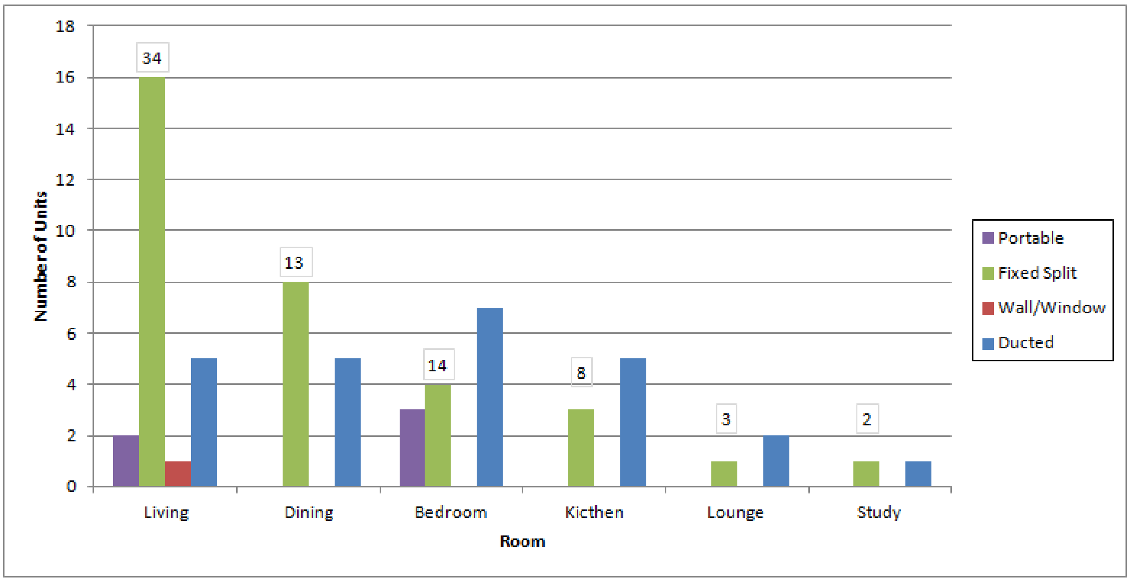


Figure 3.9: Number of A/C units according to type located in each room of participants' houses in Sydney

All the houses except for two in the Adelaide sample used centralised/ducted reverse-cycle air conditioners. Two houses had a centralised evaporative cooling system and gas heaters. With the exception of those in the apartment buildings, all rooms could be cooled or heated by the centralised system. The apartment blocks had a ventilation stack centrally positioned in the hallway connecting the living room and bedrooms to purge heat from these spaces. This stack ventilation was designed to be used in conjunction with operable windows in the living room and bedrooms. The ventilation was controlled via motorised louvers linked to a split-system air conditioning system located on the ceiling of the small hallway leading to the bedrooms. It was found during the site visits that the air diffusers of the air conditioners only faced the living room and not the bedrooms. There were no other cooling options in the bedroom except the ceiling fan. Ceiling fans were also installed in the living and dining rooms.

In terms of using their air conditioner units, 59% of the Sydney participants stated that they used a programmable thermostat while the remaining 41% simply operated their air conditioning equipment manually. In contrast, although the air conditioning systems in the Lochiel Park housing development in Adelaide had a programmable thermostat, none of the households knew how to use it and all left the thermostat setting at the same temperature throughout summer. The majority of the households believed that they had set the thermostat to 22^{0}C or less, and only two households had set it to 24~25^{0}C. However, they all controlled the operation of the air conditioning system by manually turning it on or off, instead of leaving the system on standby mode and letting the thermostat setting dictate when the system was on or off.

In the Adelaide apartment buildings, all respondents expressed dissatisfaction over the air conditioning system installed in their dwellings. As mentioned earlier, the air diffuser of the air conditioner only pointed to the living room, and as a result the cool air was never felt in the bedrooms. A number of the respondents mentioned that they had to move to the living room during hot nights as their bedroom became unbearably hot.

The Queensland homes did not require heating. The characteristics of their cooling systems are summarised below:

- Six of the homes had no air conditioning. These houses were included in the study to provide a comparison of their occupants' comfort strategies compared to those of occupants with air-conditioned houses. (These figures were consistent with regional statistics: 26% of south-east Queensland (SEQ) homes are thought to have no air conditioners).
- Split systems were the predominant type of air conditioner.
- Four households (20% of air-conditioned houses) had an air conditioner in the living room only. Of those houses with more than one air conditioner, the majority had a split system in each of the bedrooms as shown in Figure 3.10 (with a few having a split system only in the main bedroom).
- The majority of houses had ceiling fans in living areas and bedrooms.

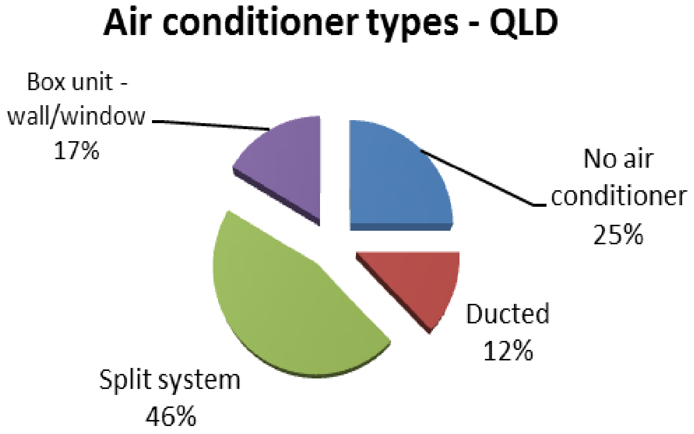


Figure 3.10: Types of air conditioner installed in participating homes in Queensland

3.7 *Indoor and Outdoor Thermal Environment*

This section provides results from the analysis of the indoor climatic measurements inside the sample houses and in particular, examines how the indoor thermal temperatures compare to the ASHRAE Standard 55-2010 (ASHRAE 2010). Particular attention was paid to those occasions when the room was occupied. Therefore, any time between 0700 hrs and 2100 hrs was designated as occupied hours. A more specific marker of occupancy was also used, namely the occupant's response on the smartphone questionnaire (see Section 3.8). Occupancy of bedrooms was deemed to occur after 2100 hrs and before 0700 hrs.

Table 3.5 presents a summary of the indoor and outdoor climate in Sydney during the 2012/13 summer season (between December 2012 and March 2013). The average temperature across the different types of room was 24.4°C, which was significantly higher than the outdoor temperature with an average daily mean of 22.7°C. The range of temperatures within each type of room was fairly consistent, ranging between 15°C and 37°C. Dining rooms recorded, on average, the coolest indoor temperatures. As shown in Figure 3.11, the majority (82.8%) of indoor temperatures recorded from the iButtons placed in the participants' living rooms were within the range of 22–28°C, with an average of 25.0°C.

Table 3.5: Statistical summary of the indoor and outdoor climate measured across the sample of Sydney households between 1 December 2012 and 6 March 2013

	Daily Mean Outdoor (°C)	7-Day Running Outdoor Mean (°C)	Living Room Temperature (°C)	Dining Temperture (°C)	Study Temperature (°C)	Kitchen Temperature (°C)	Bedroom Temperature (°C)
Mean	22.7	22.7	25.0	23.6	24.3	25.0	24.2
Min.	14.6	17.7	15.7	17.1	16.2	19.7	15.1
Max.	34.6	28.3	37.7	32.6	35.7	31.7	33.6
N	25,415	25,415	25,415	5,218	8,041	1,217	14,522
SD	3.22	1.95	2.60	2.87	3.88	2.28	2.53

Note: Temperatures within the living and dining rooms, study and kitchen were calculated between 0700 hrs and 2100 hrs and bedroom temperatures were calculated between 2100 and 0700 hrs.

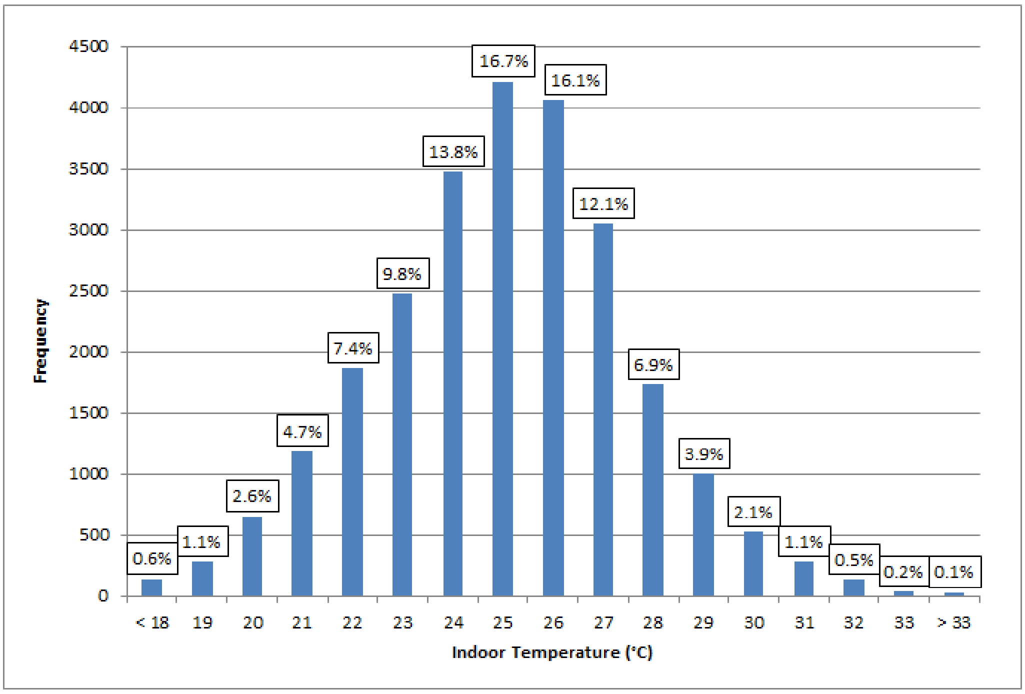


Figure 3.11: Histogram of hourly living room temperatures in the sample of Sydney houses

Table 3.6 presents a summary of the indoor and outdoor climate for the sample of Adelaide houses between January and March 2012. The average temperature inside the living room with or without the air conditioner operating was approximately 2°C warmer than the mean outdoor temperature throughout the same period. As indicated in the responses from survey participants, bedroom temperatures were higher than the living room temperatures. Figure 3.12 shows the frequency distribution of the indoor temperatures in the living rooms between January and March 2012.

Table 3.6: Statistical summary of the indoor and outdoor climate measured across the study in Adelaide between January and March 2012

	Daily Mean Outdoor (°C)	7-Day Running Mean (°C)	Living/ Dining Temperature without AC (°C)	Living/Dining Temperature with AC* (°C)	Bedroom Temperature without AC (°C)	Bedroom Temperature with AC* (°C)
Mean	22.8	22.5	24.5	24.8	27.2	25.3
Min.	15.5	17.6	15.8	21.1	14.9	22.6
Max.	34.9	29.3	33.7	28.6	38.2	28.1

*When A/C was operating

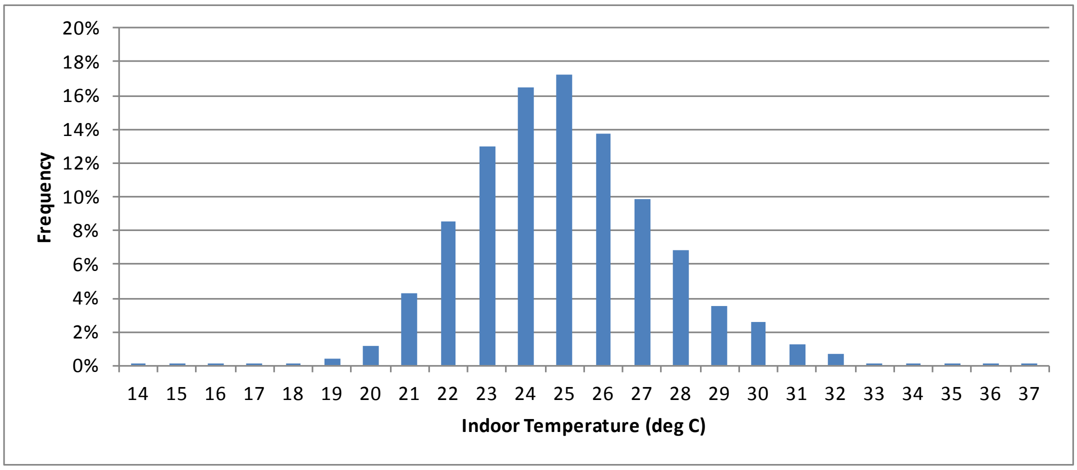


Figure 3.12 Histogram of hourly living room temperatures in the sample of Adelaide houses

Table 3.7 presents a summary of the indoor and outdoor climate in Brisbane during both the 2011/12 and 2012/13 summer seasons. The average temperature (0700–2100hrs) across all living rooms in the sample households was 26.5°C, about two degrees warmer than outdoor average temperatures during the same hours (24.4°C). As shown in Figure 3.13, the majority (77.7%) of indoor temperatures recorded from iButtons placed in the participants' living rooms were within the range of 23–28°C.

Table 3.7: Statistical summary of the indoor and outdoor climate measured across the sample of Brisbane households January–March 2012 and December 2012–March 2013

	Daily Mean Outdoor (°C)	7-Day Outdoor Running Mean (°C)	Living Room Temperature (°C)	Bedroom Temperature (°C)
Mean	24.4	24.4	26.5	NA
Min.	20.7	21.6	18.2	NA
Max.	29.6	26.8	41.5	NA
N	5,485	5,485	5,485	NA
SD	1.50	0.67	2.46	NA

Note: Temperatures within the living room were calculated between 0700–2100 hrs. Bedroom temperatures could not be calculated due to small sample size

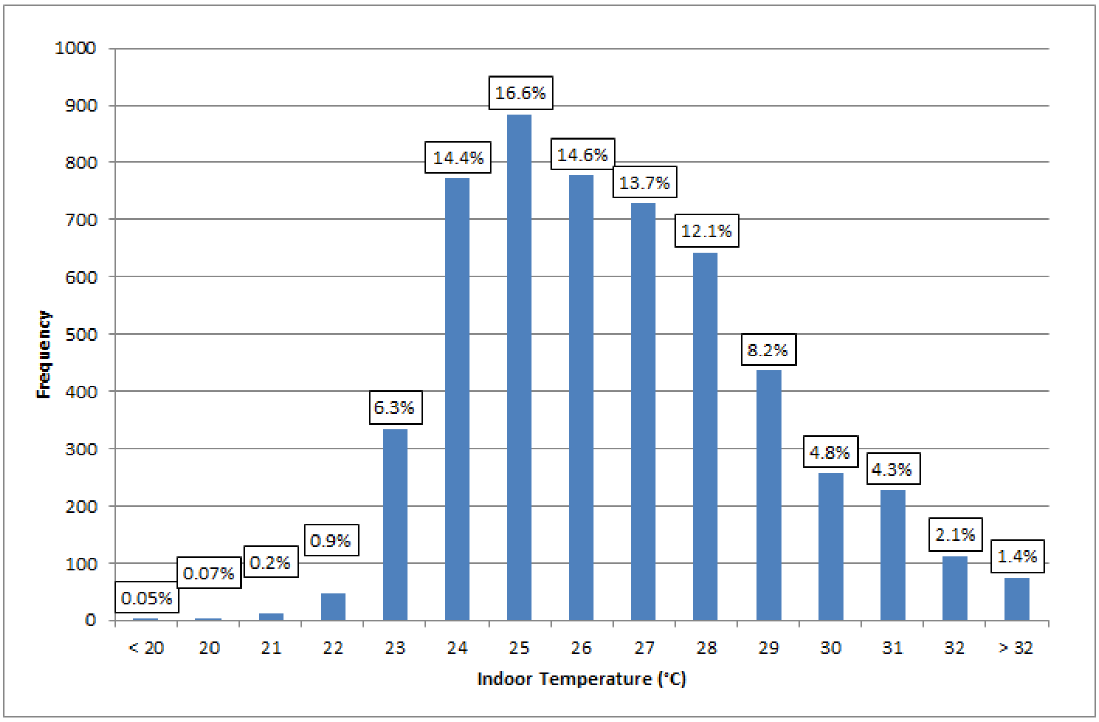


Figure 3.13 Histogram of hourly living room temperatures in the sample of Brisbane houses

Differences between types of room

Figure 3.14 illustrates the distribution of indoor temperatures for each type of room within the Sydney sample during the 2012/13 summer season. The dining rooms' temperature distribution appears to be displaced to be about 2°C cooler than the other types of rooms in the sample. The iButton data collected from the Brisbane study did not provide enough data to allow for a separate analysis by room. Since most houses studied in Adelaide had combined living and dining rooms and only a few had separate rooms used as a study, no analysis of the differences between rooms is shown here. The statistics of the bedroom temperatures were presented above in Table 3.6.

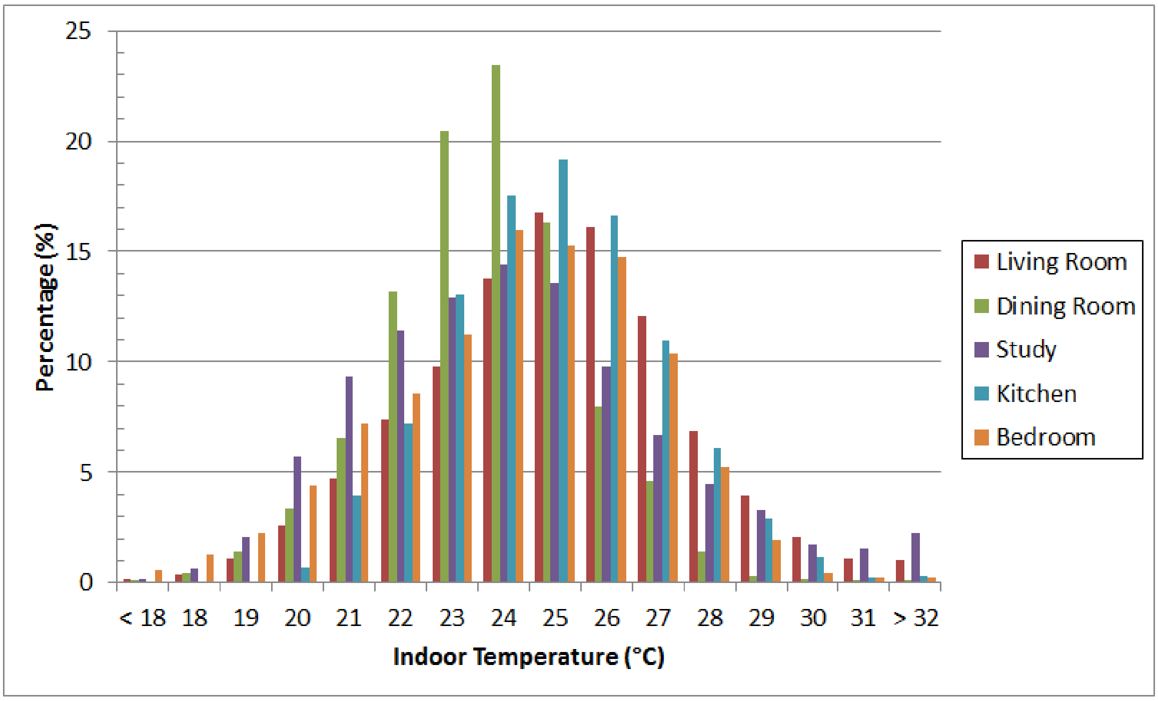


Figure 3.14 Distribution of indoor temperature between room types during occupied hours

Note: Living room, dining room, study and kitchen all for 0700–2100 hrs (bedrooms 2100–0700 hrs) in Sydney, normalised according to the number of observations per room type.

Compliance of room temperatures with ASHRAE's adaptive comfort ranges (ASHRAE 55-2010R)

Indoor temperatures recorded in each household's living room during summer were plotted against a weighted, 7-day running mean of outdoor temperature recorded from the nearest BOM weather station. These observations represent the full records made by iButton monitors, regardless of the room's occupancy status. Superimposed on the same scatter plot are the 80% and 90% ASHRAE adaptive thermal acceptability limits. These limits define the warmest and coolest acceptable indoor temperatures (de Dear & Brager 2002; ASHRAE 2010). Indoor temperatures outside these limits are deemed by ASHRAE 55-2010 to be unacceptable.

Results from the Sydney study

Figure 3.15 shows the indoor temperatures recorded between 0700 hrs and 2100 hrs (occupied hours) during summer in Sydney. As illustrated, the majority of indoor temperatures (ranging between 20–28°C) during the months of December, January and February were within the 80% and 90% ASHRAE acceptability limits suggesting that most participants would have felt comfortable during these times. It was found that 85.6% (18,779 hours) of the total number of hours of indoor living room temperatures were within the upper and lower 80% ASHRAE acceptability limits (between 20–23°C and 27–30°C). This suggests a high level of compliance with the adaptive comfort standard as proscribed in ASHRAE Standard 55-2010 (ASHRAE 2010).

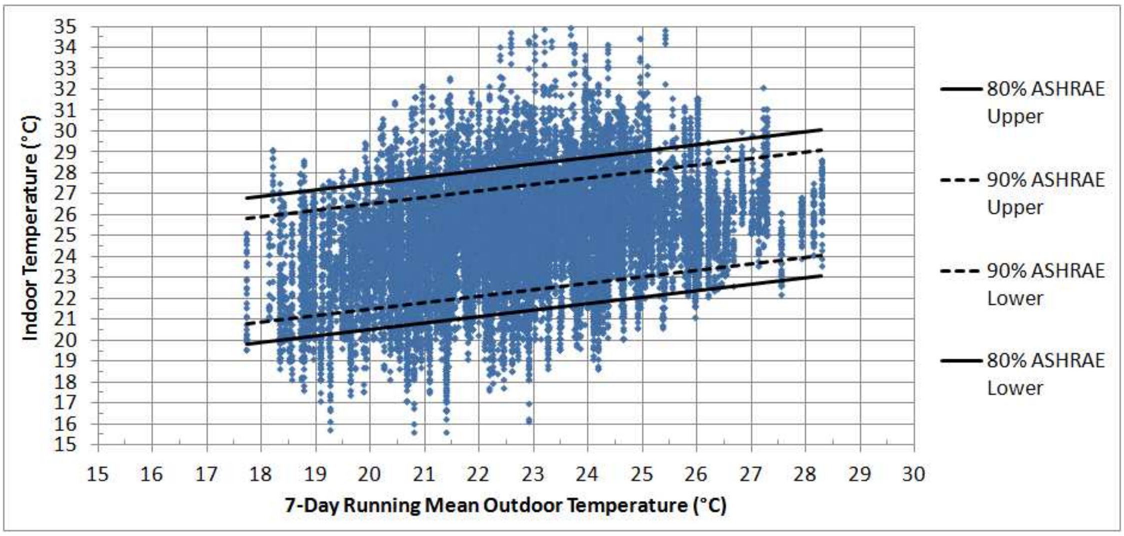


Figure 3.15: Living room temperatures (0700–2100 hrs) during summer in Sydney compared to ASHRAE Standard 55-2010, with 80% (solid line) and 90% (dashed line) acceptability limits

Note: Each data point represents an hourly average of the indoor temperature.

With regard to indoor bedroom temperatures, the times in which these rooms would most likely be used were classified as being between the hours of 2100 hrs and 0700 hrs. Figure 3.16 shows the range of indoor temperatures recorded within all bedrooms within the Sydney sample households during the 2012/13 summer season. As the times at which most people used their bedrooms corresponded to night-time temperatures, the bedroom temperatures appeared to be much cooler than those for the living rooms. Indoor temperatures within the bedrooms ranged from 20–28°C throughout the summer season. Hence, only 1,355 hours (16.3%) were outside the upper and lower 80% ASHRAE acceptability limits suggesting a wide range of acceptable temperatures.

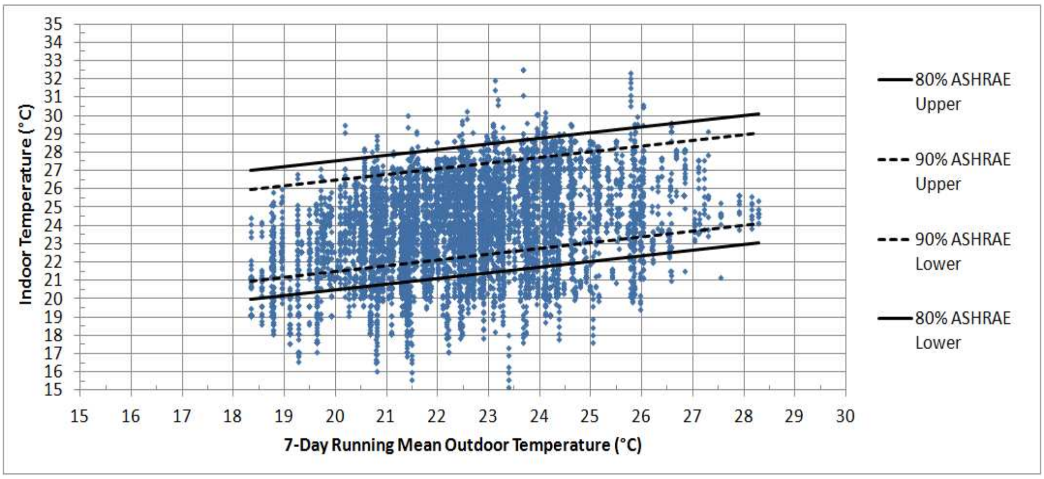


Figure 3.16: Bedroom temperatures (2100–0700 hrs) during summer in Sydney compared to the ASHRAE Standard 55-2010 80% (solid line) and 90% (dashed line) acceptability limits

Note: Each data point represents an hourly average of the indoor temperature.

Results from the Adelaide study

Figure 3.17 shows the results of the monitored indoor temperatures of the living room in the apartment building for the summer period (January–March 2013). Most of the observed temperatures within the living rooms were within the ASHRAE 80% acceptable limits, and were only outside the ASHRAE acceptable limits for 7.6% of the time spent. On the other hand, the bedrooms had a higher percentage of time spent outside the ASHRAE 80% acceptable limits, with 12% of the time spent above the upper threshold (Figure 3.18). Overall, the living rooms and bedrooms performed quite well considering the air conditioners were rarely used.

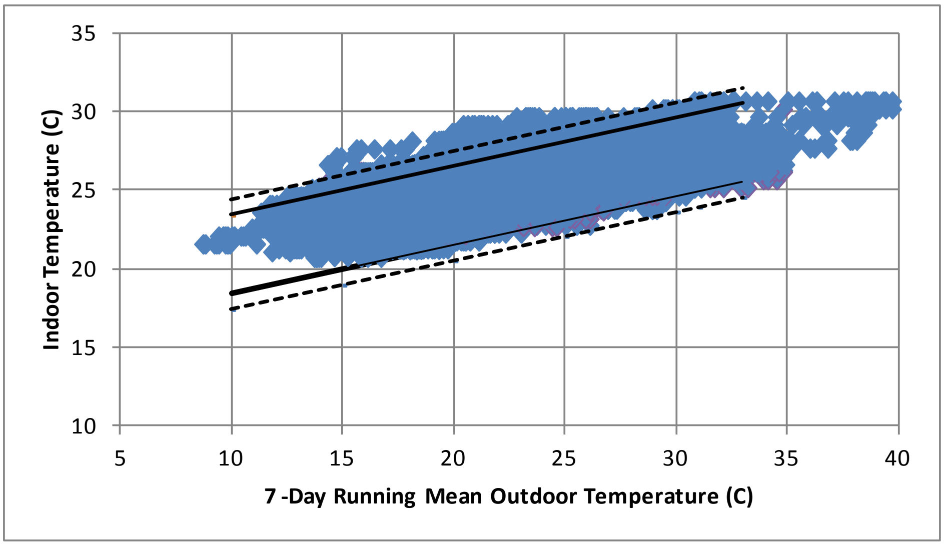


Figure 3.17: Living room temperatures (0700-2100hrs) during summer in Adelaide compared to ASHRAE Standard 55-2010 80% (solid line) and 90% (dashed line) acceptability limits

Note: Each data point represents an hourly average of the indoor temperature.

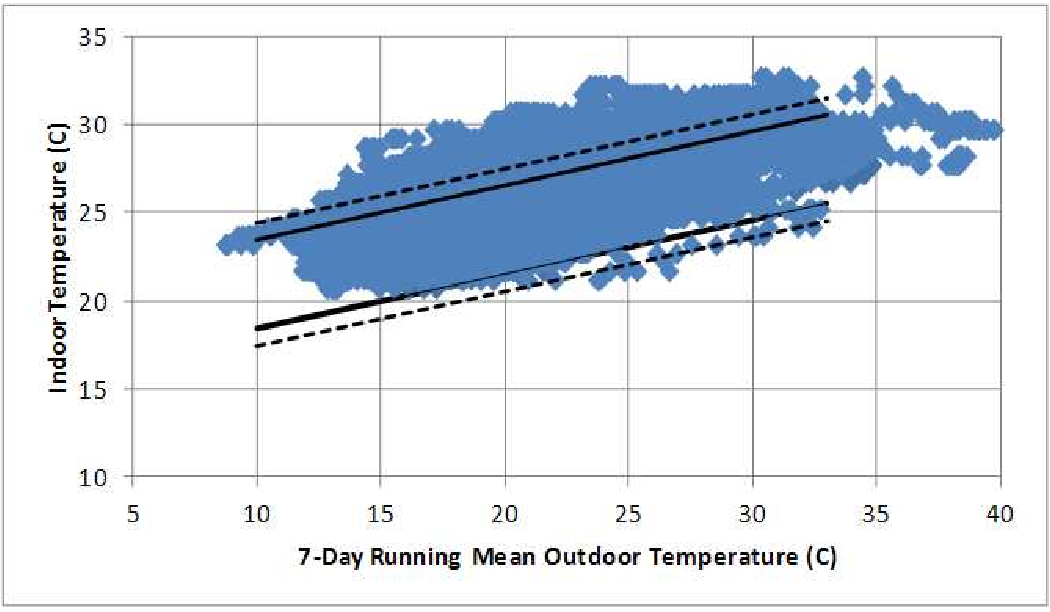


Figure 3.18: Indoor bedroom temperatures during summer in Adelaide compared to the ASHRAE Standard 55-2010 80% (solid line) and 90% (dashed line) acceptability limits

Note: Each data point represents an hourly average of the indoor temperature.

Results from the Brisbane study

Figure 3.19 shows the indoor living room temperatures recorded between 0700 hrs and 2100 hrs (occupied hours) during summer in Brisbane. Compared to the range of temperatures recorded in the Adelaide and Sydney studies, the Brisbane living room temperatures had a greater scatter, with more frequent exceedences of the ASHRAE 55-2010 acceptability limits. Nevertheless, the majority (over 80%) of indoor temperature measurements within the living rooms fell within the 80% ASHRAE acceptability limits.

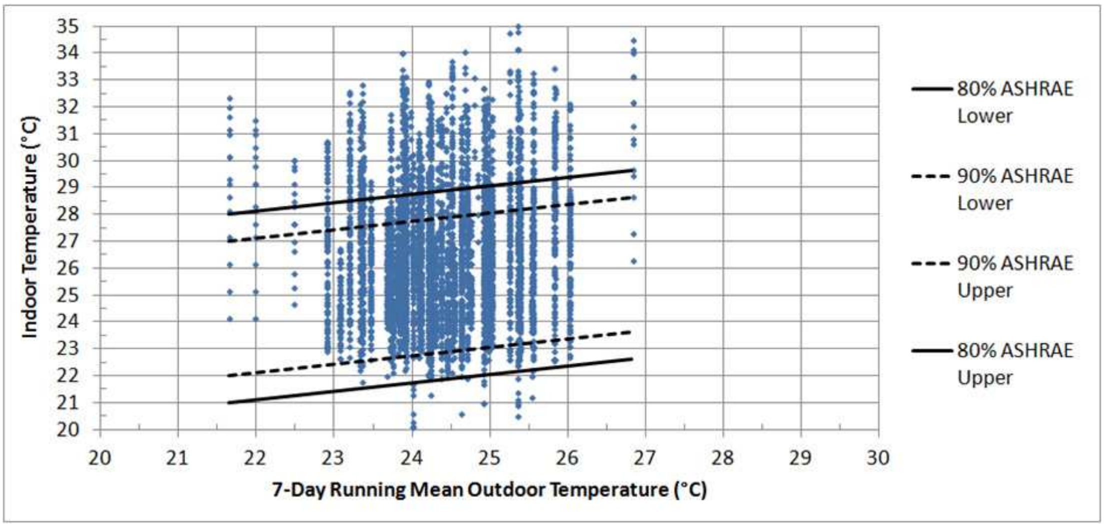


Figure 3.19: Living room temperatures (0700–2100 hrs) during summer in Brisbane compared to ASHRAE Standard 55-2010 80% (solid line) and 90% (dashed line) acceptability limits

Note: Each data point represents an hourly average of the indoor temperature.

Trigger temperature for air conditioning on cooling mode (during summer)

The preceding analyses detailed the indoor temperature of the living rooms in the sample households for Sydney, Adelaide and Brisbane between the hours of 0700 and 2100. From these results, it is possible to calculate the room temperature at which participants started to use their air conditioner units for cooling purposes. This was deemed to be when a difference > 5°C was observed between the supply air of the air conditioner unit and the occupied zone of the living room. The graph in Figure 3.20 illustrates those excerpts from the total iButton records of living room temperatures recorded when the air conditioner was operating in cooling mode. The graph illustrates that the majority (90%) of indoor temperatures when the air conditioner was on fell within the ASHRAE 80% acceptability limits. From this analysis, it was estimated that the average Sydney living room trigger temperature for the air conditioner in cooling mode was about 26°C.

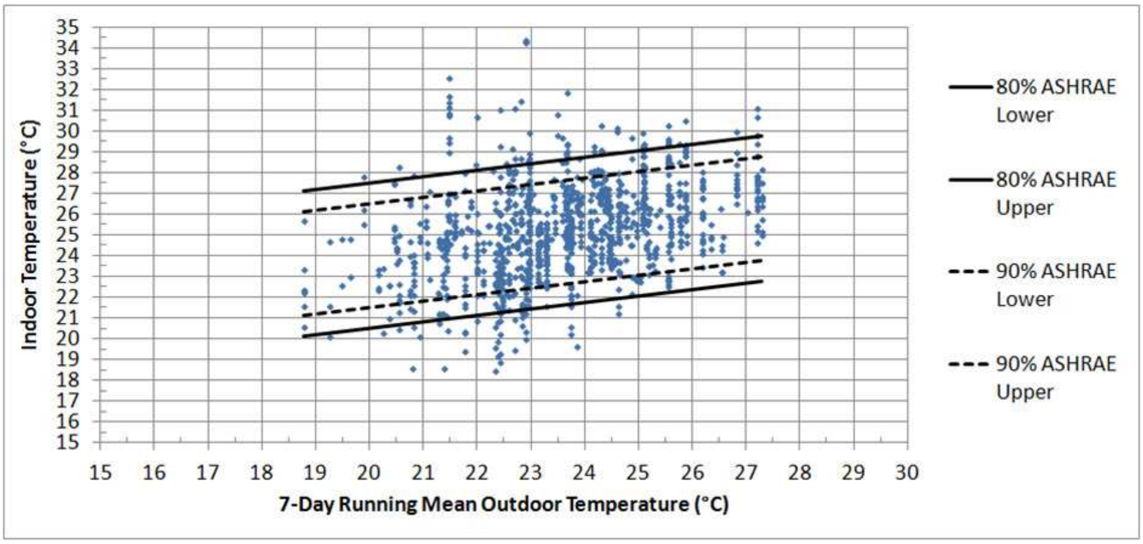


Figure 3.20: Indoor living room temperatures (0700–2100 hrs) during summer in Sydney when the living room A/C unit was operating in cooling mode compared to ASHRAE Standard 55-2010 80% (solid line) and 90% (dashed) acceptability limits

Note: Each data point represents an hourly average of the indoor temperature.

Figure 3.21 presents a similar analysis of indoor bedroom temperatures during the times in which participants were using their air conditioner unit for the Sydney sample. While the sample size was smaller than for the living room analysis above, the graph indicates that over 60% of air-conditioned bedroom occupied hours during Sydney's summer were cooler than the lower 80% ASHRAE acceptable temperature limit. The adaptive model contained no bedroom data and these observations indicate that, in its current format, it should probably not be applied to sleeping quarters. Figure 3.21 also illustrates that participants frequently left their bedroom air conditioner unit running while they slept, because the average room temperature was 17°C.

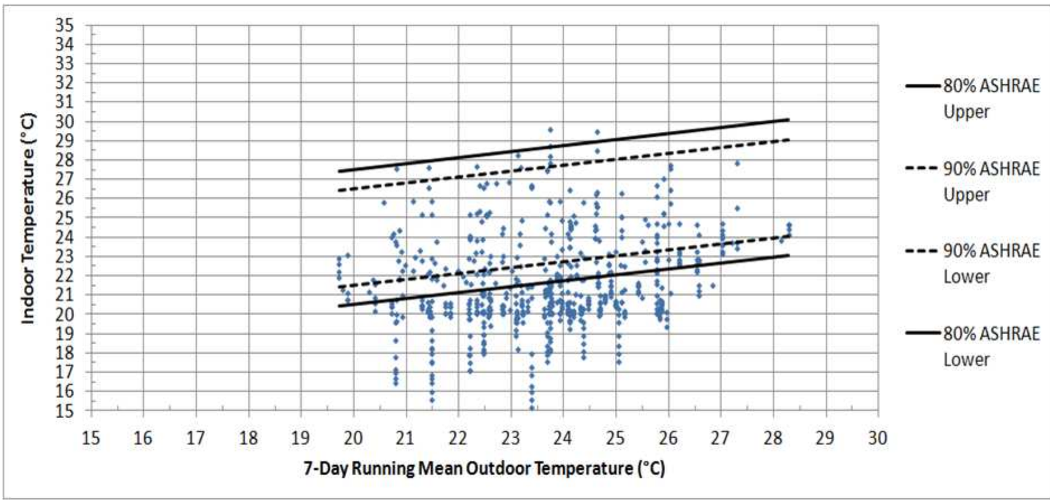


Figure 3.21: Indoor bedroom temperatures (2100–0700hrs) during summer in Sydney when the bedroom A/C unit was operating in cooling mode compared to ASHRAE Standard 55-2010 80% (solid line) and 90% (dashed line) acceptability limits

Note: Each data point represents an hourly average of the bedroom temperature.

Results from the Brisbane study

Figure 3.22 illustrates that the range of indoor living room temperatures within the Brisbane households was quite different to those from Sydney (as was shown in Figure 3.20). It should be noted that there were less data available for the Brisbane study (the Sydney study had a total of 1,052 hours of data whereas the Brisbane study only had 230 hours). The average living room temperature of 24°C in Brisbane's summer during air conditioner operation was 2°C cooler than that observed in the Sydney sample.

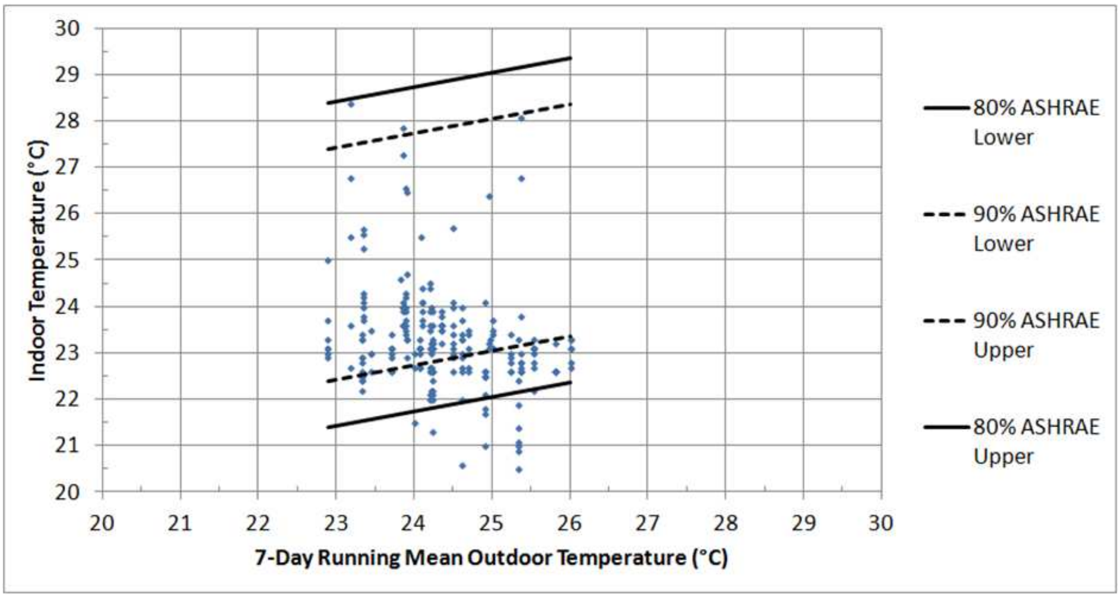


Figure 3.22: Indoor living room temperatures (0700–2100 hrs) during summer in Brisbane when the living room A/C unit was operating in cooling mode compared to ASHRAE Standard 55-2010 80% (solid line) and 90% (dashed line) acceptability limits

Note: Each data point represents an hourly average of the indoor temperature.

Indoor temperature versus ASHRAE Standard

To understand how the participants' indoor thermal environment at the time of answering the questionnaire compared to the adaptive comfort model in ASHRAE Standard 55-2010 (ASHRAE 2010), the data were plotted against a running 7-day mean of the outdoor temperature. Figures 3.23, 3.24 and 3.25 show the range of indoor temperatures experienced by the participants at the time they answered the survey in Sydney, Adelaide and Brisbane respectively. In all locations, the majority of indoor temperatures (above 80%) fell between the upper and lower limit of acceptable temperatures (20–30°C in Sydney, 19–30°C in Adelaide, and 21–30°C in Brisbane) as defined by ASHRAE Standard 55-2010.

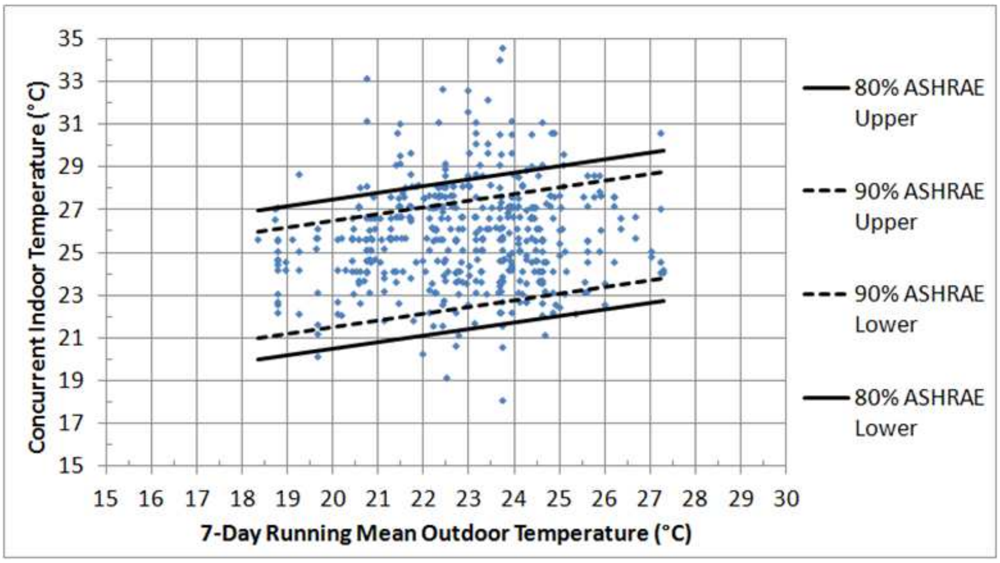


Figure 3.23: Concurrent indoor temperature for the Sydney study at the time of answering the comfort questionnaire plotted against 7-day running mean outdoor temperature compared to ASHRAE Standard 55-2010 80% and 90% acceptability limits

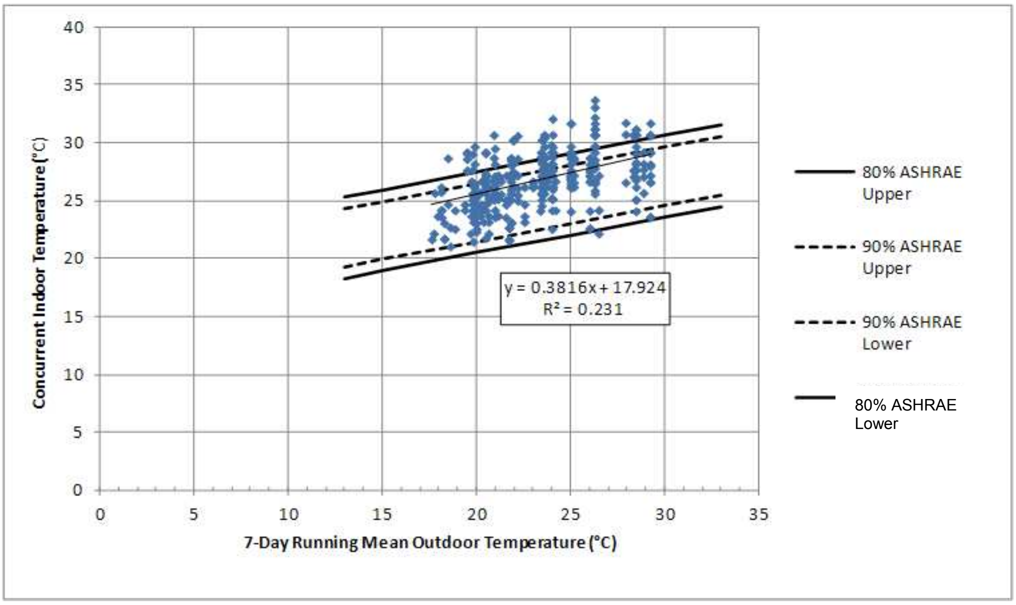


Figure 3.24: Concurrent indoor temperature for the Adelaide study at the time of the comfort questionnaire plotted against 7-day running mean outdoor temperature compared to ASHRAE Standard 55-2010 80% and 90% acceptability limits

Notwithstanding the small sample size and short duration of the Brisbane study, Figure 3.25 indicates that about three-quarters (72%) of the data points for occupied hours during air conditioner operation in living rooms were within the 80% ASHRAE acceptability limits: the remaining quarter of the observations fell above the upper threshold (28–30°C).

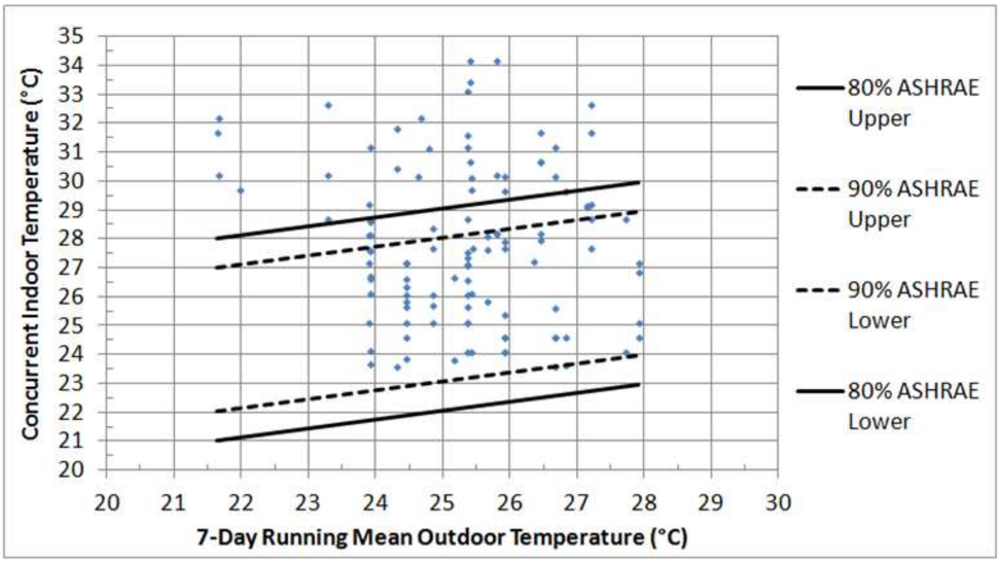


Figure 3.25: Concurrent indoor temperature for the Brisbane study at the time of the comfort questionnaire plotted against 7-day running mean outdoor temperature compared to ASHRAE Standard 55-2010 80% and 90% acceptability limits

3.8 *Subjective Assessment of the Thermal Environment*

Thermal sensation

Figure 3.26 presents the data on the participants' actual thermal sensation at the time of answering the questionnaire for the Sydney sample households. All thermal sensation votes gathered since the beginning of the study were analysed in this graph. According to Figure 3.26, over half (51.2%) of the thermal sensation votes recorded by all participants were considered *neutral*. The second most common thermal sensation vote category was *slightly warm* with 77 votes (23.6% of total). In contrast, only 14.4% of votes have been for a *slightly cool* thermal sensation. Considering that the study has not yet experienced a summer heat wave, very few votes were cast for a *hot* thermal sensation. However, a higher percentage of votes were recorded as *warm* (8.3%) compared to *cool* (5.3%). This is interesting given that most data were from June–September when Sydney usually experiences cooler weather.

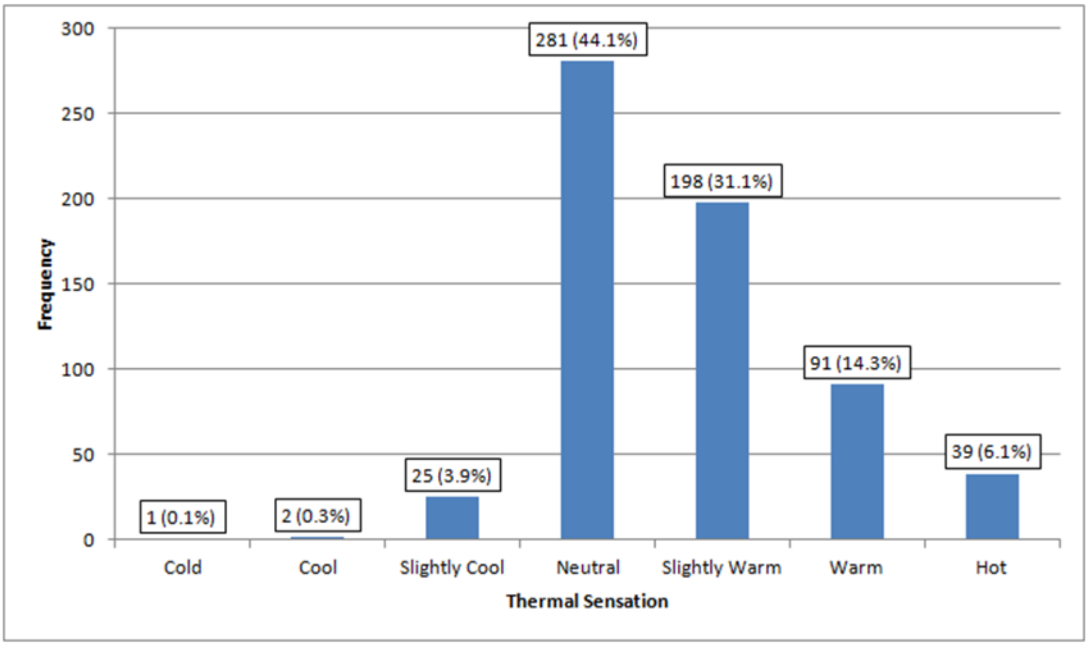


Figure 3.26: Participants' thermal sensations in the Sydney sample homes at the time of the smartphone comfort questionnaire

Thermal sensation votes were then binned at 1.0°C concurrent indoor temperature intervals, for example, all votes recorded between 21.5–22.49°C were counted and plotted according to their rank on the ASHRAE 7-point thermal sensation scale. Figure 3.27 indicates that the percentage of votes in the *slightly warm* to *warm* categories increases as the indoor temperature of the occupied room increases. Furthermore, as indoor temperatures increase, the number of *neutral* votes decreases. The proportion of *slightly warm* to *neutral* votes increases significantly above a concurrent indoor temperature of 25°C. The number of *hot* votes also seems to decrease at indoor temperatures above 30°C, but this is probably not a reliable finding given the very small number of observations at temperatures above 28°C in the Sydney study.

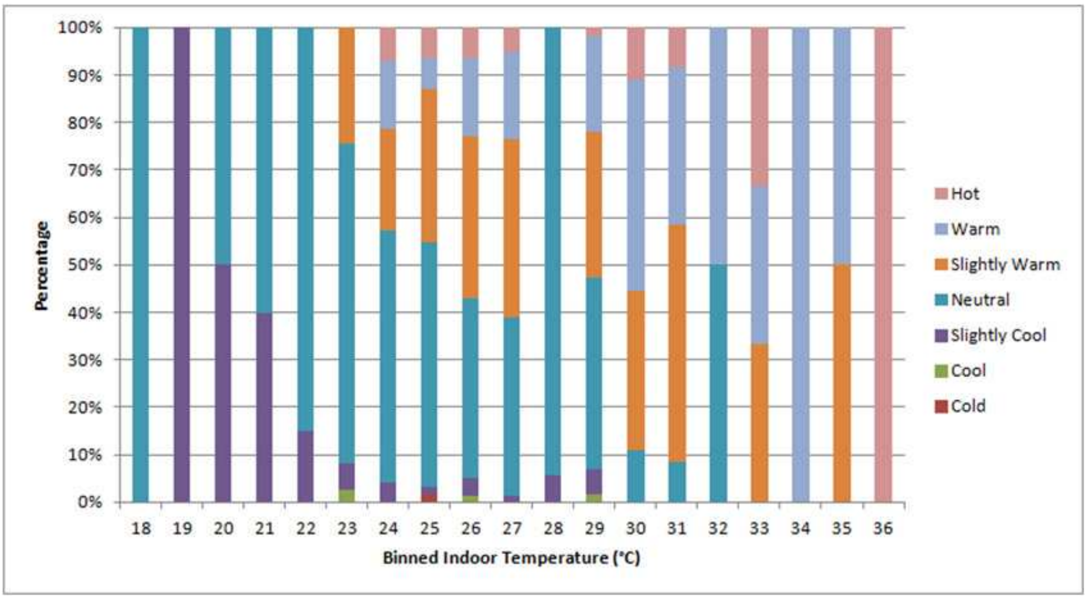


Figure 3.27: Thermal sensation votes in the Sydney study binned by concurrent indoor temperature

Figure 3.28 shows the frequency distribution of the thermal sensation votes from the Adelaide study. It can be seen that during the monitoring period and based on the occupants' comfort survey responses, the occupants felt *neutral* for 39% of the time, were *slightly warm* for 20% of the time, were *warm* for 18% of the time and were *hot* for 16% of the time while for 7% of the time, the occupant felt either *slightly cool* or *cool*.

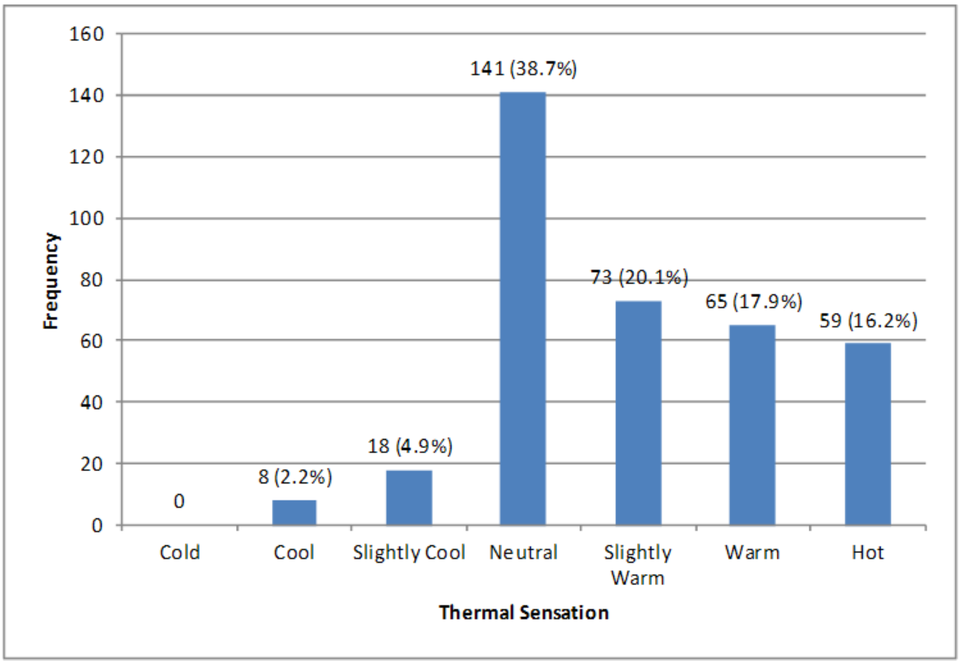


Figure 3.28: Participants' thermal sensations in the Adelaide sample homes at the time of answering the smartphone comfort questionnaire

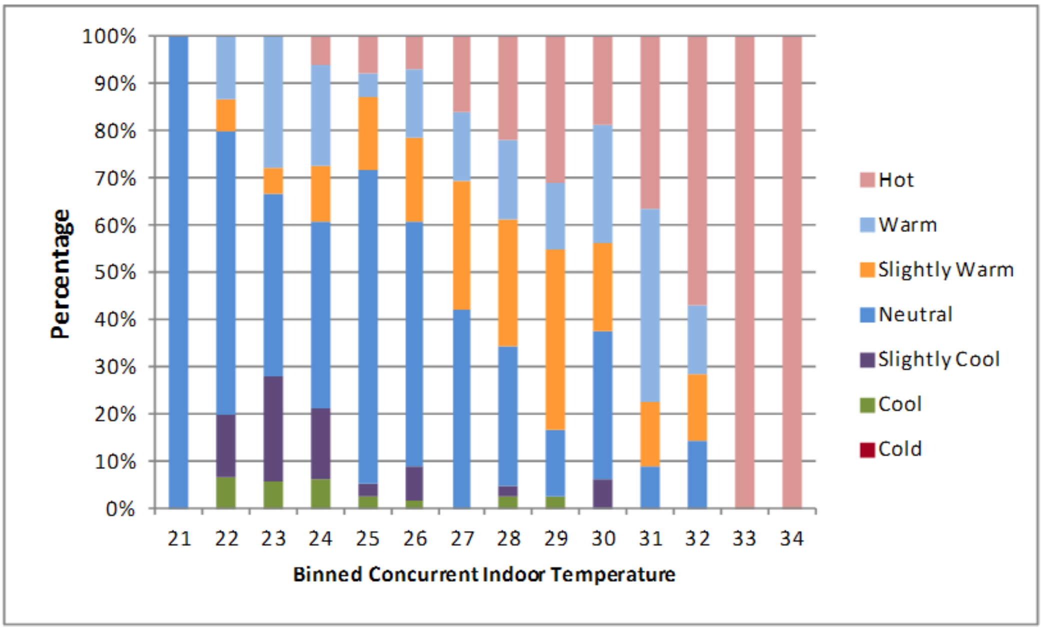


Figure 3.29: Thermal sensation votes in the Adelaide study binned by concurrent indoor temperature

Similar to the results from the Sydney study and as shown in Figure 3.29, it was suggested that the percentage of votes in the *slightly warm* to *hot* categories in the Adelaide study increased as the indoor temperature of the occupied room increased with the number of *neutral* votes decreasing at the same time. The proportion of the *slightly warm* votes increased above a concurrent indoor temperature of 26°C while the *warm* to *hot* votes noticeably increased above a concurrent indoor temperature of 30°C.

In regards to the Brisbane study (Figure 3.30), half (72, 49.3%) of the votes recorded from the comfort questionnaires indicated a *neutral* thermal sensation. Considering the warmer outdoor conditions throughout the study, there was a higher percentage of *slightly warm* (18.5%) and *warm* (9.6%) votes compared to those voting for *slightly cool* (9.6%) and *cool* (2%). There were also 15 *hot* votes, equating to just over 10% of the total number of thermal sensation votes recorded during the entire study.

When binned according to the indoor temperature at which they were recorded (i.e. concurrent indoor temperature), Figure 3.31 shows that there was a general trend towards warmer thermal sensations as indoor temperatures increased. At indoor temperatures above 29°C, a higher proportion of hot votes were registered compared to neutral votes. This was not surprising considering how much warmer the outdoor conditions experienced in Brisbane were compared to those Sydney.

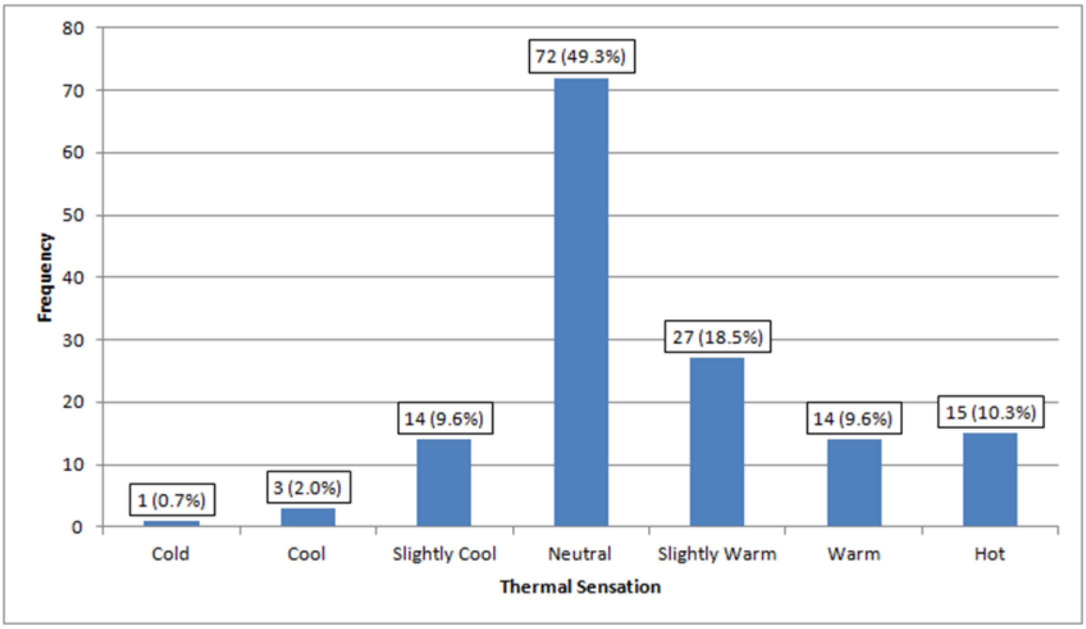


Figure 3.30: Participants' thermal sensations in the Brisbane sample homes at the time of answering the smartphone comfort questionnaire

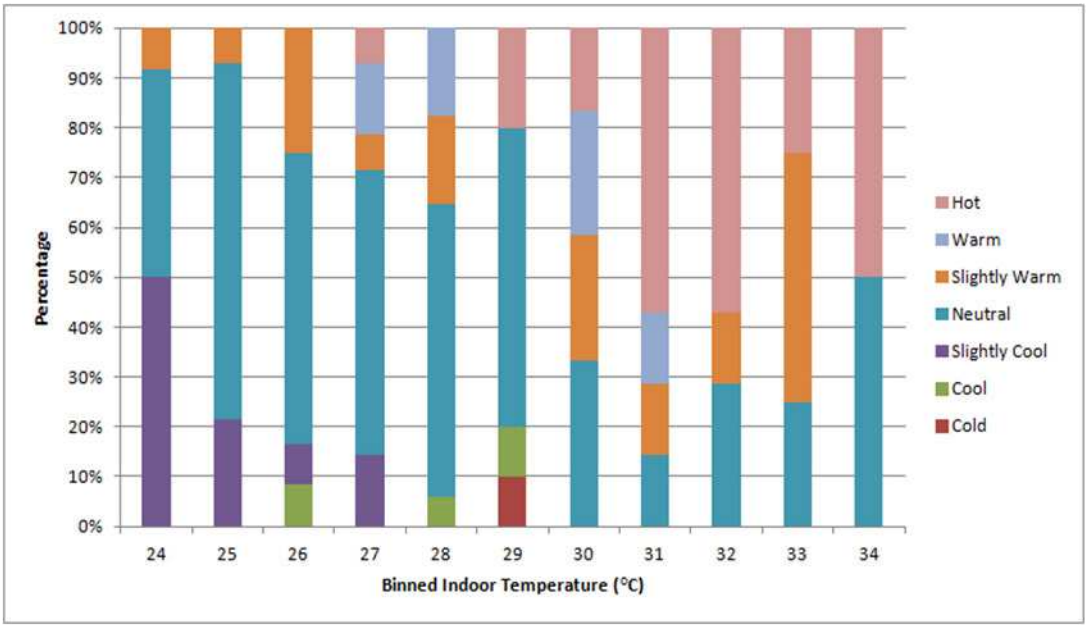


Figure 3.31: Thermal sensation votes in the Brisbane study binned by concurrent indoor temperature

Clothing

Figure 3.32 summarises the number of votes for each clothing ensemble worn at the time when the Sydney participants answered the questionnaire during summer. Participants were asked to identify their level of clothing as being 'very light', 'light', 'casual' and 'heavy'. Given that the thermal environment experienced during summer was warmer than at other times of the year, most participants were wearing light clothing ensembles (i.e. shorts and a T-shirt) at the time of the questionnaire (377 votes, 58.9% of responses). Despite warmer outdoor temperatures, a higher percentage of participants wore casual ensembles (24.8%) as opposed to the option of very light clothing (16.1%). Heavy ensembles were worn on just one occasion.

Considering most participants moved between wearing casual and light clothing ensembles across the duration of the summer season, Figure 3.33 shows that there was no discernible relationship between the indoor temperature and the type of clothing worn by the participant. As indoor temperatures increased, the percentage of participants wearing light clothing also tended to increase, especially when these temperatures were above 28°C.

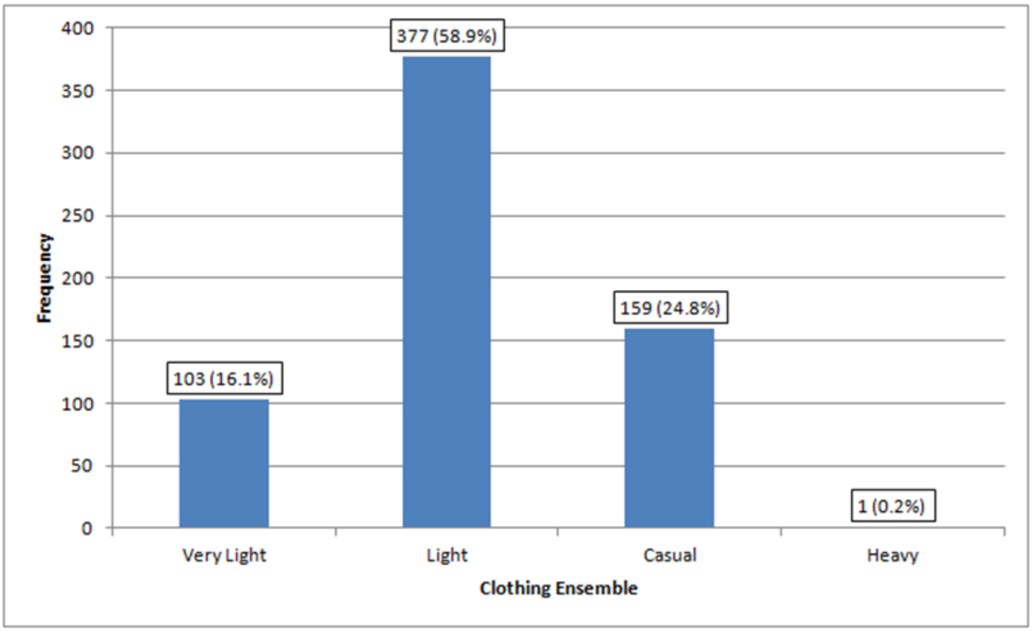


Figure 3.32: Sydney participants' clothing ensembles at the time of answering the comfort questionnaire

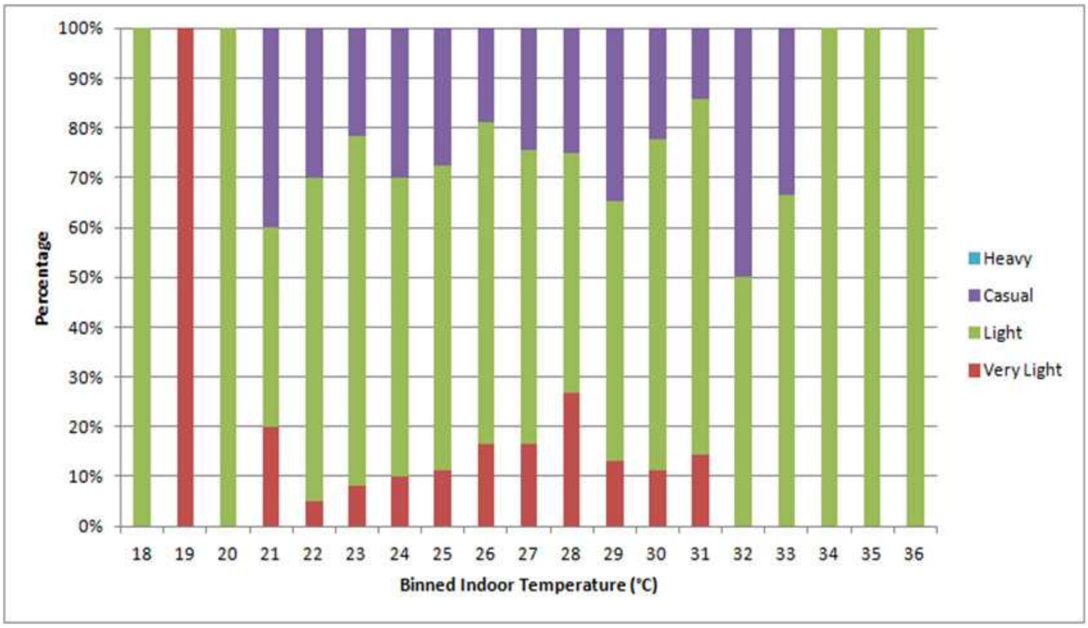


Figure 3.33: Clothing votes of Sydney participants binned by concurrent indoor temperature

At the time when participants in the Adelaide study responded to the comfort survey, 63% of their responses indicated that they were wearing light clothing while 25% were wearing casual clothing (Figure 3.34). This was very reasonable as the study was conducted in summer. In Figure 3.35, it is clearly seen that the participants adjusted their clothing according to the indoor temperatures. Much lighter clothing was worn as the temperature increased.

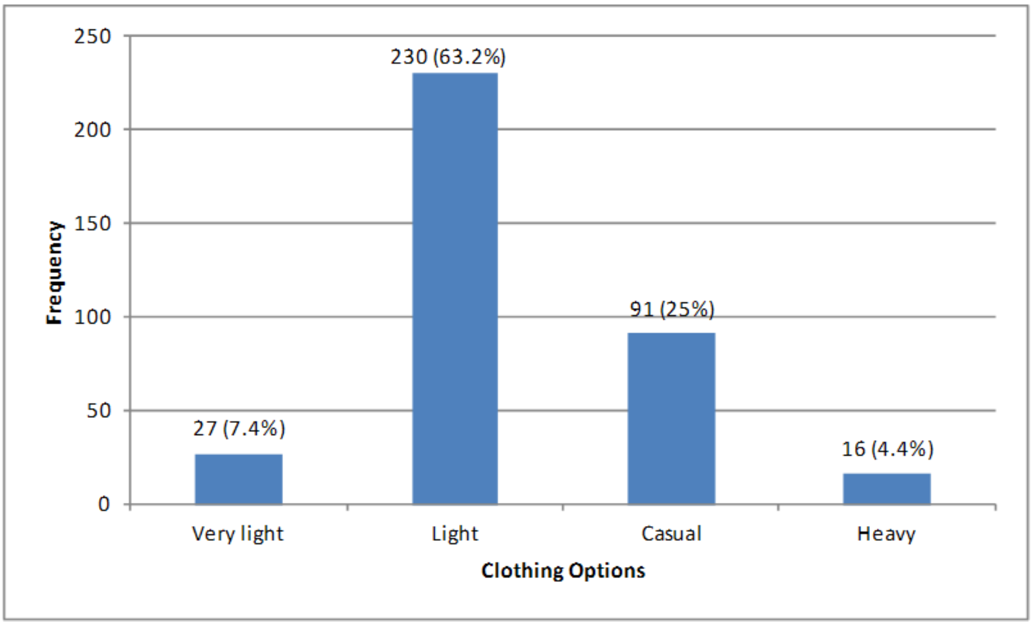


Figure 3.34: Adelaide participants' clothing ensembles at the time of answering the comfort questionnaire

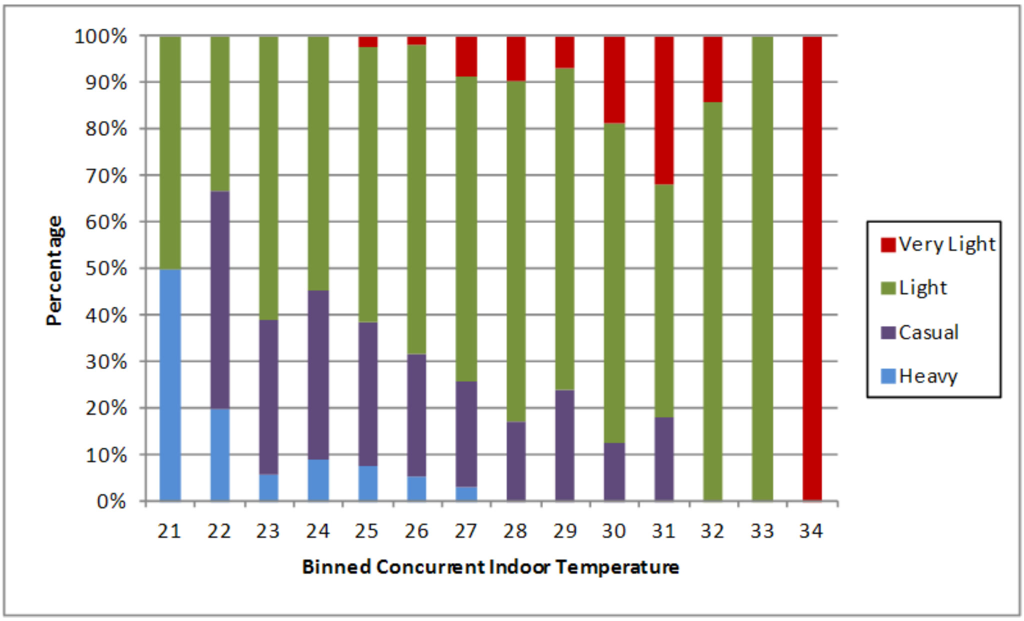


Figure 3.35: Clothing votes of Adelaide participants binned by concurrent indoor temperature

As shown in Figure 3.36, a high percentage of participants (72%) in the Brisbane study were wearing light clothing ensembles at the time they answered the questionnaire. In contrast with the results from Sydney and Adelaide, more participants in Brisbane study wore very light clothing (23 votes, 15.8%). Casual and heavy ensembles accounted for 9.6% and 2.7% of the total number of votes respectively.

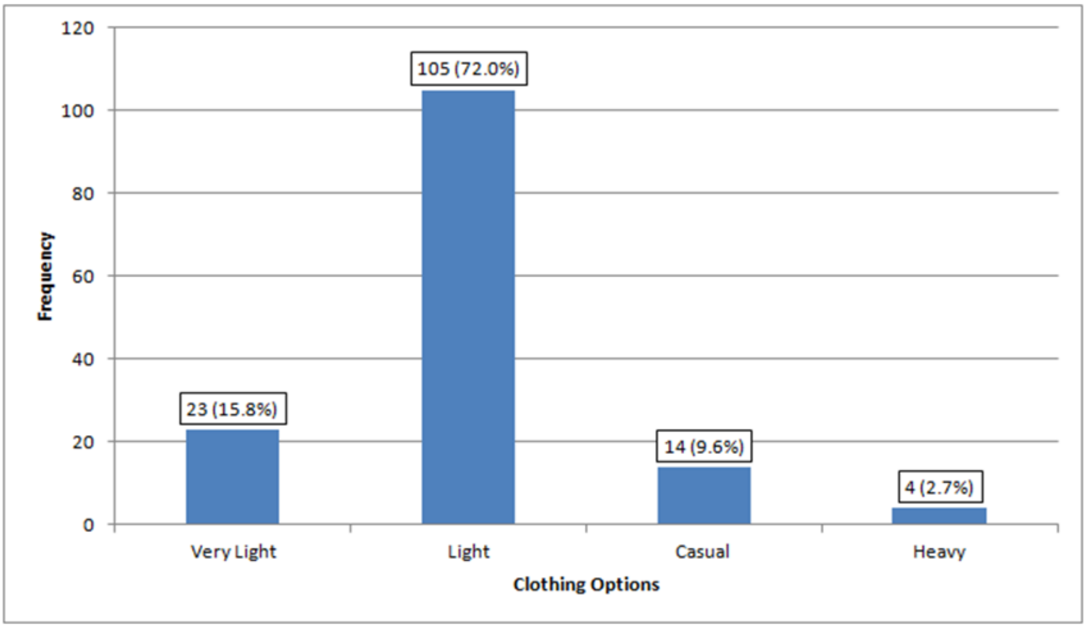


Figure 3.36: Brisbane participants' clothing ensembles at the time of answering the comfort questionnaire

While Figure 3.37 indicates that a greater proportion of participants tended to wear very light ensembles as opposed to light ensembles as the indoor temperature increased, there doesn't appear to be any significant relationship between the level of clothing worn by the occupants and the concurrent indoor temperature.

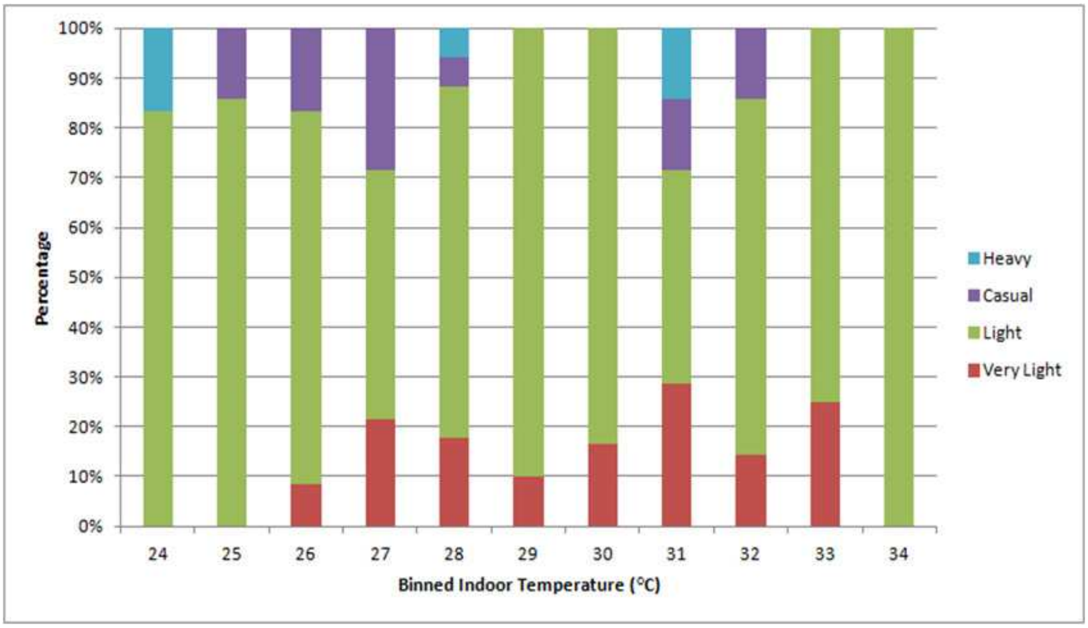


Figure 3.37: Clothing votes of Brisbane participants binned by concurrent indoor temperature

Ventilation strategies

Figure 3.38 summarises the number of responses from the Sydney participants for each ventilation option posed in the comfort questionnaire. These include opening windows and/or doors, turning on fans, using air conditioner on cooling mode, using air conditioner on heating mode, using other heating devices and no ventilation strategies. The most frequently cited individual thermal adaptation was opening windows and/or doors (41.4%) followed by the use of the air conditioner unit for cooling purposes (24.8%). Fans would appear to be underutilised in Sydney homes, scoring only 12.7% of the total questionnaire responses. Despite the study occurring during the warmest months in Sydney, 20.2% of votes indicated that no ventilation strategy was used.

These personal comfort adaptation responses were binned into 1°C intervals along the indoor temperature scale in Figure 3.39. As indoor temperatures increased, the use of more passive options, for example, opening windows and/or doors and turning on fans, became more prevalent. When temperatures exceeded 25–26°C, the number of participants using air conditioner units on cooling mode also increased. However, even at extreme indoor temperatures above 30°C, opening windows and doors was still the most preferred cooling strategy, but again this generalisation needs to be qualified by the very small number of observations at temperatures above 30°C. Figure 3.39 shows that there was no clear relationship between indoor temperature and the operation of air conditioner units for cooling which could be explained by the moderately warm summer season experienced in Sydney in 2012/13.

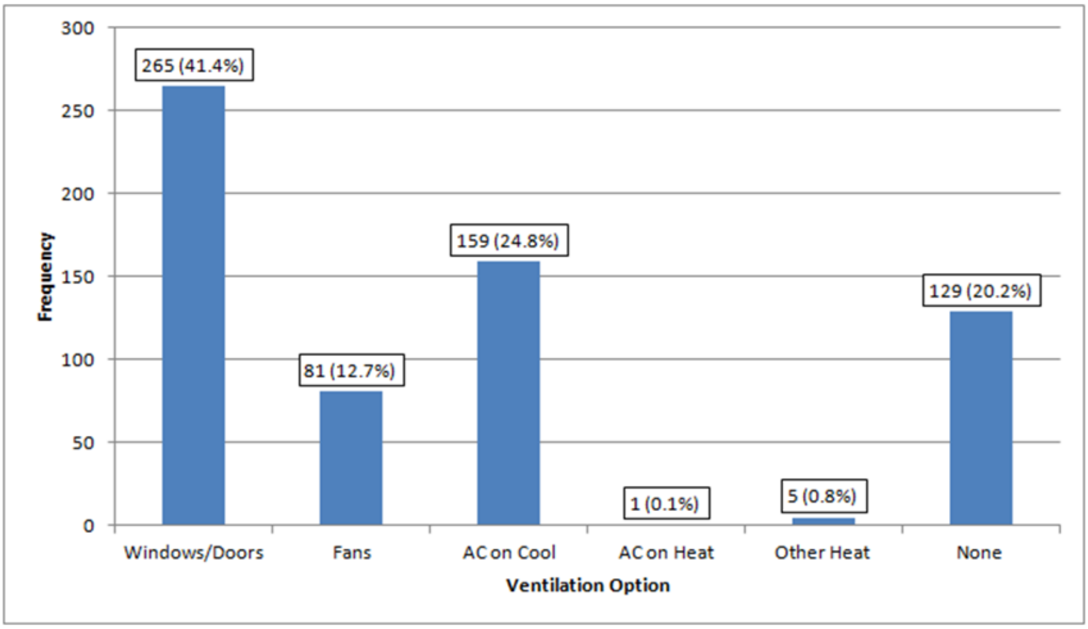


Figure 3.38: Sydney participants' ventilation strategies at the time of answering the comfort questionnaire

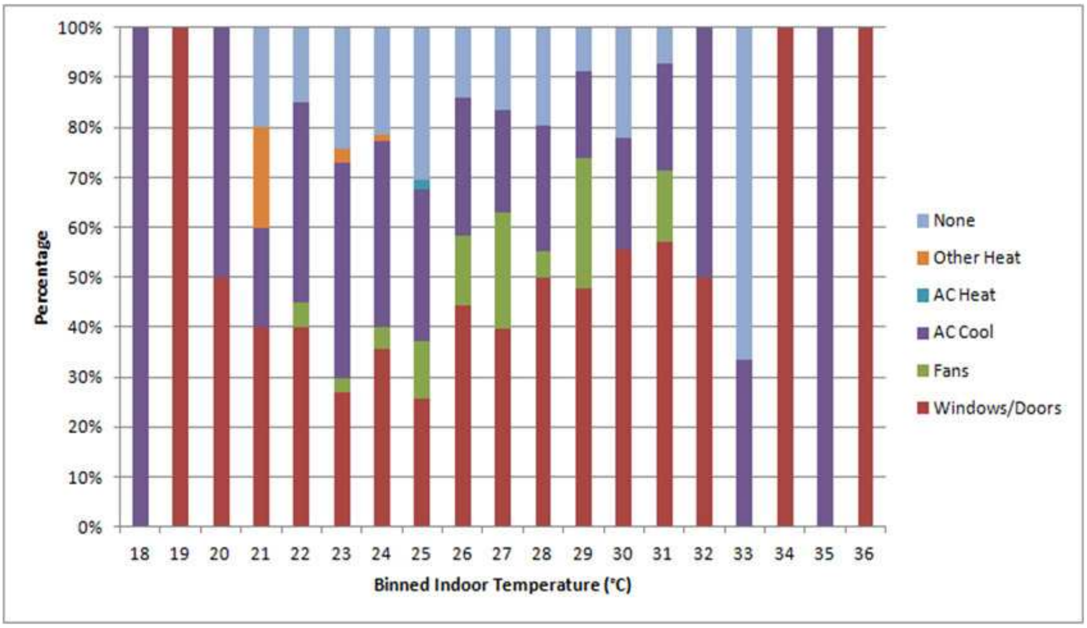


Figure 3.39: Sydney participants' ventilation strategies binned by concurrent indoor temperature

In the Adelaide study, turning on fans and opening windows and doors were the most preferred options for ventilation at the time when the participants were answering the thermal comfort survey with 33% and 31% occurrences respectively (Figure 3.40). Windows and doors were usually opened when the participants voted that their thermal sensation was *neutral*. More than 50% of the responses indicated that they were *slightly warm, warm* and *hot* but the air conditioner was utilised in less than 20% of those instances (Figure 3.41). This suggests that households did not necessarily turn on the air conditioner to make themselves more comfortable; instead, they successfully utilised other adaptive options.

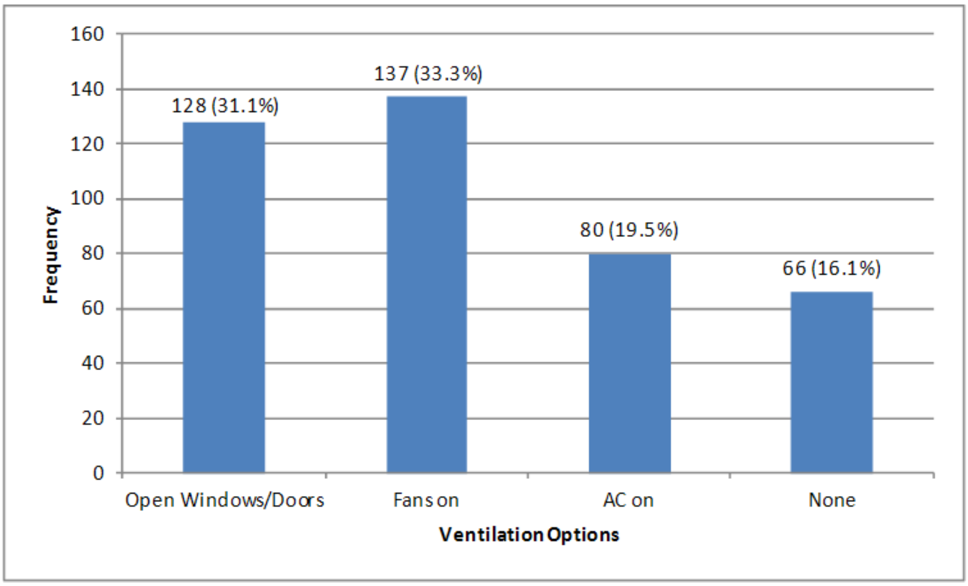


Figure 3.40: Adelaide participants' ventilation strategies at the time of answering the comfort questionnaire

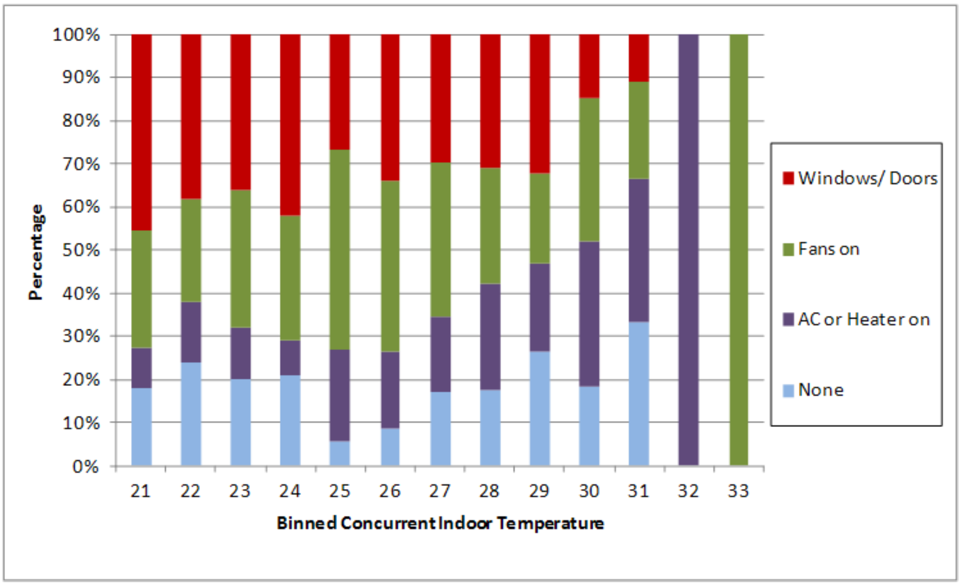


Figure 3.41: Adelaide participants' ventilation strategies binned by concurrent indoor temperature

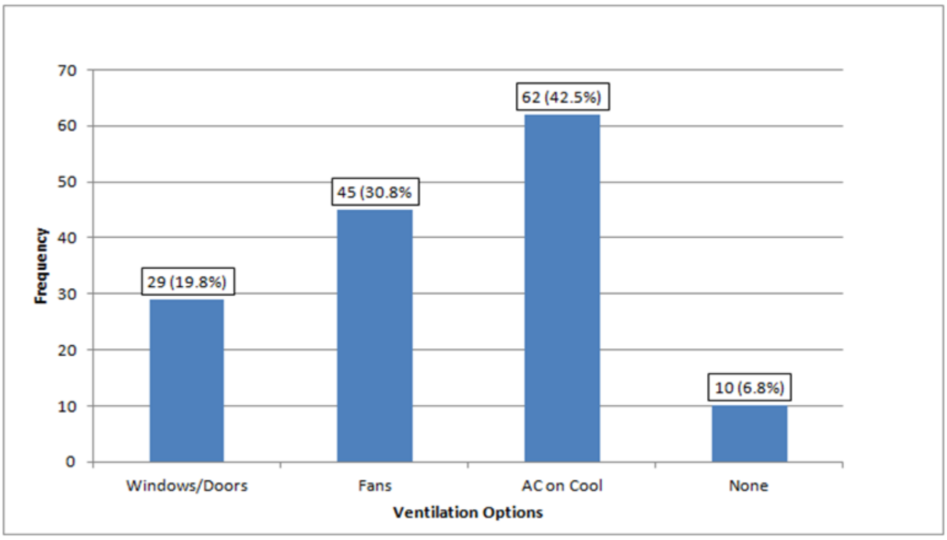


Figure 3.42: Brisbane participants' ventilation strategies at the time of answering the comfort questionnaire

Figure 3.42 illustrates that the most popular ventilation strategy as voted by the Brisbane participants was the use of air conditioning (42.5%). Next came turning on fans (30.8%) followed by opening windows and/or doors (19.8%). The use of a 'no ventilation' option received only 10 votes. When plotted against indoor temperature in Figure 3.43, there doesn't appear to be a direct relationship between the use of any ventilation strategy and the concurrent indoor temperature at which the questionnaire was answered. Generally, as the indoor temperatures increased above 28°C, a higher proportion of participants stated that they used air conditioner units on cooling mode. This trend coincided with a decrease in the use of passive ventilation options, such as turning on fans and opening windows and/or doors.

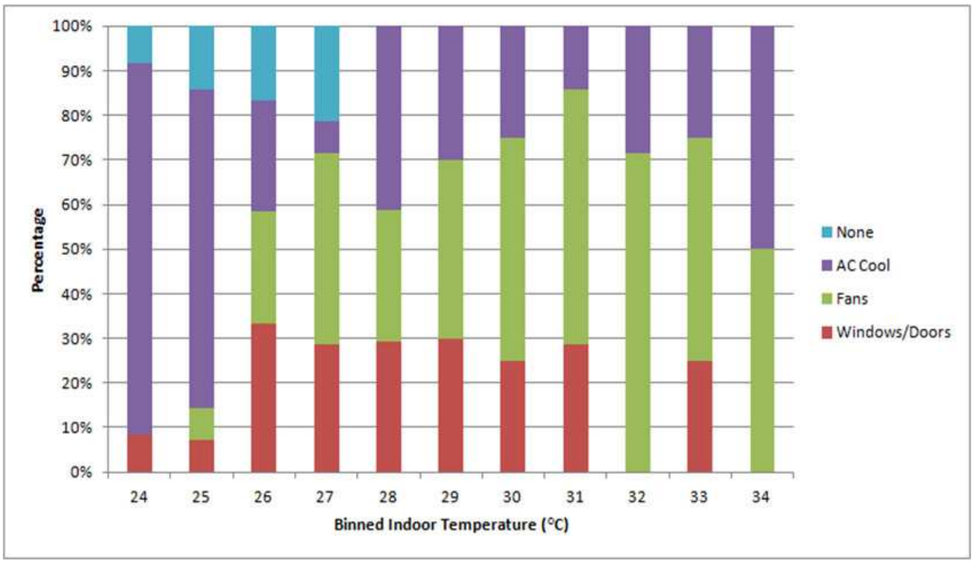


Figure 3.43: Brisbane participants' ventilation strategies binned by concurrent indoor temperature

Thermal sensation versus ventilation strategy

Figures 3.44, 3.45 and 3.46 show the analysis of participants' thermal sensations for Sydney, Adelaide and Brisbane respectively at the time when they were using different ventilation strategies. As illustrated, the most favourable thermal adaptation adopted in Sydney during summer was the opening of windows and/or doors. Similarly in Adelaide, Figure 3.45 shows that participants preferred to turn on fans instead of the air conditioner even though they voted that their thermal sensation was *slightly warm*, *warm* or *hot.* The use of fans decreased and the use of air conditioners increased as the participants voted that they were experiencing warmer thermal sensations. In Brisbane, however, it was apparent that most participants resorted to using their air conditioner units to achieve thermal comfort which was justified given the hotter outdoor temperatures experienced during the study.

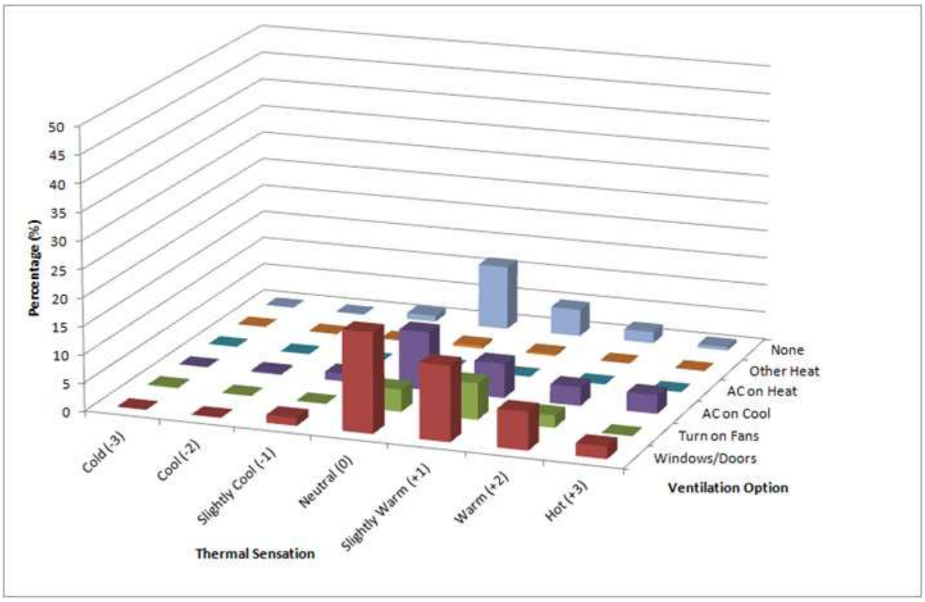


Figure 3.44: Thermal sensation votes according to each ventilation strategy of the Sydney participants

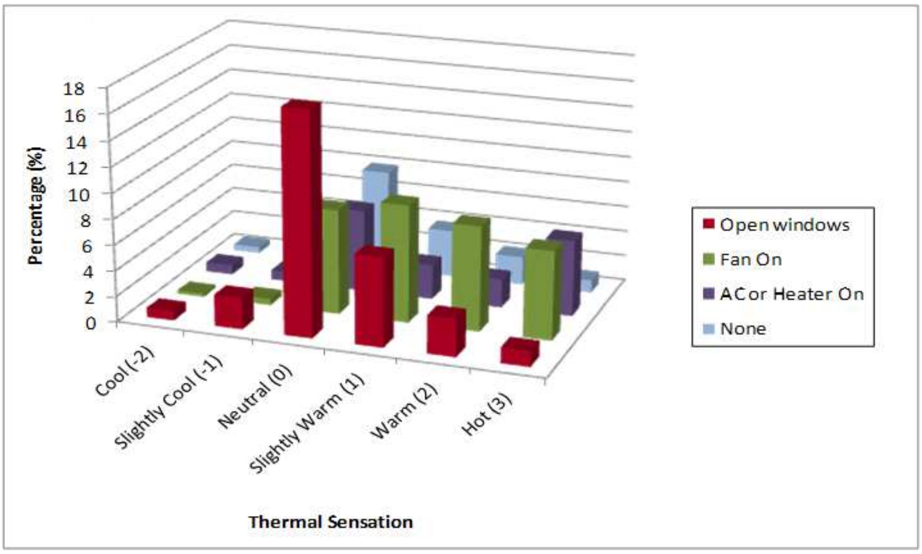


Figure 3.45: Thermal sensation votes according to each ventilation strategy of the Adelaide participants

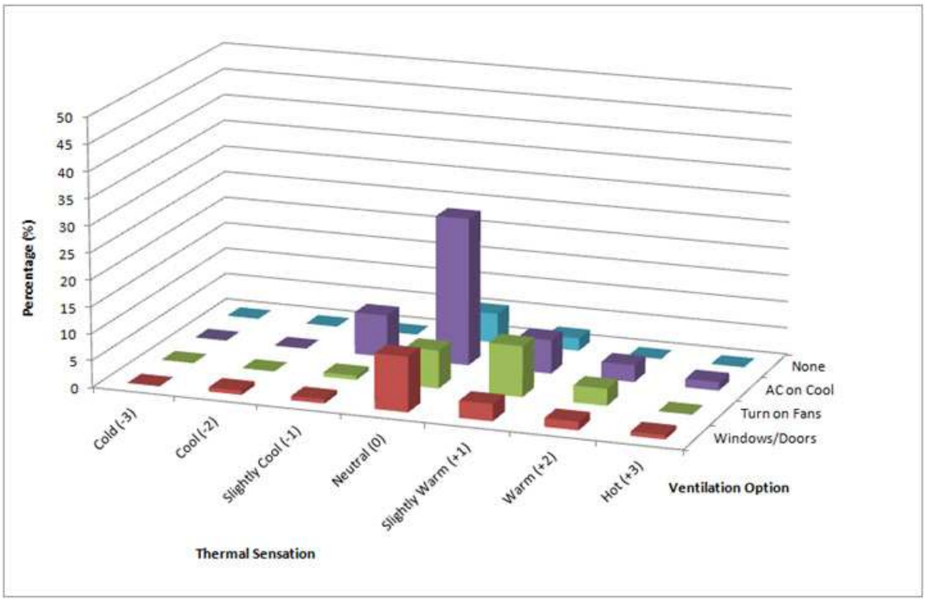


Figure 3.46: Thermal sensation votes according to each ventilation strategy of the Brisbane participants

Thermal sensation versus indoor temperature

Figures 3.47 to 3.49 illustrate the average thermal sensation vote calculated for every 1.0°C indoor temperature interval for Sydney, Adelaide and Brisbane respectively. The regression models were fitted using weights according to the number of votes in each temperature bin. For the Sydney study, the plot suggests a strong positive relationship (R^2 = 78%) for thermal sensation against the concurrent indoor temperature yielding a significant correlation ($p = 0.000$). The fitted model indicates a neutrality of about 22°C. The gradient of the model suggests that it takes about 7°C of room temperature change to shift the mean thermal sensation by one vote, strongly reinforcing the thermal adaptability in this sample.

These results were reiterated in the Adelaide and Brisbane studies as shown in Figures 3.48 and 3.49 respectively. These graphs both show that participants' thermal sensation increased as the indoor temperature increased with R^2 values of 91% in Adelaide and 82% in Brisbane, which both yielded significant correlations ($p < 0.05$). In Figure 3.48, it appears that most votes were between *neutral* to *slightly warm* at indoor temperatures of 22.7°C and 26.7°C, *slightly warm* to *warm* at 26.7°C and 30.8°C, and *warm* to *hot* at 30.8°C and 34.8°C. Adelaide's neutrality came in at about the same value, 22°C, as the Sydney sample, but in the Brisbane sample, it was significantly higher at about 26°C. The steeper gradient on Adelaide's and Brisbane's regression models (one sensation unit per 4°C in Figures 3.48 and 3.49 for Adelaide and Brisbane respectively) suggests that the samples in those cities were more thermally sensitive (or less thermally adaptable) than their Sydney counterparts.

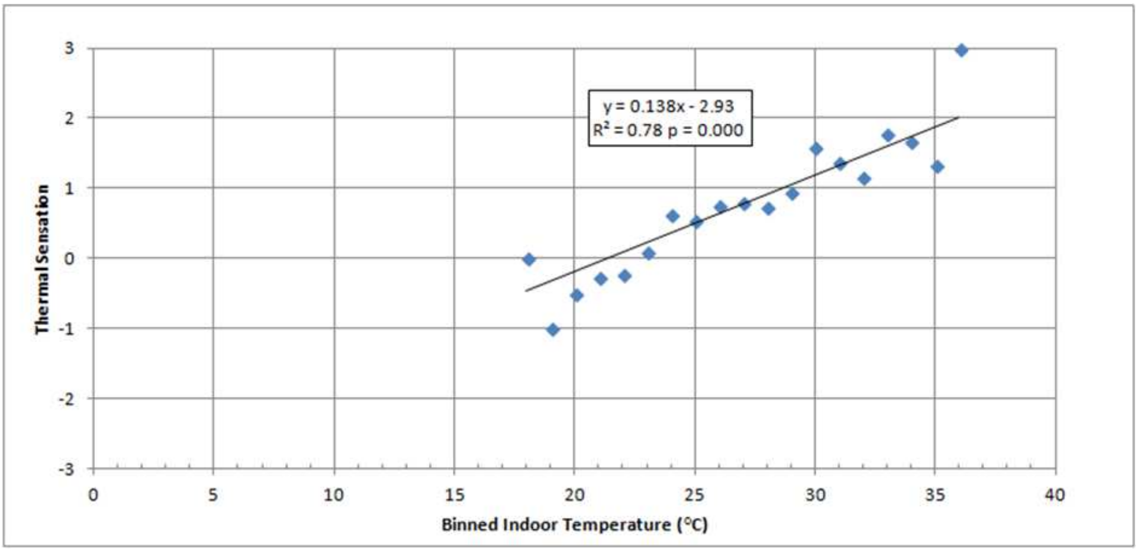


Figure 3.47: Average thermal sensations versus concurrent room temperature (binned at 1°C intervals) for Sydney households during summer

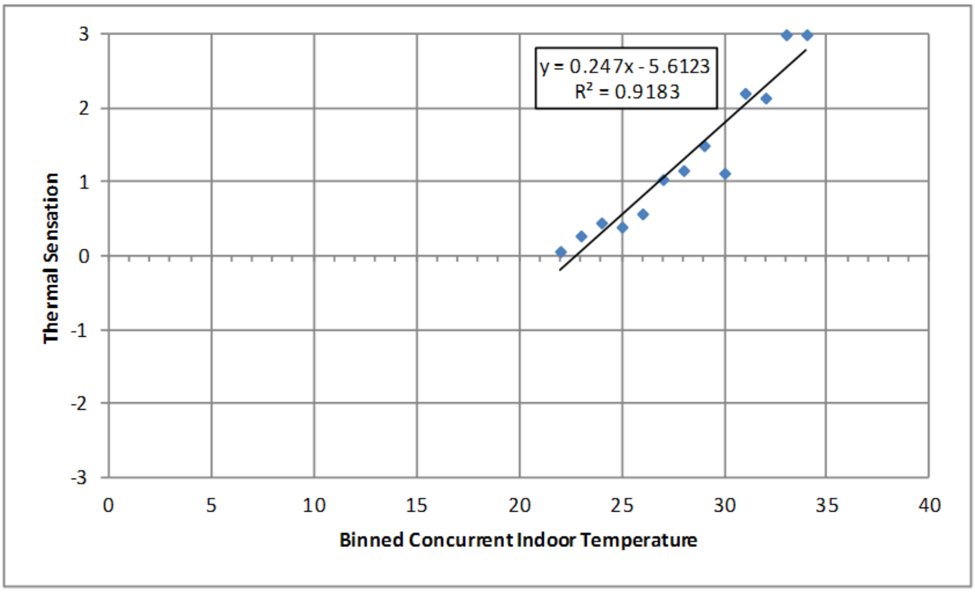


Figure 3.48: Average thermal sensations versus concurrent room temperature (binned at 1°C intervals) for Adelaide households during summer

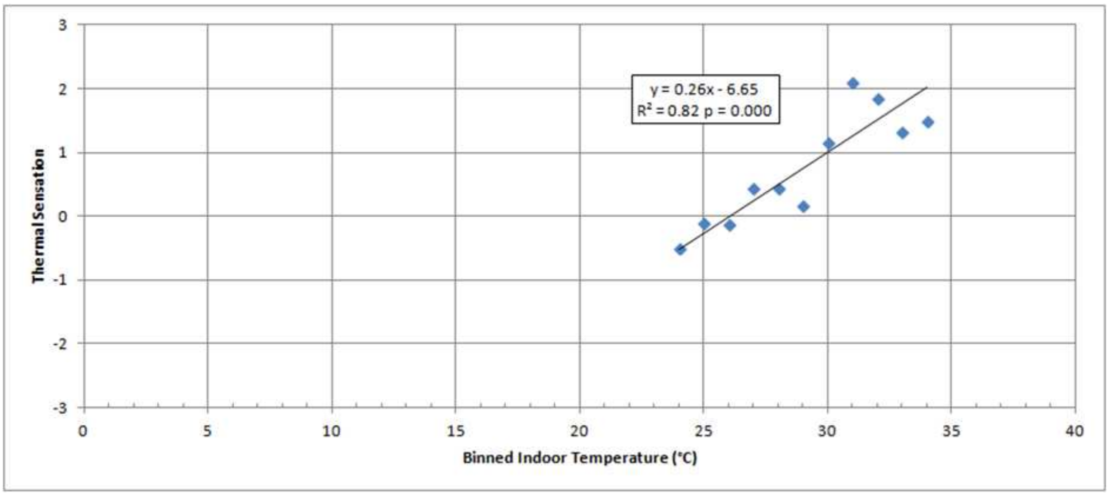


Figure 3.49: Average thermal sensations versus concurrent room temperature (binned at 1°C intervals) for Brisbane households during summer

Clothing versus indoor temperature

Traditionally, clothing ensembles are expressed in terms of their insulation level (clo) based on the standardised checklists in international comfort standards, such as ASHRAE Standard 55-2010 (ASHRAE 2010). However, in this case clothing ensembles were assigned numerical values ranging from ‘1’ (very light) to ‘4’ (heavy). Plotted against the binned concurrent indoor temperature, Figure 3.50 presents the analysis for clothing ensembles for the Sydney study. Since the average level of clothing worn by the participants at each indoor temperature interval was within the light category, there is a weak negative relationship (R^2 = 8%, $p > 0.05$) between the clothing ensemble and the indoor temperature. Figure 3.51 presents the results from the Adelaide study, also showing a strong negative relationship (R^2 = 86%, $p = 0.000$) between the clothing ensemble and indoor temperatures. The occupants wore less clothing as the indoor temperature increased. Similarly, in the Brisbane context, the clothing ensemble was also negatively related to the indoor temperature (R^2 = 53%, $p = 0.01$) suggesting participants would wear less clothing at warmer indoor temperatures (Figure 3.52).

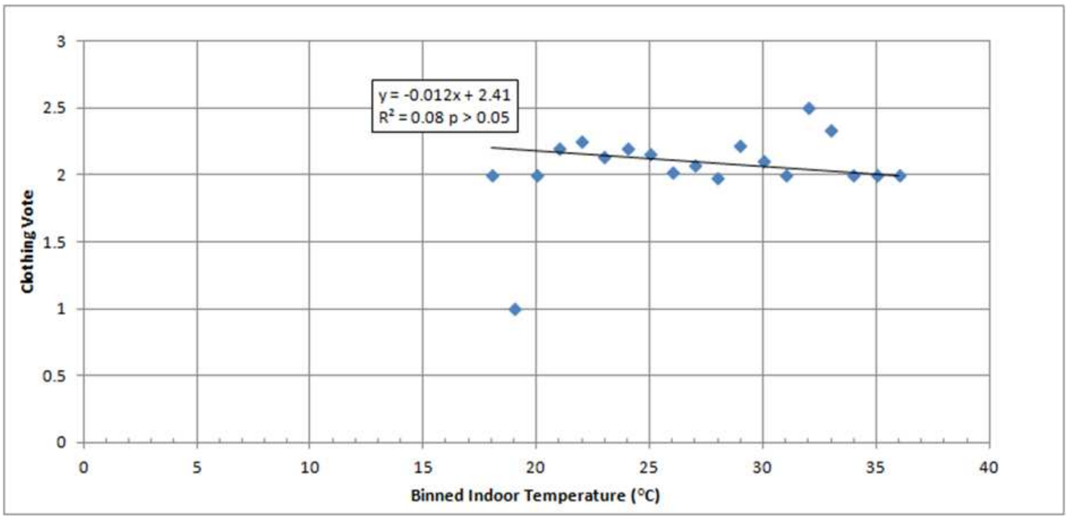


Figure 3.50: Average clothing ensemble votes from the Sydney study plotted against binned concurrent indoor temperature

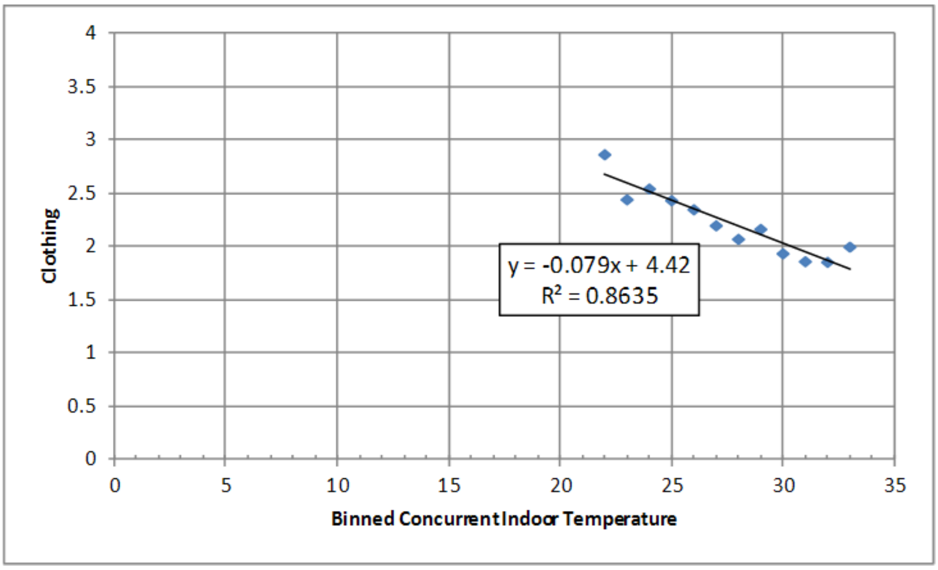


Figure 3.51: Average clothing ensemble votes from the Adelaide study plotted against binned concurrent indoor temperature

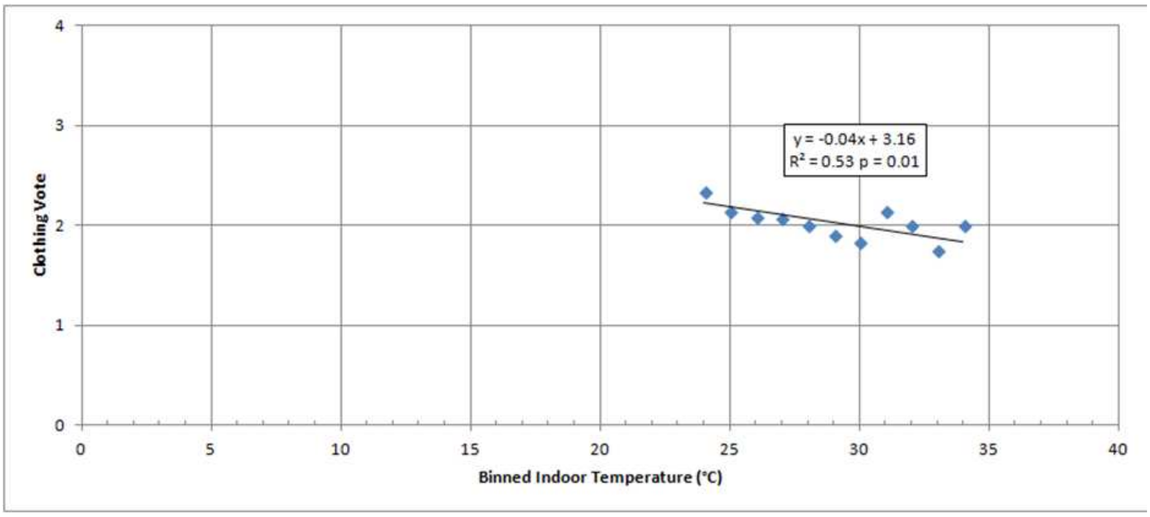


Figure 3.52: Average clothing ensemble votes from the Brisbane study plotted against binned concurrent indoor temperature

Neutral thermal sensation versus ASHRAE Standard

Figures 3.53, 3.54 and 3.55 show the concurrent indoor temperatures at which the participants' thermal sensations were rated as *neutral* in Sydney, Adelaide and Brisbane respectively. These were plotted against the 7-day running mean and compared with the ASHRAE Standard 55-2010 80% and 90% acceptability ranges. As illustrated in the graphs, the majority of *neutral* votes from each study were registered at indoor temperatures ranging between 18°C to 30°C (the lower and upper limits of ASHRAE's 80% acceptability). These observed *neutral* temperatures are overwhelmingly within the ASHRAE 55-2010 acceptability ranges, which demonstrate that the adaptive model could be used to describe thermal comfort in all rooms of these houses during waking hours. However, there were some occasions on which indoor temperatures described by the occupants as *neutral* fell outside ASHRAE's acceptable range.

Upon further analysis, it was found that 43% of *neutral* thermal sensations of the Sydney and Adelaide samples were expressed at a time when participants had their doors and windows open. In Sydney, 'A/C on cool' and 'no ventilation' both coincided with a quarter of the total number of thermally *neutral* votes depicted in Figure 3.54. In Adelaide, 22% of the *neutral* votes occurred when the participants had turned on their fans, and another 18% when their air conditioner was on cooling mode, while 17% of the participants who voted *neutral* selected no ventilation options. It seems that the use of passive cooling strategies, that is, opening windows and/or doors was the preferred adaptive opportunity, especially during warmer temperatures.

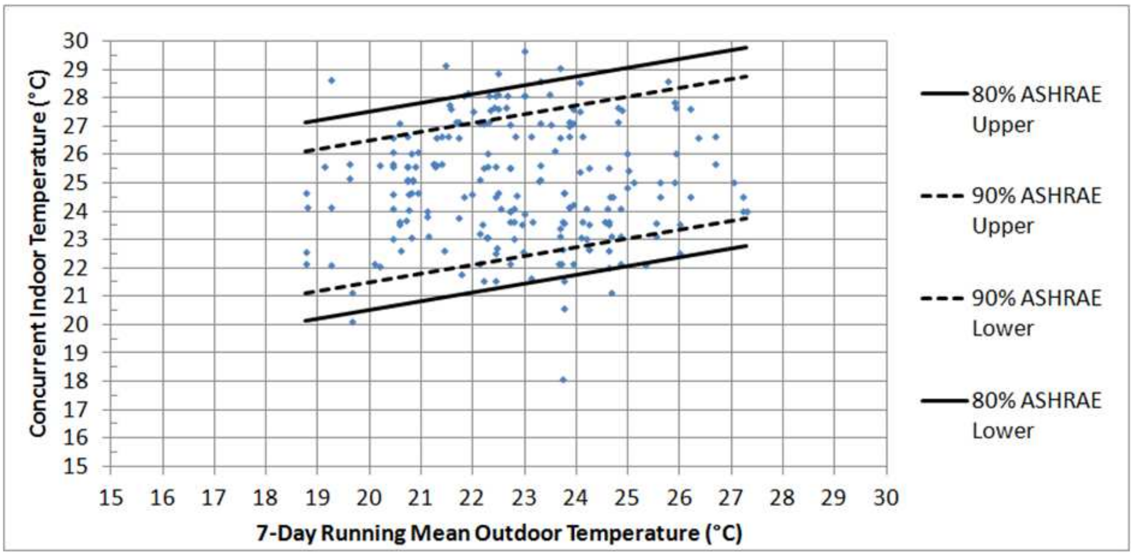


Figure 3.53: Concurrent indoor temperature when '*neutral'* thermal sensations from the Sydney study were registered, plotted against 7-day running mean outdoor temperature compared, overlaid with the ASHRAE Standard 55-2010 80% and 90% acceptability limits

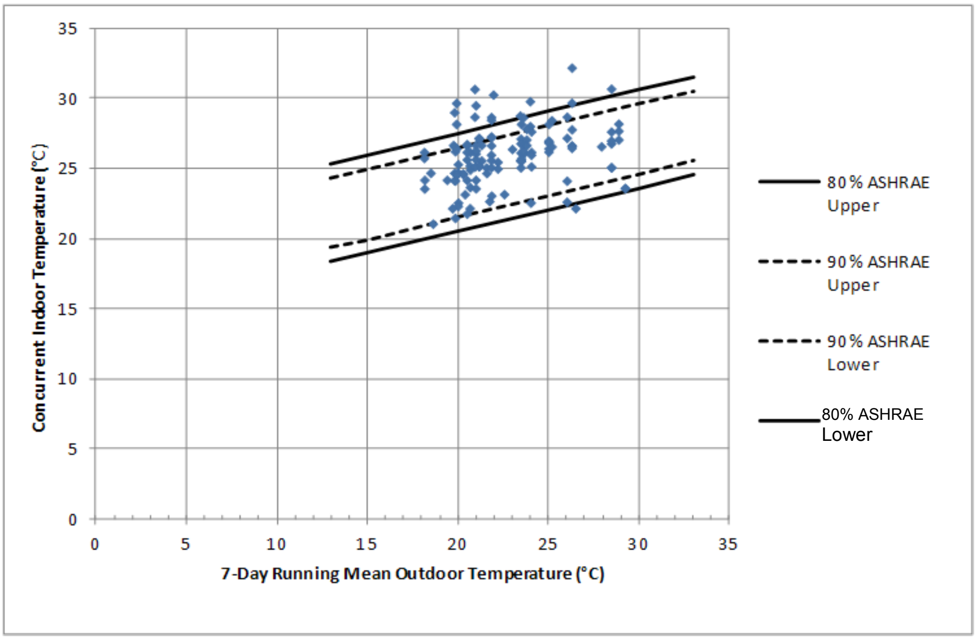


Figure 3.54: Concurrent indoor temperature when '*neutral'* thermal sensations from the Adelaide study were registered, plotted against 7-day running mean outdoor temperature compared, overlaid with the ASHRAE Standard 55-2010 80% and 90% acceptability limits

In comparison to the Sydney and Adelaide studies, the Brisbane data analysis shown in Figure 3.55 revealed a more varied range of indoor temperatures at which the participants expressed thermal sensations that were *neutral*. Considering that nearly half of the votes were recorded when participants were operating the air conditioner unit on cooling mode, this suggests that the outliers visible in this graph were attributed to the use of these devices influencing the participants' thermal sensation vote.

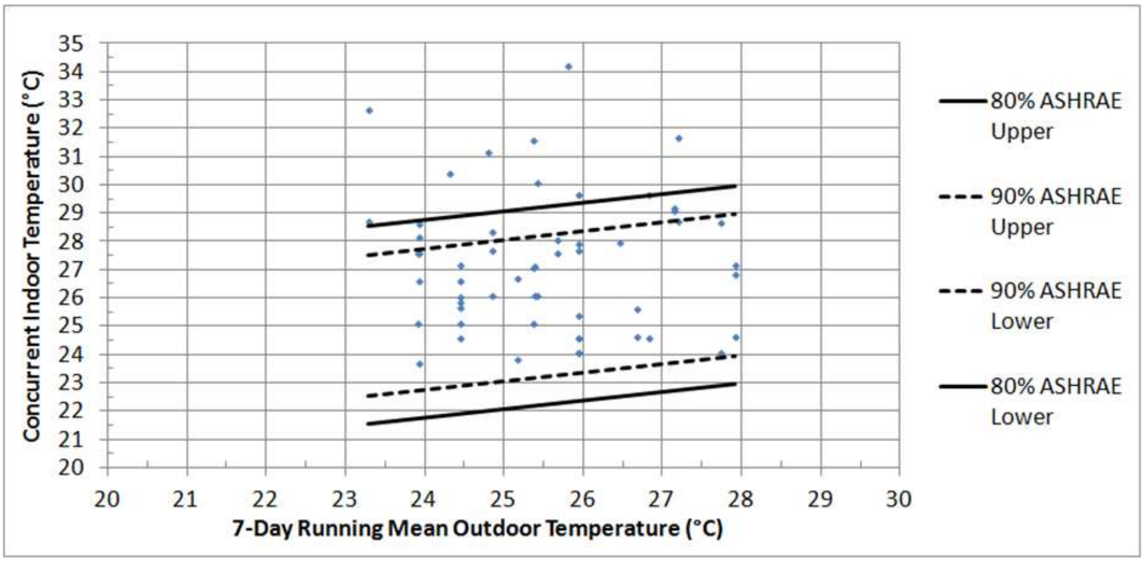


Figure 3.55: Concurrent indoor temperature when '*neutral'* thermal sensations from the Brisbane study were registered, plotted against 7-day running mean outdoor temperature compared, overlaid with the ASHRAE Standard 55-2010 80% and 90% acceptability limits

The use of air conditioners in cooling mode compared to the ASHRAE 55-2010 Adaptive Comfort Standard

The following graphs show the range of indoor temperatures at which participants in the Sydney and Brisbane studies reported on the comfort questionnaire that they were using their air conditioner units for cooling purposes. In the case of the Sydney study, shown on Figure 3.56, almost all indoor temperatures corresponding to air conditioner usage fell within ASHRAE's adaptive 80% temperature acceptability limits. On the other hand, Figure 3.57 suggests otherwise for the Brisbane participants, but the small sample size restricts the drawing of any firm conclusions.

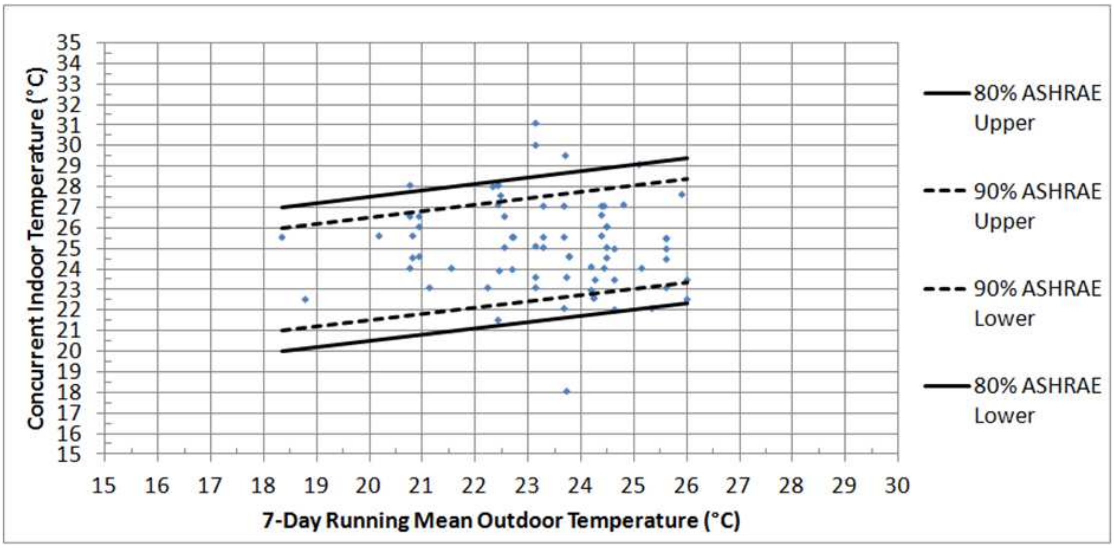


Figure 3.56: Concurrent indoor temperature from the Sydney study when A/C unit was on cooling mode, was registered, plotted against 7-day running mean outdoor temperature compared to ASHRAE Standard 55-2010 80% and 90% acceptability limits

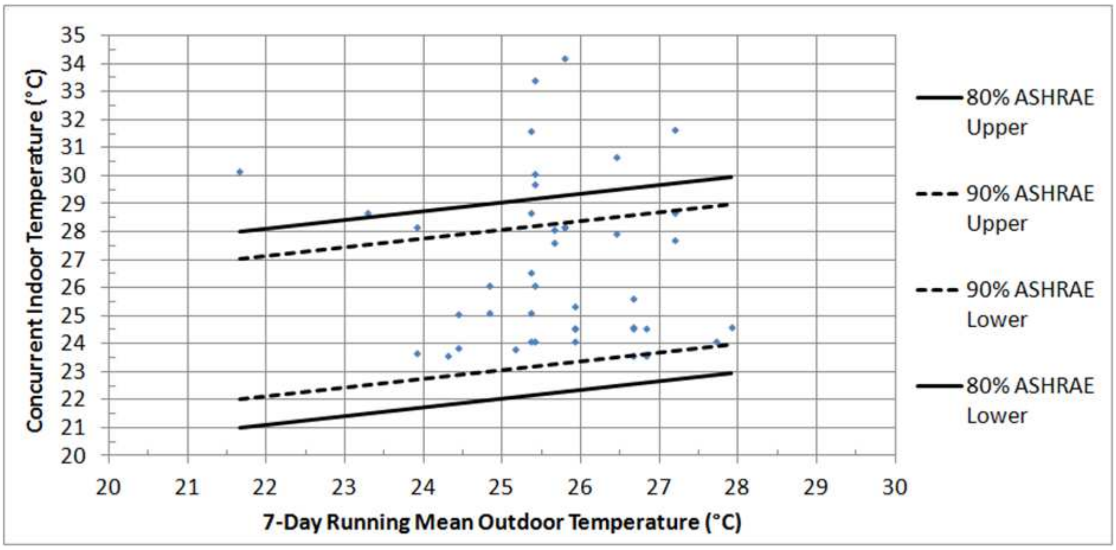


Figure 3.57: Concurrent indoor temperature from the Brisbane study when A/C unit was on cooling mode, was registered, plotted against 7-day running mean outdoor temperature compared to ASHRAE Standard 55-2010 80% and 90% acceptability limits

'No ventilation' option compared to the ASHRAE 55-2010 Adaptive Comfort Standard

The fundamental principle of the adaptive comfort theory can be stated as: *if a change occurs such as to produce discomfort, people will react in ways which tend to restore their comfort* (Brager et al. 2004; Nicol & Humphreys 2010). In other words, people will only resort to using a ventilation strategy when they feel uncomfortable. From the questionnaire data, it can be inferred that participants were comfortable at times when they were not using any thermal adaptations. The concurrent indoor temperatures at which these responses were recorded were plotted along ASHRAE Standard 55-2010 80% and 90% acceptability limits as shown in Figures 3.58, 3.59 and 3.60 for Sydney, Adelaide and Brisbane respectively. As highlighted, in the Sydney study, most temperatures at which no ventilation was being used fell within the ASHRAE 55-100 80% adaptive acceptability limits.

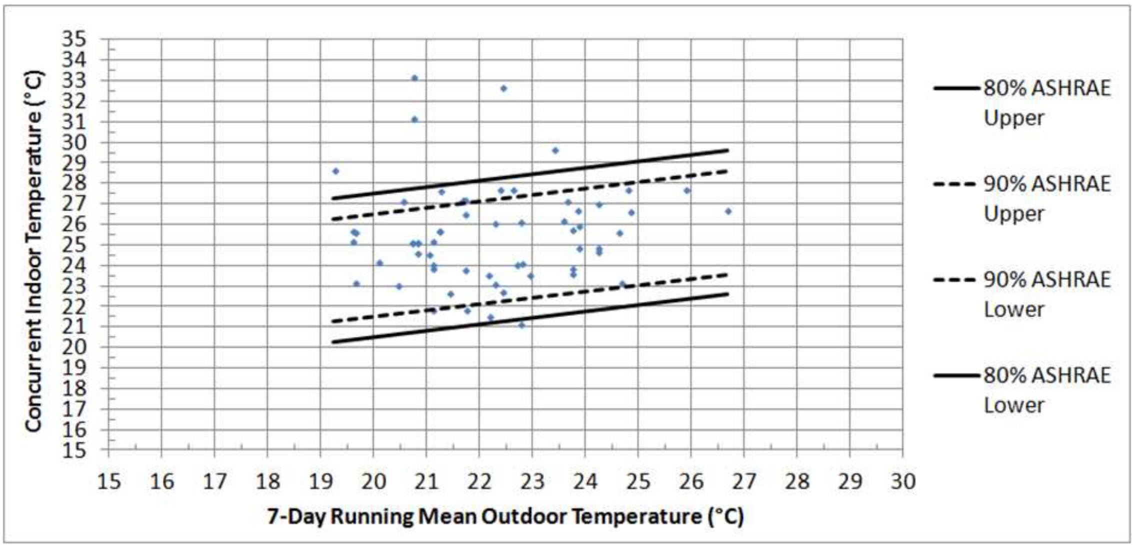


Figure 3.58: Concurrent indoor temperature from the Sydney study for the 'no ventilation' option, plotted against 7-day running mean outdoor temperature compared to ASHRAE Standard 55-2010 80% and 90% acceptability limits

In the Adelaide study (Figure 3.59), most temperatures at which 'no ventilation' was indicated, fell within ASHRAE's 80% acceptability limits, with only 4% falling above the upper acceptability limit. Insufficient 'no ventilation' votes were recorded during the Brisbane study to sustain any generalisations (Figure 3.60).

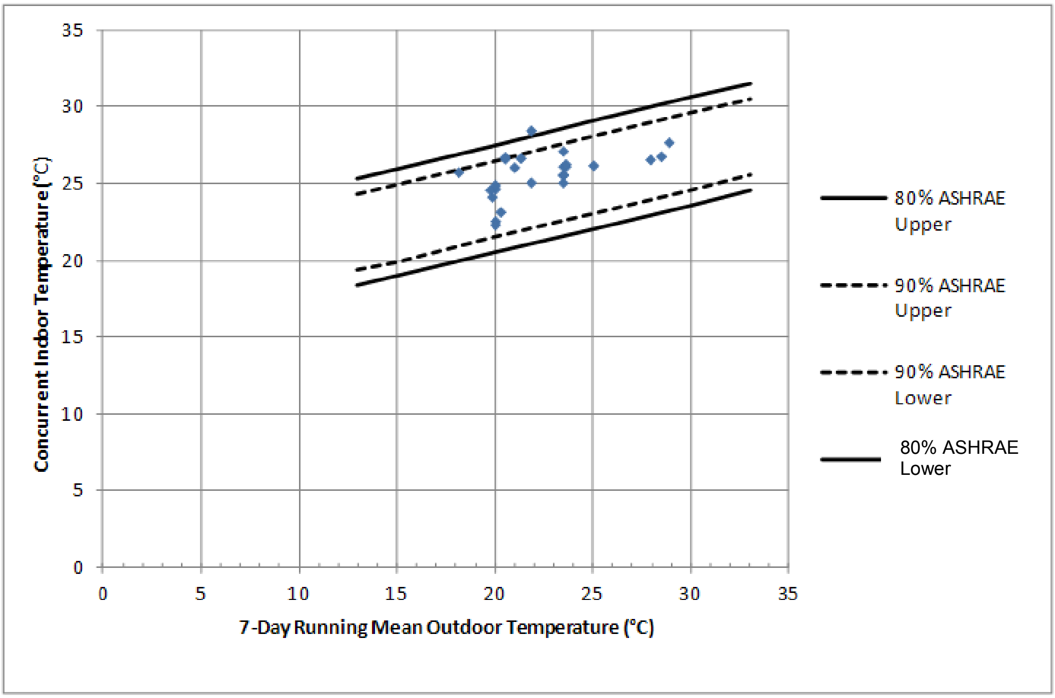


Figure 3.59: Concurrent indoor temperature from the Adelaide study for the 'no ventilation' option plotted against 7-day running mean outdoor temperature compared to ASHRAE Standard 55-2010 80% and 90% acceptability limits

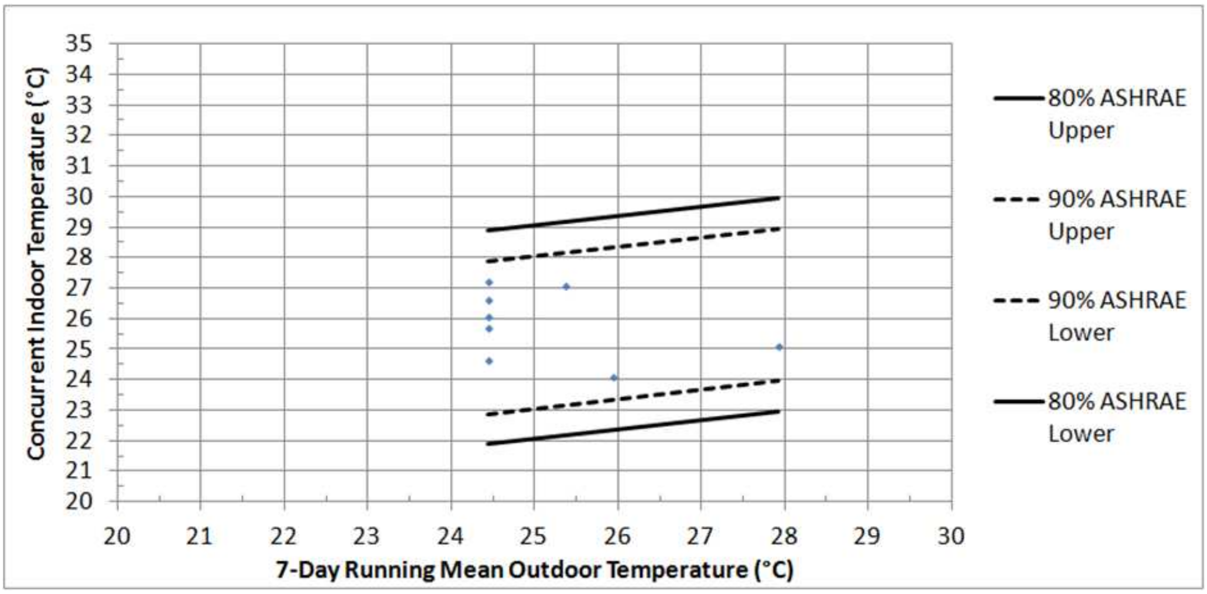


Figure 3.60: Concurrent indoor temperature from the Brisbane study for 'no ventilation' option, plotted against 7-day running mean outdoor temperature compared to ASHRAE Standard 55-2010 80% and 90% acceptability limits

3.9 *Limitations*

It is acknowledged that there are limitations in this present study which may affect the results.

Lack of summer heat waves

The outdoor weather experienced during the recent summer seasons in Sydney, Adelaide and Brisbane were, on average, some of the warmest temperatures recorded during the calendar year. All cities often recorded daily maximum temperatures exceeding 40°C. That being said, they did not experience an official heat wave period, as defined by BoM. Therefore, the results presented here are about thermal comfort during moderate-to-hot summertime temperatures rather than during heat waves.

Indoor climate data

The amount of reliable data collected from the Brisbane households during the summer season was very low.

Adaptive comfort model applicability

The ASHRAE adaptive comfort model (de Dear & Brager 1998, 2002) and the associated adaptive comfort standard (ASHRAE 55-2010R) were based on large samples of office occupants (n = 22,000) from 160 buildings scattered across four continents. Whether or not that adaptive comfort concept can be generalised from office settings to a residential context was one of the key questions of this research. This generalisation was strongly supported by the Sydney data in hand. Results from the study conducted in Adelaide indicated that the model was applicable for assessing thermal comfort in mixed-mode (naturally ventilated and air-conditioned) residential buildings.

3.10 *Conclusions*

This section presents the preliminary results from a thermal comfort study across residential houses in Sydney, Brisbane and in a housing development in Adelaide. So far, the Sydney study has recruited 30 participant households located throughout the Greater Sydney region. Compared to the population of Greater Sydney, participants in the sample had an average age of 30–39 and were highly educated with most having attended university and obtaining a degree at postgraduate or higher levels. The participants also had above-average income levels. Participants' homes were a variety of stand-alone dwellings and apartments built from common construction materials, for example, concrete, timber and corrugated steel. The air conditioner units within these houses represented the more common air conditioner technologies found within residential buildings, for example, ducted and spilt systems.

The study in Adelaide included 20 householders involving 22 participants. While the number of samples was relatively small for a generalisation to be made for Greater Adelaide, there was a more even distribution of age groups, academic backgrounds and income levels of the participants in Adelaide than in Sydney. However, in terms of house locations, construction types and air conditioning systems used in houses, the majority of the samples in Adelaide were more homogenous as they nearly all came from the same housing development. The Brisbane sample, by comparison, comprised a range of family types ranging from a single adult to households of adults and children. Consistent with the demographics in the Sydney and Adelaide studies, the Brisbane participants also had above average income levels with 50% of households containing at least one adult working full-time.

The Brisbane houses did not require heating; however, split systems were the most common type of air conditioner throughout the sample population. These units were mainly located in the living room and bedroom, with the majority of houses having ceiling fans in their living areas and bedrooms.

In the Sydney study, between December 2012 and March 2013 (2012/13 summer season), the average indoor living room temperature during occupied hours (0700–2100 hrs) was 25.0°C. Ranging between 20°C and 30°C, these temperatures were well within the boundaries of ASHRAE's 80% acceptability limits (18°C to 28°C). These temperature ranges were fairly similar across other types of room, with the dining room apparently being slightly cooler, with an average indoor temperature of 23.6°C. These results are consistent with the finding that the majority (44%) of thermal sensation votes recorded within the participants' houses were described as *neutral*. In the Adelaide study conducted between January and March 2012, from all the data from 20 houses, the average indoor temperature in the living room and bedroom without the air conditioner running was 24.5°C and 27.2°C respectively. Based on all the data recorded, the temperatures in the living room and bedroom were also mainly within the boundaries of ASHRAE's 80% acceptability limits except for 7.2% and 12% of the time, respectively. The average indoor living room temperature recorded for the Brisbane sample was slightly warmer at 26.5°C, possibly due to the warmer outdoor conditions experienced during the study.

According to the data obtained from the comfort questionnaires, most participants adjusted what they wore according to the indoor temperatures. The participants in Sydney predominantly wore light clothing ensembles (59%): when binned according to concurrent indoor temperature, it was found that the percentage of participants who expressed their thermal sensation as *slightly warm* to *warm* increased. To accommodate for these warmer conditions, that is, indoor temperatures above 25°C, most participants were wearing light clothing ensembles. Furthermore, above this threshold, participants increased their usage of passive ventilation strategies, especially in the Sydney and Adelaide studies. Despite the availability of an air conditioner unit, the most preferred thermal adaptation employed by the participants was the opening of windows and/or doors (over 90%). In the Brisbane sample, however, the findings did not seem to fit this generalisation since the most commonly used ventilation strategy during the study was having the air conditioner on cooling mode (42.5%). These findings suggest that the participants were comfortable across a fairly broad range of temperatures. Between indoor temperatures of 18°C to 28°C, the range of average thermal sensations was within the region of *slightly cool* (-1) to *slightly warm* (+1).

Light clothing was also the most preferred ensemble option in the Brisbane and Adelaide samples, representing 72% and 63% of the total number of votes, which was reasonable considering that the study was conducted in summer. In terms of passive ventilation strategies, opening windows and doors as well as turning on fans were the two strategies that were most frequently employed. It was found that windows and/or doors were opened most of the time; however, employing this strategy to provide passive ventilation and cooling steadily decreased as the indoor temperatures increased. Conversely, the air conditioner was more frequently used as the temperatures increased, particularly in Brisbane.

In comparison with the adaptive comfort model, as presented in the ASHRAE Standard 55-2010 (ASHRAE 2010), the majority of *neutral* temperatures calculated for each participant in the Sydney study fell within the upper and lower limits of 80% acceptability, confirming that the adaptive comfort model's scope extends to residential settings. It appears that indoor temperatures between 20°C and 30°C could be deemed as an acceptable range of temperature for this sample of residential buildings.

In the Adelaide study, it appeared that indoor temperatures between 21°C and 30°C were acceptable during summer, These temperatures corresponded to times when the participants felt *neutral* and during which, for 43% of the time, windows and/or doors were opened, fans were turned on for 22% of the time, 18% of the time the air conditioner was turned on, while 17% of participants did nothing. Regression analysis of the data indicated that the participants started feeling *slightly warm* at indoor temperatures of about 27°C.

If a person is not employing any thermal adaptation at a given indoor temperature, then they can be assumed to be comfortable at that temperature. In the Sydney and Adelaide studies, 28°C was the maximum temperature at which ‘no ventilation’ strategies were in use and yet occupants still voted *neutral*. This temperature may suggest a new thermostat setting for cooling in the Adelaide climate (as opposed to 25.0°C as determined in the NatHERS); however, further studies will be required to validate this suggestion.

From the findings presented in this report, it is clear that existing adaptive comfort models, as described in ASHRAE Standard 55-2010 (2010), can be applied to residential homes, during hot weather, especially those in the context of Sydney.

4. BUILDING DESIGN

4.1 *Introduction*

Building design is an important parameter for consideration in both climate change mitigation and adaptation. Until recently, much of the information related to building design and climate change had been concerned with mitigating the effects of climate change through reducing the CO_2 emissions associated with the building sector across the building life cycle. According to statistics from the World Business Council for Sustainable Development (WBCSD), buildings contribute more than 40% of energy consumption in most countries (WBCSD 2007). Indeed, the building sector is one of the biggest energy consumers and carbon emitters (Zuo et al. 2012) and hence such mitigation approaches are indeed critical. Mitigation frequently receives preference over adaptation strategies which are equally as important particularly to future heat wave adaptation scenarios.

Many publications aimed at a wide readership provide information about the relationship between residential building design and climate change (see, for example, Roaf et al. 2005; Smith 2005; Simon 2008; Steenbergen et al. 2012; Williams et al. 2012). The information is often wide-ranging in nature with suggestions for reducing building energy use through passive design and, in some cases, the use of renewable energy sources. As with various studies undertaken on commercial buildings (Henze et al. 2007; Pfafferott et al. 2007), such publications identify the benefits of passive design techniques in adapting buildings to summer conditions by employing thermal heat sinks, night ventilation, thermally activated building systems, etc. Whilst such approaches successfully improve comfort conditions and reduce building energy demand in summer periods, they are not enough to deal with long duration heat waves (Pfafferotter et al. 2007).

The majority of adaptive comfort studies have been undertaken in commercial environments. However, the differentiation between building types, occupancy patterns and associated thermal comfort conditions is critical to effective residential building design. Peacock et al. (2010) argued that "... thermal comfort … is an amalgam of physiological and mental response to a climatic condition. Our mental state at home and the range of adaptive behaviour possible is distinct to that in the office and therefore perceptions of comfort are likely to be quite different".

Within the residential housing sector, there exists a range of housing and household types which require consideration in the proposal of design strategies. Studying overheating in 3,456 dwellings in London, Mavrogianni et al. (2012) found that dwelling type, age and insulation are the main determinants of overheating, all being more important than orientation. Whilst the climatic conditions in London differ from most regions of Australia, and given recent planning policies encouraging intensification around activity and transport centres, it is relevant that the study by Mavrogianni et al. (2012) also found that overheating risk seems to increase with the floor level in high-rise structures, with top-floor flats being warmer, followed by mid-floor flats.

Given the longevity of housing stock, any new Australian residential building would ideally be conceived and constructed to provide appropriate conditions for occupants over the coming decades, during which time increased heat wave conditions are predicted. The rate of construction of new housing stock is relatively slow: "over the past decade Sydney and Melbourne have added on average 1.4% and 2.1% overall stock each year" (Kelly, Weidmann et al. 2011, p. 37). Hence, modification to existing housing stock is equally as important as new construction.

Ren et al. (2011) investigated the impacts of global warming on energy consumption and CO_2 emissions for two residential house designs in a number of Australian locations. They provided recommendations for adapting new and existing houses so that energy use remains the same with future temperature increases. The house designs are modelled using AccuRate software with weather files adjusted to represent future temperature increases up to 6^0C. They considered space heating and cooling as well as water heating but excluded lighting and appliances. It was found that for existing houses in heating-dominated climate zones, retrofitting from the average base case of 2 stars to 5 stars (NatHERS rating) is required to avoid the need for greater energy input. In climates where there is a balance between heating and cooling, increasing the star rating is required in conjunction with increasing the energy efficiency of air conditioning and appliances. In cooling-dominated Darwin, all these measures are required plus the installation of an on-site solar photovoltaic system.

The study outlined above demonstrates the need for a multi-pronged approach to heat waves integrating changes to building design, appliance efficiency and alternative energy sources. However, it is of concern that Ren et al. (2011) have demonstrated that all of these changes are needed simply to maintain existing energy consumption levels, something which is not viable given future energy price increases, the imperative to reduce greenhouse gas (GHG) emissions, diminishing resources and negative consequences on occupants of systemic energy failure during heat waves.

Interestingly, Ren et al. (2011) showed that new houses must be designed to a 7-star rating or more to accommodate a temperature increase of 2^0C in order to achieve comfort in all climate zones without consuming more energy. This demonstrates the need to increase the energy efficiency of housing across the country. However, they also stated that new high energy-efficient housing is more sensitive to climate change (p. 2408). Therefore, the challenge is to determine additional means of measuring building performance specifically during heat waves, and to investigate options for achieving thermal comfort via means other than the routine air conditioning of residences – to consider how social and behavioural variables might be utilised.

In this context, it is worth noting that having a more energy-efficient house design while generally improving the occupants' thermal comfort does not directly lead to better protection against heat waves. An extensive study carried out by Saman and Halawa (2009) demonstrated, through detailed monitoring of energy consumption of six energy-efficient houses for two years, that while the energy consumption dropped by an average of 35% compared with the local average, the peak electricity demand for air conditioning during heat waves was still very high and constituted a larger proportion of the total electrical demand.

Housing and house design are an important consideration in relation to health. The majority of people spend most of their time indoors (WHO 2004) and the link between health and housing is well established (Maller & Strengers 2011); therefore, the connection between building design and thermal comfort during heat waves is an important area of research. There is little information about specific aspects of building design and the heat-related health of the occupants. At a general level, studies have shown that most heat-related deaths are likely to occur in the home or in nursing homes (O'Neill et al. 2003; Dhainaut et al. 2004; Bi et al. 2011). Bedrooms have been singled out as an area of particular concern as "this is often where an occupant will find adaptation difficult, particularly at night" (Patidar et al. 2011). Patidar et al. (2012) modelled the probability of overheating in a typical 3-bedroom residence in 2030, 2050 and 2080. Their study found that the night temperature in bedrooms will increase in the future (to 30^0+ in the 2080s during the summer heat wave period) and the overheating duration will increase accordingly (up to 40%). Lack of sleep is one of the factors that predisposes people to heat-related illness (WHO 2004, p. 21). Increased heat-related morbidity and mortality have been identified after a second night of elevated minimum temperature (Loughnan et al. 2010; Nitschke et al. 2011).

Taking into account the issues highlighted above, this section of the report will:

- identify the future dwelling profile based on current population and household trends to determine what house types will predominantly be constructed in the coming decades and how this might inform building design for heat waves
- briefly review current regulatory mechanisms for dealing with heat waves in relation to building design
- outline typical design adaptation strategies in Australia and identify opportunities for their advancement
- discuss behavioural adaptation to heat waves, particularly in relation to building design
- propose design strategies aimed at improving building performance in relation to occupant comfort during heat waves.

4.2 *Building Design*

4.2.1 Future Dwelling Profile

In Australia, the main type of dwelling (78%) is currently the separate house. The proportion of separate houses has only decreased by 1% in the decade since 1997. Flats, units and apartments account for 13% of the dwelling stock, with semi-detached, row and terrace houses accounting for 9%. The percentage of separate houses differs in capital cities: Brisbane has the highest percentage of separate houses (81%) and Sydney the lowest (61%) (ABS 2010a).The pattern varies from city to city as described below.

High concentrations of multi-storey residential apartment buildings are usually found around central business districts (CBDs), with decreasing densities towards the outer areas. The exceptions to this pattern can be found in Gold Coast city, where high-rise residential buildings extend along the coastline, and in Sydney, where higher density residential development can be found around each of the major centres encompassed by the metropolitan area (DIT 2010).

In Sydney and Melbourne, there is a significant increase in the proportion of flats and apartments built during the 1990s. In Sydney, nearly one in four people live in flats, units and apartments (ABS 2010). A recent study has suggested that there is a cultural or experiential aspect to housing preferences with 85% of migrants from European countries living in a separate house while 34% of American migrants and 41% of Asian migrants live in a townhouse or a flat (Deloitte Access Economics 2011).

Over the periods 1993/94 to 2008/09, the average size of a new detached house in Australia increased from 188.7 m^2 to 245.3 m^2 (ABS 2009). In 2009–2010, the most common dwelling was a 3-bedroom house (41%) and 28% of dwellings had four or more bedrooms (ABS 2010a). However, in 2007 more than three-quarters of dwellings in Australia had more bedrooms than were needed to accommodate the occupants (ABS 2007). According to a report prepared by Consult Australia (2011), the density of dwellings in Australia has been increasing but the number of persons per dwelling or per household has been decreasing. In the period from 1994/95 to 2007, the average number of bedrooms in dwellings increased from 2.88 to 3.06: at the same time, the number of persons per household decreased from 2.69 to 2.51. This trend of increased house size along with reduced persons per household has been noticeable since the early 1900s. Recently, the first sign of a change in this trend occurred with a slight increase in persons/household from 2.51–2.56 in the 2007/08 period (ABS 2009). This was attributed to increasing housing costs and the related trend of adult children staying in their parents' home into their 20s.

Since the 1990s, the density of new housing development has increased. A study conducted by Hall (2009) of housing developments in a number of states found a net density in pre-1990 housing developments of 9-13 dwellings per hectare (dph) with the density of more recent developments ranging from 13-23 dph. Hall (2009) maintained that while this falls short of the densities found in European cities, it has combined with smaller lot sizes and larger house sizes to drastically reduce the size of the traditional Australian backyard. The average floor area of new homes in Australia has increased with recent figures indicating that these new homes are now the largest in the world (ABS 2009). At the same time, lot sizes in many new housing estates are only about a third of the size that they were 50 years ago. Houses have less space between them, privacy is an increasing issue and it is more difficult to open windows and doors for natural ventilation. In many new housing estates, the usable outdoor area is less than 50 m^2: this has implications for green spaces such as gardens and trees, and for stormwater retention.

The factors that will affect future dwelling structure in Australia include population growth and profile, household structure, current housing stock, location, migration and social acceptance (Figure 4.1).

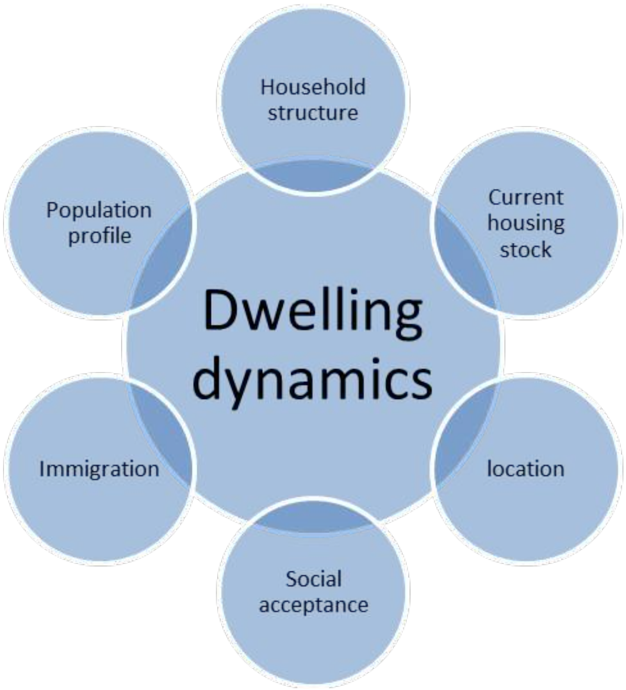


Figure 4.1: Dwelling dynamics in Australia

Australia's population is both increasing and ageing. The population has grown substantially in recent decades with an annual growth of 1.4% during the last four decades (DSEWPC 2011). The total population reached 22,696,000 in September 2011 (ABS 2012) and the constantly growing population will be an important driver of demand for dwellings in the future (McLaughlin 2012).

The proportion of people aged over 65 is predicted to increase from 13% in 2010 to more than 23% in 2050 (Commonwealth of Australia 2010). This change in the demographics of the population will also affect the number of persons per household.

For example, it is predicted that the proportion of single-person households will grow from 23% in 1996 to 28% in 2026 (Australian Government 2008). Estimates are that, in Melbourne for example, one- and two-person households will account for 90% of all new households by 2030 (Dept of Sustainability and Environment 2005). Donald (2011) pointed out that the household growth is greater than the population growth. He went on to say that the proportion of two-parent families is projected to decrease further from 31% in 2010 to 27% in 2030 (Donald 2011). Based on medium household growth scenario projections made by the National Housing Supply Council (NHSC), the number of households will increase from 8.7 million in June 2010 to 12 million in 2030 and the gap between supply and demand of dwellings is projected to triple by 2030, reaching 640,200 (NHSC 2011).

In addition, there is increasing stress on land, particularly in capital cities, and concerns about the affordability of housing. These factors combine to suggest that in capital cities there will be a higher proportion of flats, townhouses and apartments in the future. Governments around Australia are basing future housing policy on higher density and smaller dwelling size (City of Sydney n.d.; Dept of Sustainability and Environment 2005; Dept of Planning and Local Government 2010). This policy will influence the type of housing built between now and 2030–2050.

Ranged against these points are a number of factors. Replacement of housing stock is slow – “over the past decade Sydney and Melbourne have added on average 1.4% and 2.1% overall stock each year” (Kelly et al. 2011, p. 37). Single-person households may not equate to a desire for smaller dwellings. People stay in houses for a long time, despite changes in needs. Wulff, Healy et al. (2004) pointed out that “too great a trust in a demographic imperative in the determination of dwelling choice can lead to urban policies that fail to understand the complexities involved in people’s choices concerning dwelling size and type. The expectation that smaller households ‘need’ smaller dwellings often results from too static a view of the lives of persons in small households”.

Many people still favour detached housing and have misgivings about living in flats and apartments, particularly in those that are high-rise (Buys & Miller 2012). Consult Australia (2011) identified concerns about the social acceptance of increased density. “The current focus on high density, high rise housing for urban consolidation in major cities has been largely driven by the desire by government and others for a quick fix to achieve the maximum possible ‘density benefit’ from the minimum available land area in the shortest time. In the longer term this ignores the clear potential adverse community and social implications of developing large concentrations of high rise, high density housing in inner urban areas”.

Change to the housing stock is partly dependent on what is available. Kelly, Weidmann et al. (2011) investigated the mismatch between the current stock of housing in Sydney and Melbourne, and the type of housing that respondents said they might prefer. Their report identified a shortfall, particularly in semi-detached houses, but also in apartments in zones around both city centres. This was supported by research undertaken by the Property Council of Australia (2012).

Residents were more likely to support, rather than oppose, a series of housing developments to would support population growth. The highest level of support was for: new neighbourhoods of free-standing houses built on the outskirts of the city close to jobs; the conversion of old industrial sites to apartments and townhouses; and more medium-density housing (like townhouses) in middle and outer suburbs (p. 34).

Efforts have been made by some scholars to predict the dwelling structure of the future. Commissioned by the NHSC, McDonald and Temple (2009) applied a medium household growth scenario and predicted that there would be a higher demand at the national level for flats rather than separate houses. However, this pattern differs according to location.

In most regions, the expected relative increase in demand for flats would be higher than for separate houses. The higher relative increase in demand for flats would be particularly evident in Western Australia and in the balance of South Australia. However, there are some exceptions to this rule. In Sydney, the relative increase in demand would be a little higher for separate houses than for flats and, in Queensland, there would be essentially no difference (McDonald & Temple 2009, p. 12).

As shown in Figure 4.2., the demand for semi-detached houses and flats is increasing; however, it is clear that separate houses will still dominate the dwelling mix in the next two decades in Australia.

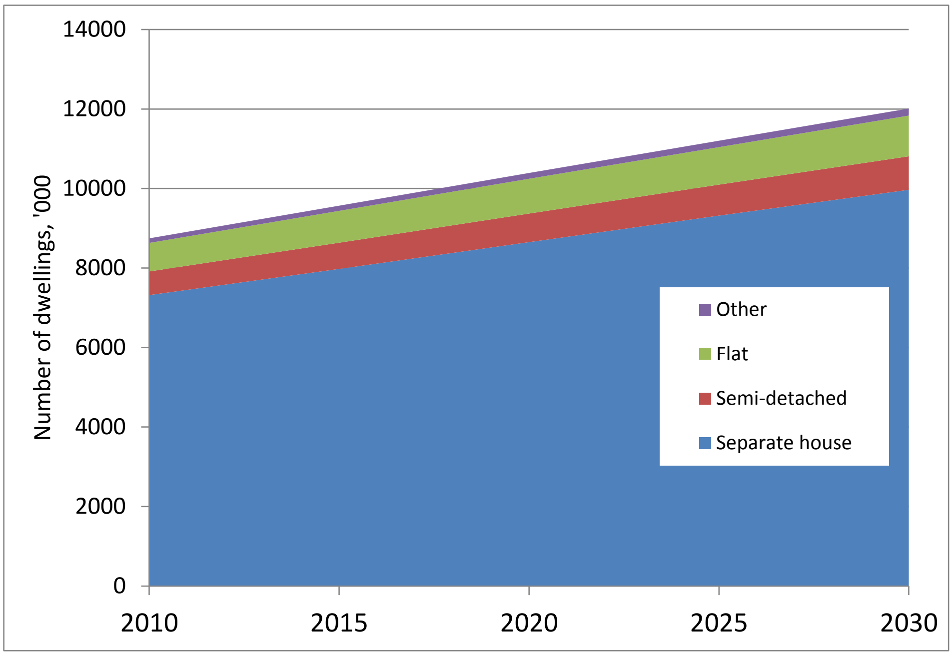


Figure 4.2: The underlying demand for dwellings 2010–2030, unit: ’000 dwellings. Source: NHSC 2011

With this in mind, five case studies were selected for further analysis according to this future dwelling profile. The analysis of the performance of these dwelling types is provided later in this section.

Case study 1: a small, single-storey 2-bedroom house; typical new housing for those on low incomes and elderly people who are more vulnerable during heat waves

Case study 2: a 3-bedroom brick veneer home; a typical design for new houses

Case study 3: a 2-storey home of new house design with a small allotment

Case study 4: a 2-storey apartment; typical medium-height, medium-density development

Case study 5: a 2-bedroom apartment in a multi-storey block (medium- to high-density development).

4.2.2 Regulatory Mechanisms for Dealing with Heat Waves

In recent years, the range of impacts associated with heat waves has been well researched. Less clear is the connection between residential buildings, the increased heat waves anticipated in the future and their impact on the occupants. It has been suggested that new buildings in Australia that comply with the energy-efficiency requirements of the National Construction Code, Building Code of Australia (NCC BCA) are reasonably resilient to the average changes expected with climate change. However, they may not be so resilient to extremes such as heat waves: dwellings constructed before the introduction of the BCA, which comprise the bulk of the current building stock, have far less resilience (BRANZ 2007).

Kwok and Rajkovich maintained that “even if greenhouse gas concentrations are stabilized in the atmosphere, extreme climatic events and sea level rise will continue for several centuries due to the inertia of the atmosphere. Therefore, adaptation will be a necessary complement to carbon dioxide mitigation efforts” (2010, p. 18). Hence, they asserted that policy needs to address both mitigation and adaptation at the levels of regional planning, urban design and building design.

The performance of buildings is affected by a combination of government policy (at federal, state and local levels), and standards and codes (PC 2012a). The National Climate Change Adaptation Framework, endorsed in 2007, specifically refers to the need for building codes, standards and guides to increase resilience to climate change and to the need for the Australian Building Codes Board (ABCB) to consider climate change as part of their periodic reviews of the BCA (COAG 2007).

A recent study by Pitt & Sherry (2010) included a review of international and Australian literature about the potential energy and CO_2 savings possible in the building sector. This reveals a wide range of estimates from about 80% of current energy use to less than 30%. The study investigated the possibility of using the Building Code of Australia (BCA) as a vehicle to reduce energy use and greenhouse gas emissions in new residential and commercial buildings. A number of different scenarios were modelled from business as usual through to current best practice (low scenario) to a ‘high scenario’ example with stringent targets and policies. This concluded that possible savings in the residential sector range from 37% (low scenario) to 56% (high scenario).

In 2010, the ABCB released a study of possible adaptation measures for climate change that could be incorporated into the BCA (ABCB 2010). The study considered a wide range of climate change impacts including extreme temperatures. As with the BRANZ study, the report found that, “by and large, the bulk of the BCA’s energy provisions will contribute to positive adaptation outcomes” (ABCB 2010). However, when discussing heat waves, it maintained that “despite heat waves posing a clear health and life safety risk, it remains unclear the role buildings have played; relative to other factors such as age and health of those persons affected. Clearly a building’s ability to maintain stable internal temperatures will reduce some of the health risks associated with heat waves; however, the BCA does not currently address issues of thermal comfort directly. Rather, energy-efficiency requirements affecting material selection, passive solar design and minimum levels of insulation serve to regulate a building’s internal temperature and therefore reduce risks during heat waves”.

The recent Productivity Commission draft report, ‘Barriers to effective climate change adaptation’ (PC 2012a), noted that although there have been numerous requests that climate change be addressed in the BCA, to date this has not happened. One important consideration is that the BCA is based on historical weather and climate data and that this needs to be reviewed and updated. The Productivity Commission noted that the BCA deals with new buildings. However, existing buildings pose a greater problem as they are not required to keep abreast of the BCA requirements: issues include the lack of information, costs associated with adaptation measures, and ‘split incentives’ (with rental properties).

The current mechanism of rating building efficiency by annual heating and cooling load does not specifically address the World Health Organization’s (WHO) advice regarding building design and heat waves. This advice suggests that “climate-adapted building and energy-efficient design should be stressed over air conditioning” (WHO 2004, p. 93) partly because of the greenhouse impact of power use and also to guard against energy cuts during heat waves. Many publications about climate change and/or heat waves and health include general comments about using passive design for cooling (WHO 2004; Snow & Prasad 2011).

There have been suggestions in the past that the current National House Energy Rating Scheme (NatHERS) should be supplemented by a measure of a dwelling’s performance during days of peak electricity demand (generally days of extreme heat). Different approaches have been investigated. Woolcock, Joy and Williamson (2007) compared the NatHERS ratings and performance on a peak load day for 12 dwelling types built of various construction materials and with varied orientations. They found a relatively strong and significant linear relationship between the peak load and star rating of the cases; however, for a given star rating, there was a ±30% variation in peak load values. Hence, the thermal performance of houses with a given star rating does not directly relate to performance under peak load conditions caused by heat waves. Saman and Halawa (2009) investigated a different approach based on heating and cooling appliances. Neither study progressed beyond the initial research.

Porritt et al. (2012) examined the effectiveness of interventions in dwelling adaptation in the UK context focusing on terrace houses. The study demonstrated that building regulations addressing dwelling construction are inadequate in isolation, with the types of occupants and their corresponding occupancy profiles being equally as important. “Occupancy type was found to have a very significant impact on overheating exposure. This is particularly pronounced for living rooms, where overheating exposure is often three times higher for elderly occupancy than for family occupancy. This is because elderly residents occupy the dwellings during the hottest parts of the day and are often subject to disproportionately higher overheating for the extra hours of occupancy.”

The elderly are one of the groups most vulnerable to the effects of heat waves. The majority of older Australians live in private dwellings and it is anticipated that this will continue to be the case in the future. Recent government policy aims to support older people staying in their own homes (Department of Health and Ageing 2012). Harvison, Newman and Judd (2011) maintained that the combination of an ageing population and the impact of aspects of climate change, such as increasing heat waves, introduce particular concerns in relation to the built environment.

In discussing the modification of existing dwellings, Porrit et al. (2012) recommended a series of building construction alterations but noted that “implementation of some of the interventions may not be possible due to external factors, such as local planning constraints and visual impact (changes to the external appearance), obstruction (overhangs) or noise, security and/or air quality (night ventilation).” Such examples highlight the need for planning policy to work in conjunction with standards and codes (BRANZ 2007; PC 2012a).

Many of the recent planning reviews undertaken by state and territory governments to guide growth in the coming decades referred to climate change mitigation and adaptation measures and encouraged densification around activity and transport centres (see, for example, City of Sydney n.d.; Dept of Sustainability and Environment 2005; Dept of Planning and Local Government 2010). Many of these documents referred to passive design strategies related to cooling: ventilation, shading, insulation and thermal mass, but seldom sought performance levels above the minimum requirements of the BCA.

In response to the National Climate Change Adaptation Framework and the heat waves of 2008/09, many states, territories and local councils have developed heat wave response plans (see, for example, Qld Health 2004; SA SES 2010; Dept of Health 2011). These plans include strategies for issuing warnings and alerts about forthcoming heat waves, provision of information about what to do in a heat wave and mobilisation plans for various government agencies. In some cases they also refer to building design issues. For example, the Department of Human Services (2009) recommended that heat wave plans include advice about reducing exposure to heat both indoors and outdoors with recommendations such as:

- Identify and promote safe, public places during heat waves that are air conditioned, such as libraries or movie theatres.
- Establish cooling centres in air-conditioned council buildings, or use mobile air conditioning units.
- Promote the use of external shading and blinds to delay internal temperature rise.
- Designate parking in shaded areas for the elderly and people with a disability.
- Provide shade and shaded seating in public areas during heat waves.
- Plant trees for shade in public open spaces. (Department of Human Services 2009, p. 37)

In South Australia, the State Emergency Service (SES) has worked with key South Australian Government departments to develop the 'State Extreme Heat Plan'. The main purpose of this plan is to deliver accurate and timely information and advice to local residents. The following points are stated in the 'Extreme Heat Guide for Local Government':

- "The primary role of Local Government should be to promote community awareness and education about the dangers of heat stress and the measures that can be adopted to mitigate the effect. This includes reinforcement of the health messages promoted by appropriate Government agencies such as the SA SES and the Department of Health.
- The SA SES in the State Extreme Heat Plan does not recommend the establishment of specific "cooling centres" by State, Local Government or community groups. However the extension of operating or opening hours of existing facilities and services is encouraged. If Councils choose this option they should clearly indicate that it is the extension of an existing service and not create a community perception that additional services are being offered.
- Councils may choose to make community facilities such as community centres, libraries, theatres, halls, swimming centres and sports stadiums available during extreme heat events but in doing so should recognise that there may be significant cost and risk issues involved."

The New South Wales Ministry of Health's advice about how to cope with a heat wave includes suggestions about ventilation, shading and insulation:

- Check that your home can be properly ventilated without compromising security.
- If possible, have curtains with pale linings in rooms that get a lot of sunlight to help reflect the heat. Avoid dark reflective curtain linings and metal Venetian blinds as they absorb heat and may make rooms hotter.
- Consider putting external blinds, shutters or some other shading on windows in rooms which face west.
- Insulate your house – not only will this keep it cool in summer, but it will also keep it warm in winter.
- Create a cool room or cool area to go to during extreme heat. This room or area ideally should be east or south facing in the house and can be cooled using indoor and outdoor shading, ventilation and the use of a fan or air conditioning (NSW Ministry of Health n.d.).

Much of the current information and existing and proposed policy can be characterised in one of two ways: either it is building-focused and concentrates on energy use with little mention of the occupants' comfort or health or it is people-focused and the references to dwellings and building design are in the form of broad generalisations of passive design principles.

4.2.3 Typical Design Adaptation to Reduce Overheating/Minimise Cooling

While not as extensive as the literature for temperate and cold climates, there is considerable international literature about designing for hot climates (see, for example, work by Fathy et al. [1986] and Oliver [2003] about vernacular architecture and Koenigsberger [1974] and Konya [1980] for early scientific approaches to design for hot climates).

In Australia, Drysdale (1975) and the Experimental Building Station produced a range of work about design for various Australian climates. More recently 'Your Home Technical Manual' (Commonwealth of Australia 2010a) and writers such as Hyde (2008) have produced material aimed at a broad market including architects, builders, developers and occupants. Common recommendations from such sources include:

- effective shading to reduce direct and indirect solar gains and reduce building surface temperatures
- effective utilisation of thermal mass to reduce diurnal variation
- insulation to reduce heat gains through building materials via conduction, including glazing
- promotion of natural ventilation to introduce fresh air and remove heat from the building interior
- appropriate spatial planning, with particular reference to orientation.

Each of these common recommendations is briefly discussed below to place them within a historical context and highlight the challenges.

Shading

The sun in Australia can be fierce: providing shade from heat and from glare was an important concern in colonial Australia with the early protection for windows in the form of blinds and screens originally constructed from paper or cloth (Lewis n.d.).

Shading is often integrated into the form of the building, for example, with eaves, overhangs and verandahs. There are records of verandahs on dwellings in Australia as early as 1802 with some debate about the inspiration for this design coming from South Africa, India or North America (King 1986). These early examples are claimed to be “a practical response to the climate and a reflection of a colonial stereotype” (Lewis n.d.).

The traditional verandah, whether located in Australia, India or elsewhere, provides shade to exterior walls and windows at the same time as creating shaded external spaces for household activities at various times of the day. The potential to enclose verandah spaces with various vertical membranes (blinds, woven mats, wetted screens, etc.) enables further conditioning of exterior and interior space (King 1986). American and Australian ‘bungalow’ houses of the 19th and 20th centuries often included screened sleeping porches accessible from an interior corridor as well as directly from bedrooms (Comstock & Schermerhorn 1990).

Excessive use of verandahs without regard to orientation can lead to lack of access to direct sun when it is required in winter and hence they should be employed selectively. With recent trends towards the reduced size of dwellings and lots, the inclusion of the ‘occupied’ verandah which formed part of the habitable space of a dwelling, typically facing the street, has significantly diminished. In many locations, eaves are also becoming less common due to both spatial opportunity and aesthetic preference. This results in large expanses of walls being directly exposed to the direct sun, increasing the chance of overheating both the building interior and adjacent external space. Windows located in such walls are often shaded by opaque devices which provide both shade and security, but which also compromise natural ventilation and day lighting, leading to increased energy requirements for lighting and cooling.

Thermal mass

Massive construction using stone or earth walls, and heavyweight floors and sometimes roofs was a traditional strategy for dealing with heat particularly in regions that had a large diurnal range. In the Lake Eyre basin, early explorers reported that Aboriginal people built mud-covered dome structures. Charles Sturt wrote that this meant that the “hut was impervious to wind or heat” (quoted in Memmot 2007).

Some of the earliest European settlements in regional Australia were associated with mining – often in locations with inhospitable climates. No time or money was ‘wasted’ on accommodation that was likely to be temporary and people often lived in tents. However, in many regions, dwellings were excavated into hillsides or creek beds or created underground to escape the desert heat (Bell 1998, p. 30). Lewis reported that “in miners' houses built at Broken Hill from the 1890s, it was common to include a stone-walled sleepout below floor level for the use of miners working night shifts” (Lewis n.d.). Dugouts still exist in old mining towns such as Coober Pedy, Andamooka and White Cliffs.

Whilst a significant majority of Australian dwellings are currently constructed using slab-on-ground flooring, design solutions for future Australian housing which increasingly use the benefits of earth-coupled construction may offer an economical means of providing thermal comfort during heat waves. Numerous construction techniques and spatial relationships are possible, as demonstrated by a variety of global examples. The courtyard or atrium houses of Islamic cities (Warren & Fethi 1982), the terraced dwellings of Afghanistan (Samizay 2003), the shaft dwellings of

Tunisia (Mamtaz 1969; Oliver 1997) and the pit houses of Shanxi Province in north-eastern China (Knapp 1989) each utilise differing connections between interior and exterior spaces together with variable relationships to the natural ground plane.

As higher thermal mass delays and reduces the impact of external temperature fluctuations, it has a positive impact on comfort during both heating and cooling seasons. However, the stored heat during a prolonged heat wave will take longer to overcome. The combination of massive and lightweight construction is recommended in various Australian locations (Drysdale 1975; Commonwealth of Australia 2010a; etc.) with design solutions typically demonstrated for low-density suburbs. Historical construction techniques employed in Turkey provide a useful precedent for translating these practices to medium-density environment. These techniques incorporate thermally massive ground floor construction with lightweight timber upper stories (Ertug 1980).

Insulation

Lightweight construction can be very responsive to changes in the temperature and adaptable for ventilation and shading. For framed construction, the appropriate use of thermal insulation to reduce heat transfer is important. There are examples of 19th century houses in Australia using natural materials such as seagrass, sawdust or straw for insulation (Lewis n.d.). However, these are relatively isolated examples and the use of insulation in domestic buildings has only become widespread in the past 20 years.

The BCA sets minimum standards for insulation requirements in all climate zones. It assumes the employment of mechanical cooling systems and aims to reduce the load placed on these systems. However, little guidance exists in relation to ‘best practice’ insulation levels and its effective implementation in non-conditioned spaces. Modelling has shown that, in the context of overheating, increasing the insulation will have a progressively reduced impact on the cooling load.

The current trend towards higher performance glazing with higher insulation properties also provides challenges as any passive design solution is a fine balance between preventing heat gain in summer and promoting solar gains in winter. In relation to direct solar gains, well-designed shading provides good potential for reducing solar gains in summer and maximising them in winter.

The BCA has increased the insulation performance of new Australian dwellings by setting minimum requirements; however, challenges still remain for designers and homeowners in gaining access to information regarding ideal insulation levels and how these relate to different seasons. Correct installation practice also requires further effort to maximise the benefits of insulation.

Ventilation

All occupied spaces require a degree of ventilation to maintain indoor air quality. Following short periods of high temperatures, it is desirable to ventilate the building interior with cooler outdoor air. However, during heat wave conditions, the requirement to introduce fresh air brings with it unwanted heat gains. It is therefore necessary to ensure that the air that is introduced is as cool as possible and to this end active mechanical conditioning is typically employed.

At times when cooler external air is available, homes located in increasingly dense urban environments often have little or no access to prevailing breezes and heat wave periods frequently coincide with periods of little or no external air movement. Ventilation can be encouraged through natural buoyancy, a technique employed in many hot and arid regions around the globe. Effective ventilation via natural buoyancy relies on a significant temperature differential between the floor level and the top of the space

(Kwok & Grondzik 2007). The relatively low, flat ceilings of typical modern Australian houses effectively reduce the volume of air to be heated in winter conditions, but also reduce the opportunity for natural ventilation via buoyancy. Again, a compromise between seasons is required.

Spatial planning

The following planning techniques can be employed in both the design of new residences and the redesign or adaptation of existing dwellings:

- Enable thermal separation of spaces generating high internal heat loads (latent and sensible) from the living and sleeping spaces used during heat wave conditions. This includes the separation of living and kitchen spaces which are typically combined in open plan living.
- Locate living and sleeping spaces used during heat wave periods in the coolest possible position in the building, away from areas of high solar gain and with maximum earth coupling/mass.
- Utilise unconditioned internal zones such as wet areas and storage areas as thermal buffers between exterior loads and living and sleeping spaces used during heat wave periods.

4.2.4 Advancing Design Adaptation to Reduce Overheating/Minimise Cooling

Whilst the common recommendations discussed above provide an initial approach to reducing heat gains and subsequent cooling loads in periods of hot weather and heat wave conditions, their effectiveness is arguably limited by the relatively conservative nature of the housing and construction industry in Australia. These recommendations are applied to existing housing solutions in a manner which can be described as ‘ecotechnic logic’, an approach to sustainability which “places its optimism and faith in the potential and possibilities of technological development as a panacea for our environmental ills” (Guy & Farmer 1997, p. 142). Current policies and design adaptations focus on material technology and improved performance without questioning the base building design and its suitability to location or comfort needs. In the mass housing market, adaptation through the introduction of alternative spatial or construction solutions is seldom evident as the industry experiences many barriers to change.

Gul and Menzies (2012) claimed that conventional domestic building design approaches inadequately address the future overheating risk derived from climate change. They asserted that “[a] dwelling design should take account of both passive and active measures to reduce the risk of overheating, and the ability of additional measures to be adapted in the future”.

The ability for future adaptation is limited by the current mechanisms for assessing the thermal performance of Australian dwellings that remain focused on the reduction of mechanical heating and cooling loads required to maintain a set comfort temperature range in all occupied zones (as per NatHERS). The following section provides a brief overview of alternative design adaptations which offer the opportunity to progress beyond the technological and remedial. In many cases, these are not effectively recognised through current performance assessment tools and are not typical within the Australian construction industry.

Shading

One design adaptation is shading walls in denser urban environments. Whilst broad, return verandahs are most appropriate for free-standing, isolated homes on spacious allotments, ventilated shaded external wall systems can effectively reduce solar gains through walls for dwellings on tight allotments. The ventilated wall consists of an external layer that is fixed to create an air gap between this layer and the inner, insulated layer. The external layer shades the internal layer from sun penetration. In recent years, a number of research projects have investigated ventilated walls often with the aim of developing algorithms to describe the optimal sizes of the masonry outer layer of a south-facing wall. In the northern hemisphere, it was found that the higher the channel, the greater the air velocity and cooling effect (Stazi et al. 2010). Adelaide architect John Maitland has incorporated a ventilated wall in the western façade of his Ada Street residence (Maitland 2008). This consists of a steel-skinned external layer with a layer of reflective foil fixed over the outside of the insulated leaf, which reduces radiation gains.

Roofs experience high levels of insolation (the measure of solar radiation energy received on a given surface area). The shading of roof surfaces can be costly and challenging and consequently is seldom considered for Australian buildings. Nonetheless, there are a number of examples that suggest viable methods for shading roofs. Architect Peter McIntyre’s 1954 design for the Beulah Hospital, Victoria included louvered screens to permanently shade both the walls and roof. Light baffles are supported above the main roof which drains into an internal water storage tank that acts as internal thermal mass (Saini 1963). Robin Boyd’s McClune House (1969) incorporates a parasol roof and a number of contemporary architects such as Troppo and Iredale Pederson Hook have constructed such shaded roofs in hot regions in the past decades.

Another option is to shade walls and roofs with greenery – either through landscaping or greenery growing on the wall. In Japan, there has been a program to encourage the use of ‘green curtains’ as a way of reducing air conditioner use given the electricity shortages in summer. Simple construction techniques also exist to enable creepers to be grown above low pitched roofs as a secondary shading layer: the plants are grown on simple cable systems and careful plant selection ensures material damage is avoided. A number of green walls and green roofs have been employed in many buildings in Australia and elsewhere in the past decade.

While material options are available to improve the shading of external walls and roofs, each square metre of additional shading has cost implications in its construction and limitations to its thermal potential. Prior to employing such techniques, it is appropriate to consider how to reduce the need for shading through building design. Two-storey dwellings incur half the heat gain through the roof compared with the equivalent sized single-storey dwelling and dwellings which share party walls with neighbours reduce solar and heat conduction gains. Traditional densely constructed urban environments have exploited the positive effects of self-shading for centuries. Many courtyard houses with internalised planning effectively restrict solar exposure to the roof only with all external walls and windows oriented into external courtyards (Talib 1894; Elawa 1981; Varanda 1982; Rabbat 2010). In discussing the urban form generated by multi-storey courtyard houses in Saudi Arabia, Talib (1984) highlighted the benefits of houses clustering not only to collectively achieve thermal comfort internally by limiting solar and thermal exposure to the roof only, but also so the buildings could effectively shade streets (narrower streets with low traffic volume) and public spaces defined by the building form.

Thermal mass

The thermal mass in current Australian dwellings is typically located in floors and walls. However, most wall mass is insulated from the building interior and is ineffective in regulating diurnal temperatures. One example of thermally massive spaces employed in high temperatures is the basement which exploits increased earth coupling. Basements have been traditionally used as heat wave shelters in many hot regions.

South Australia has a number of larger residences built in the 19th century that incorporate basements or sub-grade rooms that appeared to have been designed specifically for use during hot weather as evidenced by their names: the 'summer drawing rooms' of Parkin House (West Torrens Historical Society n.d.), and the 'summer room' of Ayers House (Williams 2005). This tradition of dwellings with basements for hot weather use was not confined to Adelaide. Miles (Lewis n.d.) listed a number of 19th century examples in the more temperate climates of Melbourne and Ballarat as well as in hotter areas such as Hay, south-western Queensland and Mildura (where irrigation pioneer W. B. Chaffey had an underground ballroom).

The early Australian examples of urban basement spaces typically represent the construction of spaces which were additional to the typical dwelling requirements and were most commonly seen in residences of the upper classes. Many historical examples of medium-density urban dwellings in locations such as Afghanistan, Iraq, Saudi Arabia and India, to name a few, utilise below-grade and sub-grade 'summer rooms' which form an integral part of the day-to-day dwelling (Alp 1990-91; Soflaee & Shokouhian 2005; Kharrufa 2008; Almusaed 2011).

Insulation

The insulation approach used in current Australian dwellings typically provides a comprehensive 'wrapping' of the entire building to minimise heat transfer, with occasional use of internal wall or floor insulation for zoning or sound insulation. An alternative approach would be to insulate thermal zones within a dwelling based on use and need.

While the use of high levels of insulation is common in the design of cool rooms for food preservation and industrial applications, little use has been made of the 'cool room' concept for thermal comfort. The Filter House designed by Sustainable Built Environments, a Melbourne-based architectural practice, for the 2003 Sustainable House Design Competition held by the Western Australian Department of Housing and Works demonstrates the effective deployment of a 'cool room' approach. Constructed in Broome, the Filter House employs two 'cool cells' for the living and sleeping zones which are well sealed and heavily insulated. These are the only zones of the building to be actively cooled: monitoring of the Filter House against a control house for a period of two years has shown that it consumes only 27% of the cooling energy used by the control house when temperatures were less than 30°C and only 48% of the energy used by the control house when it was over 30°C (Government of Western Australia n.d.). The cool cells are lightweight and are shown to be more responsive to diurnal changes than the concrete-floored control house. While higher temperatures can be experienced during the day, the Filter House is typically cooler at night than the control house. The shading of exterior living spaces also increases the potential for external living, reducing the need for conditioning of the internal spaces (Jensen & Taylor 2006).

Ventilation

Ceiling height can play a key role in extending comfort conditions in spaces occupied during heat waves. The relatively low, flat ceilings of typical modern Australian houses reduce the volume of air that needs to be heated in winter conditions, but also result in a heat build-up at ceiling level in warmer weather which quickly affects occupants' comfort. Early Australian houses typically employed higher ceilings where possible. Higher ceilings and inclined ceilings with an opportunity for heat escape at the highest point promote air movement and maintain comfort conditions in the occupied levels for longer periods. Each of these features can be seen in hot arid zone designs throughout the world (Saini 1963; Elawa 1981; Fathy 1986). House types designed for hot climates, such as the Indian bungalow and the Middle Eastern courtyard houses have high volume spaces that allow hot air to rise above the occupied zone and promote ventilation via natural buoyancy (Warren & Fethi 1982, King 1986).

Writing about Denham Court, constructed in New South Wales in 1835, Roxburgh (1974) noted that "the early settlers were more troubled by the heat than the cold and the fine stone-flagged hall was probably designed as a hot-weather sitting room." In January 1850, Christina Bloomfield wrote to her son John that the young people had gone for a picnic. "They said they enjoyed themselves. I know we were hot enough sitting at home in our nice cool hall" (Roxburgh 1974, p. 78). The hall, a large mass-lined space with all but one wall internalised, was utilised as a summer room. The coolness of the room was enhanced by its connection to the volume of the upper levels of the house via the open stairwell which enabled heat to rise via buoyancy.

A similar approach is employed in the 'sofa' room of traditional Turkish houses (Ertug 1980). The sofa room is located in the centre of the ground floor of the 2- or 3-storey home with typically only one short wall exposed directly to the exterior. It provides the social nexus of the home whilst also acting as the primary circulation hub connecting all floors. It is able to be thermally zoned from all other spaces and often borrows light, views and ventilation from adjacent closable porches, which themselves act as thermal buffer zones and shading devices for the central space.

As air movement is an effective means of improving summer thermal comfort, traditional designs have often attempted to make use of cool breezes to improve summer comfort. Homes located in urban environments often have little or no access to prevailing breezes. Windcatchers (known as *badgirs* in Iran, *malkafs* in Egypt and by various other names throughout the Middle East) offer an option for taking advantage of available breezes throughout all levels of a home. Heat wave periods frequently coincide with periods of little or no external air movement, occasionally requiring mechanical means to either supply or extract air. The combination of passive and active techniques in this manner reduces the reliance on purely active mechanical conditioning, increasing the range of conditions over which the dwelling can passively achieve comfort and reducing the negative impacts of system failure.

The natural cycles of the sun can also be employed to drive ventilation. One example of this is seen in traditional atrium designs which encourage the brief entry of midday sun to the internal paved courtyard to instigate a column of air to rise above the paved surface, drawing air through the adjacent spaces for the remainder of the afternoon. As the paving cools at night, the cooler air sinks into the volume of the courtyard, creating an oasis of denser air until the sun arrives again the following midday. This system does rely on the night conditions cooling sufficiently to cool the paving. Taller courtyards of above three storeys do not encourage solar entry and promote air movement through occupied spaces via a stack effect (Talib 1984).

Timber lattice screens are used in housing throughout the Middle East and Asia to minimise solar gain and glare whilst maintaining privacy and allowing for air movement and filtered light entry (Elawa 1981; Varanda 1982; Pramar & Patel 1989; Oliver 2003; Sobti 2003).

Evaporative cooling of the incoming air is another effective tool in reducing the summer temperature in dry climates. Many regions of Australia, with the exception of the tropics where high humidity levels are experienced, have the opportunity to take advantage of passive evaporative cooling techniques during heat wave periods. Lewis (n.d.) gives examples of early 'cool rooms' that were based on the Coolgardie safe principle. These had fabric walls, or sections of walls, that were sprayed with water to evaporatively cool the contents. Similar principles were used in many public and private buildings with wetted curtains or screens cooling the interior.

In the Middle East, there are examples of cooled air supplied via underground tunnels, sometimes passing over an underground water supply (Alp 1990-91). In a 1962 speculative design for Australian arid regions, architect V. Trompf proposed the use of floor-level vents to introduce air into the living zone from adjacent, cooler sub-floor zones (Saini 1963). The introduction of air at floor level ensures that the supply air passes over the occupants and building mass as it heats and rises through the space via natural buoyancy effects. Similarly, cooling tubes for air supply have been shown to be effective in contemporary homes, although incurring greater costs.

Passive evaporative techniques are seen in various international housing examples in combination with ventilation systems. Earthenware pots containing water are placed in specially designed window boxes (known as *meshrabeyh*) in Egyptian homes (Elawa 1981). Like the system employed in the South Australian Parliament House, this approach aims to pass a cool air stream over the occupant rather than to cool the entire air volume of the occupied space. Similarly, pools of water, water pots or fountains are also utilised in combination with windcatchers and water trickled over blinds or screens of straw in arid courtyard housing, pre-cooling the entering air. Fountains are also used to provide both physiological and psychological cooling effects.

Spatial planning

Interior/exterior spatial relationships are understood as an important component of the Australian lifestyle. Improving thermal conditions in external spaces reduces the time spent indoors and hence the duration of active thermal conditioning, as noted in the analysis of the Filter House, Broome. Design examples such as the traditional houses of Zhejang, China which have a deep, shaded terrace for household activities under the main house roof provide moderated external conditions throughout the year, not just in summer periods (Knapp 1989).

Lightweight Indian bungalows of the 17th to 19th centuries employed a careful balance of materials across both interior and exterior spaces, with these predominantly lightweight buildings constructed on earth and brick plinths that extended to form the flooring surface of external verandahs (King 1986). Together with the paved courtyards of typical Middle Eastern houses, this precedent offers an example of the use of thermal mass in occupied external spaces and its relationship to achieving comfort conditions both in interior and exterior zones that can be applied to Australian environments and lifestyles.

As the Australian housing market experiences a transition to higher densities, it is well positioned to redefine the relationship between interior and exterior spaces, particularly in regard to the urban realm. Discussing the contrast between Indian urban dwellings and colonial bungalows, King (1984) noted that the bungalow, "being of only one storey, and with an extensive thatch covering the whole, the dwelling depended on the space around for ventilation and light. In fact, the compound was simply an extension of the bungalow's internal space, an outdoor room, fulfilling a variety of social, political, cultural and psychological needs" (King 1976). This layout, comparable to Australian suburban housing, requires spatial distance between housing units, a spatial quality which King suggested also contributes to a social distance. In comparison, the urban housing forms contained "a central courtyard [which] allowed the penetration of light and air; as the houses were three to four storeys high and there were closely clustered, cellular structured buildings all around, the lower rooms were dark and cool. Activity in the courtyard house was centripetal: movement was inwards, towards the courtyard." (King 1984)

The spatial planning intention which was stated previously to 'locate living and sleeping spaces used during heat wave periods in the coolest possible position in the building, away from areas of high solar gain and with maximum earth coupling/mass' is often limited by urban planning policies and the requirement for on-site car parking. In many townhouse or mews-type developments, almost 100% of the urban ground plane is dedicated to vehicular movement and the ground floor of dwellings, the coolest space in the home, is required by planning policy to house the car. As future urban environments move away from reliance upon private transport, the positive cooling and other social benefits of alternative housing typologies should be considered, particularly as they relate to the provision of climatically appropriate external spaces for community use, such as public squares and play areas. Other traditional pedestrian urban plans, such as those formed by shaft houses in Tunisia, Lobi villages in Ghana and pit houses in China, provide precedents as to what benefits may be obtained by the separation of the urban circulation plane from the occupied dwelling plan, which is not currently possible in a car-dominated city (Mumtaz 1969; Golany 1988; Samizay 2003; Sobti 2003).

4.2.5 Behavioural Adaptation to Heat Waves

In many cases, design for heat waves may be different from designing for climates that are generally hot – the period of discomfort may be brief but intense. Design solutions that focus on adaptation may involve not just changes to the building stock but also to the way in which we occupy spaces and to design practices and cultural attitudes. For instance, Yu et al. (2012) argued that prolonged exposure to static air-conditioned environments may weaken residents' physiological thermal adaptability and natural ability to deal with heat waves, apart from increasing the energy consumption.

Traditional adaptation to the climate by the Aboriginal population in the hot regions of northern Australia would have involved a range of strategies including avoiding activity during the hottest/wettest times of the day, seeking out comfortable locations (e.g. for shade, wind protection, access to water) as well as building shelter appropriate to the season. Unlike the European concept of two seasons in this region – the wet and the dry – Aboriginal people recognise many more seasons based on nuances of the weather and changes to the flora and fauna (BOM 2010; FRATA 2011). Anthropologist Donald Thomson, working in the 1920s to 1930s in northern Australia, documented a variety of shelters built by Aboriginal people for the different seasons (Memmot 2007). These included windbreaks built during the windy period of the dry season to protect against wind-blown dust; sleeping platforms for use during the end of the wet season when water on the ground harboured mosquitoes; sitting platforms to catch breezes and keep people off the hot ground during hot, dry times; and waterproof, dome-like structures that were built for protection during the wet season.

The shelters were small and fairly quickly built by their occupants from readily available local materials. They were occupied seasonally, lived out of and around as much as in, and moved on from regularly, although sometimes returned to and renovated with later seasonal movements (Sanders 2000). This approach to 'thermal adaptation' called on a wide range of strategies appropriate to a mobile lifestyle and an intimate knowledge of place, materials and climate and is far removed from contemporary, static, technology-driven notions of thermal comfort.

The following section reviews adaptive strategies from other cultures and pre-air conditioning times that can inform the design of dwellings for greater thermal comfort during heat waves. It specifically considers issues to do with the way people inhabit space.

Behavioural adaptation

In recent decades, with the advent and widespread adoption of mechanical heating and cooling, certain assumptions about occupant behaviour have become embedded in residential design theory and practice. Perhaps the most pervasive of these is that the ideal is to provide whole-house heating and cooling. Comfort is frequently described in terms of a relatively narrow band of temperatures and rooms are presumed to have particular and specific functions, being occupied at particular times of the day and night. These assumed comfort expectations and fixed-use patterns have become embedded in many building design guidelines, methodologies, policies and standards, including those applicable to the thermal performance of residential buildings in Australia. Whilst these assumptions provide a platform for the comparison of building performance, they have become entrenched in the design, construction and marketing of new homes and in the specification of mechanical conditioning systems. Hence, such assumptions about occupant behaviour run the risk of limiting occupant choice through inflexible design.

Adaptive comfort theory provides a less static approach to understanding thermal comfort, recognising that thermal perception is not limited to factors measurable through the physical and physiological sciences. de Dear et al. (1997) articulated three categories of adaption: behavioural, physiological and psychological adjustment. Both the physiological and psychological categories highlight the relationship between people’s perception of a comfortable temperature and their past experience, acclimatisation and heritage (genetic and cultural). The occupants of buildings with a constant internal environment “detached from the diurnal, synoptic and seasonal drifts outdoors” (Jendritzky & de Dear 2009, p. 27) tend to have a fixed and narrow comfort range. Occupants in buildings that are not air conditioned are reported to be comfortable across a greater range of temperatures (de Dear & Brager 2002; de Dear 2007; van Hoof et al. 2010) with their responses being more closely linked to the external temperature. This work has been expanded for residential homes as detailed in Chapter 3, showing potentially greater levels of adaptation than have been previously found.

Chappells and Shove maintained that the notion that movement between contrasting conditions is an important part of being and of making oneself comfortable might justify lower energy solutions that maximise adaptive opportunities (Chappells & Shove 2005, p. 38).

Adaption includes modifications that occupants engage with to achieve comfort, be it through conscious or unconscious actions. In the case of residential buildings, occupants have a wide range of behavioural adjustment strategies at their disposal from changing location or clothing to opening and closing windows and blinds, etc. Whilst building occupants may express a willingness to adapt behaviour to achieve comfort, or to adapt the building to the same ends, the potential for them to undertake effective actions is influenced by social and cultural contexts as well as by their individual knowledge and the design of the building that they occupy.

In concluding a discussion of comfort and culture, Oliver (2006) commented that “[d]emands that we place upon the building in the interests of our concepts of comfort are heavily conditioned by the nature of our culture. Were this to change and to adapt to the climate, many of the difficulties would disappear. But this is unlikely for, as we have seen, the tenacity of our cultural inheritance is such that we will continue to strive for an impossible resolution. Design in the hot, humid zones requires of the architect an understanding not only of the practicalities of climate modification, but of the far more subtle, intangible, but fundamental cultural imperatives that direct the pursuit of comfort. In the final analysis, the problem is not the question of ‘comfort conditions’ but one of *comfort conditioning.”*

One result of the widespread use of air conditioning is that many ways of ‘dealing with’ hot weather are being lost. In previous times (and other cultures), there were many adaptive behaviour patterns for coping with heat. These ranged from changing clothes, reducing activity and drinking more water to ‘manipulating’ the building, by changing floor coverings and opening or closing screens and blinds. In Australia, before the widespread use of domestic air conditioning, people would ‘shut down the house’ – closing doors and shutting blinds and curtains to exclude the sun. At the first hint of a change or cooling breeze, the windows would be opened.

One strategy for dealing with heat is to move – either within a building, from the building to more pleasant outdoor areas or to another location. In many parts of the colonial world, summers were spent in the cooler mountainous regions. This tradition was employed in Australia with richer families constructing summer residences in the hills outside the capital cities. For those who could not afford this, relief was sought by sleeping outside, in local parks or on beaches.

Numerous cultures in climates that experience seasonal extremes occupy space in a seasonally appropriate manner. People move between rooms over the year and, when necessary, relocate bedding to the coolest room of the house (Al-Azzawi 1969; Elawa 1981; Warren & Fethi 1982; Sobti 2003; Oliver 2006). Daily movement through the house is also important in summer months, with morning activities undertaken in cool, ground-level spaces, siestas taken in basement rooms ventilated by evaporative windcatchers and, for night-time sleeping, moving to the roof when temperatures permit (Al-Azzawi 1969). Many traditional buildings also include outdoor spaces of different orientations and shading appropriate to different seasons, each directly linked with the seasonally appropriate living spaces (Elawa 1981; Warren & Fethi 1982).

Such movement through the house discourages elaborate equipment of rooms for special functions and encourages the use of minimal, movable furnishings. For example, in Turkey and Pakistan, lightweight movable beds are shifted easily between interior and exterior spaces. Walls have niches to display household objects and artifacts, and elaborate inbuilt cupboards for storing objects. The design of the space minimises the need for additional furniture and allows a living space to be easily transformed into a dining or sleeping space as required whilst also providing rich interior ornamentation (Ertug 1980; Stead 1980).

Built-in furniture such as sofas or day beds, known as *sedirs* in Turkish sofa rooms, allows spaces to easily perform dual functions and promotes positive cooling relationships between the occupant and the building not possible with free-standing furniture. “… [B]uilt along the walls which have window openings, the ‘*sedirs*’ are 50-60 cm in depth and 40 cm height in dimensions. When one sits on it, and leans on the supporter of the pillow the lowest edge of the window is on the same level with the arm support” (Ertug 1980) providing the sitting or sleeping occupant with direct exposure to cooling air. Similar to summer rooms in other cultures, the sofa room and *sedirs* are frequently employed during the hottest part of the day for siestas as the daily routine is modified seasonally.

Whilst the *sedir* requires external air movement to be effective, the same results are achieved by the use of appropriately positioned fans or moving furniture, such as the southern American porch swing or the charpoy-like swing of Pakistan, which require minimal energy to be expended by the occupant to induce airflow and subsequent cooling.

The examples above highlight the benefits of seasonal scheduling, such as the summer siesta, as well as the potential for conditioning the occupant directly in contrast to conditioning an entire air space. The Japanese culture is one which has historically exploited the effectiveness of comforting people in preference to buildings. Japanese housing has traditionally placed priority on achieving comfort in the summer seasons with lightweight, flexible constructions which, unable to effectively retain heat in winter, have led to traditions of occupation and comfort which vary throughout the seasons. While houses are opened to the outdoors in summer providing comfort throughout via ventilation in the hot humid conditions, a more localised ideal of personal comfort is achieved in the winter. *Kairo*, small metal vessels containing embers, are often worn between layers of clothing as personal heaters and *kotatsu*, under-table foot warmers, are employed when occupants gather, providing a collective comfort which promotes communal activity and co-location of occupants (Morse 1972). In contrast to extensive year round conditioning of occupied spaces, this seasonal prioritisation of comfort leads to contrasting thermal experiences which inevitably influence behaviours and social interaction within the household on an annual cycle.

Where basements are employed as summer rooms, adaptation of spatial expectations is required as occupants gather for comfort and inhabit reduced space. Whilst the desire for thermal comfort drives relocation, psychological comfort is critical, requiring an adaptation of activity patterns. Over time, Australian residential spaces have become increasingly specialised and individualised, spreading domestic activities throughout the home and arguably leading to the excessive inflation of dwelling size that is being currently experienced – which in itself is concerning in relation to energy costs. Historically, such specialisation of space has been less desirable, with activities congregating around the point of shared thermal comfort, the hearth. In his book ‘Village in the Vaucluse’ (1974), Lawrence Wylie discussed the transition of his American family, accustomed to constant central heating, to a French rural villa. He noted that, in the first instance, the family attempted to spread their activities throughout the various rooms of the villa as had been the case in their previous residence, but in a short time they found themselves congregating in a single heated living space. “I had to learn to work where the children were playing. The children had to learn to play more quietly. I had to learn to pick up my paper from the table so that it might be used as a dining-room table ... without realising it, we had adapted ourselves to a necessary condition of life ... where families learn to live together in one room” (Wylie 1974).

While the two preceding examples demonstrate solutions to heating rather than cooling needs, they highlight opportunities for social and cultural variation to existing comfort expectations which are applicable to climatic extremes, be they heating or cooling related.

Oliver suggested that “[W]esterners seeking comfort surround themselves with objects, facilities and gadgets that simplify the process of daily living in an otherwise strange environment. Comfort, in these circumstances, is cushioning against physical reality” (Oliver 2006). This Western focus on objects as commodities and symbols of social status restricts the flexibility of spaces within the home and leads to rooms taking on specific functions. Whilst Australian dwelling spaces are made specific through building planning and intensive furnishing, the thermal qualities of spaces are typically generic, with sleeping, living and dining rooms employing consistent materials, constructions and ceiling heights. Occupants therefore have access to an extremely limited set of thermal options, discouraging adaptive behaviours and promoting mechanical conditioning. This situation gradually leads to a loss of adaptive knowledge in the community and increased reliance on active energy-consuming technology.

In a detailed study of the thermal properties of vernacular housing, Wilkins (2007) observed the evolution of 'silent technologies' of thermal choice and thermal control. Discussing "the range of thermal states and microclimates that a building is capable of providing to its occupants", the study demonstrated that early vernacular buildings which provided their occupants with minimal thermal choice fell out of use. In contrast, thermally-complex buildings offered their occupants greater thermal choice and thermal control and have persisted through time, evolving into highly-complex climatically appropriate dwellings. "The later vernacular buildings of Egypt and Pakistan ... were highly complex, with more rooms, more levels, more transitional space, more courtyards, and more variation in room size and shape ... they possessed a wide range of potentially different thermal environments: high thermal choices" (Wilkins 2007). Wilkins demonstrated the capacity of 'silent technologies' to provide more thermal satisfaction through variation.

Australia's typical free-standing family homes located on individual allotments do not provide a high degree of thermal choice. Hence, they require the provision of comfort through mechanical services rather than taking advantage of 'silent technologies'. In the historic examples discussed above, thermal comfort is achieved through a combination of building performance and occupant choices (physical and social), the success of which is dependent upon an occupant's understanding of, and active participation in, the building's operation. This understanding is developed through thermal variation, through experience of discomfort and the availability of thermal choices. Whilst an occupant may express an interest in 'green living', one cannot expect significant alteration to occupant behaviour if building designs do not provide opportunities for choice and learning, promoting positive adaptation.

Dwelling design needs to encourage an increased engagement with adaptive behaviours and to promote building solutions employing 'silent technologies' which enable these to occur. One such solution which will be pursued in further detail in the report is the design of 'cool retreats' to provide increased thermal choice and achieve an appropriate level of comfort during heat wave periods within a portion of the dwelling. The 'cool retreat' draws upon the experiences of 'summer rooms' in both Australian and international precedents. Two distinct 'cool retreat' models are possible; one which draws upon the experiences of sub-ground or basement construction employing mass materials, and the other utilising above-ground space which features thermal control capabilities that are greater than in the remainder of the building.

4.2.6 The 'Cool Retreat' Proposal

Lessons from the past and from other cultures can be utilised when aiming to create acceptable thermal comfort conditions in dwellings during heat waves. A combination of occupant behaviour adjustment (personal, environmental and cultural) and design modifications offers solutions for dealing with extreme weather conditions.

To manage the risks to dwelling occupants during future heat waves, a greater degree of adaption (thermal and behavioural) is required. The concept of a 'cool retreat' is proposed to offer a lower energy solution for maintaining comfort conditions during heat waves for both new and existing housing.

A number of typical Australian housing designs have been modified to examine the effectiveness of the 'cool retreat' proposal. The modified designs provide an increased degree of thermal choice: the choice to create thermal zones as needed, the choice to move between these zones throughout the day and/or year as conditions vary, the choice to alter daily activities in relation to comfort options, and increased choice regarding the need to employ active cooling technologies. The introduction of a 'cool retreat' does not seek to provide comfort for 100% of household activities during extreme conditions, but provides contrasting conditions, encouraging an adaptive understating of comfort and questioning the perceived need for constant conditions.

4.3 *Investigation of Building Design Solutions*

4.3.1 Case Studies

The following section presents five case studies that investigated the performance of different dwelling types during a 4-day period of very hot weather. The impacts of a number of design modifications were modelled; both those suitable for retrofitting to an existing house and those that could be incorporated into a new house design. Internal temperatures and energy use were calculated for the base design, the base design with a number of retrofitted measures and a modified new design.

Base case

The base cases were chosen to represent a range of common housing types for low-to-middle income occupants. They were all 2- or 3-bedroom homes and were smaller than the average house size. The base cases achieved a 6-star energy rating according to the Australian Nationwide House Energy Rating Scheme (NatHERS). This is the current mandated minimum for building approval for a number of states in Australia.

Retrofitted measures

For each case study, building improvements that might be possible for retrofitting to an existing house were modelled. Construction changes appropriate to the particular case study were selected from a range of measures that are likely to improve building performance in hot weather. Table 4.1 lists the characteristics of all the measures used in the modelling. Other changes to the design might have produced better results (e.g. adding thermal mass) but were less likely to be appropriate for existing houses.

The ceiling fans were a special case. Whereas the other measures were intended to affect the thermal performance of the house design, the air movement created by ceiling fans improved the comfort sensation for the occupants rather than affecting the internal temperature of a room. This was particularly important in bedrooms where it has been estimated that increased air movement can mean a 2–3°C increase in the perceived comfort temperature. Thus, the cases in which a ceiling fan was included had a higher comfort temperature in the bedroom.

For the modelling, the retrofitted measures were applied individually to the base case and the resulting internal temperatures of the main living area and bedroom were presented graphically. A combination of possible measures was then applied to represent a ‘best case’ retrofitted package with the resultant temperatures and energy use then presented.

Table 4.1: Retrofitted measures

Improved glazing	Retrofitted double glazing or replacing glazing with low-e (emissivity) glass to give U value = 4.63, SHGC = 0.69
External blinds	External canvas vented blinds to all windows
Increased insulation	Ceiling insulation increased to R6
Foil	Reflective attic space and anti-glare air gap beneath metal sheet (40 mm 0.2/0.9)
Light-coloured roof	External surface = light coloured, solar absorptance = 30%, emissivity = 0.9
Attic vent	Highly ventilated (i.e. "well-ventilated with large openings")
Light-coloured walls	External surface = light coloured, solar absorptance = 30%
Ceiling fans	1200 mm ceiling fans to habitable zones (living room/kitchen and bedrooms)

Note: SHGC = solar heat gain coefficient

Design modifications to new dwellings

The modified designs presented were a re-working of the base case for each dwelling type. The modifications to the designs aimed to improve the performance of the dwelling and to increase thermal comfort and thermal choices for occupants through one or more of the following:

1. Employing materials appropriate to thermal needs whilst remaining within the existing knowledge and practice of typical mass-produced housing models.
2. Making use of the benefits of earth-coupled construction as a means of providing thermal comfort during heat waves. Various relationships to the natural ground plane were examined.
3. Integrating 'cool retreats' for use during heat wave conditions and which are also appropriate for day-to-day use year round.
4. Improving interior/exterior living relationships through the introduction of courtyards or atriums.
5. Thermally separating spaces that generate high internal heat loads (latent and sensible) from living and sleeping spaces used during heat wave conditions. This includes the separation of living and kitchen spaces that are typically combined in open plan living.
6. Locating living and sleeping spaces used during heat wave periods in the coolest possible position in the building, away from areas of high solar gains.
7. Utilising unconditioned internal zones as thermal buffers between exterior loads and living and sleeping spaces used during heat wave periods.
8. The modifications assumed occupants would employ the full range of adaptive strategies such as:
    a. adjusting clothing levels and activity
    b. adjusting window shading
    c. adjusting ventilation – opening and closing windows and external doors as appropriate

d. zoning – closing internal doors when cooling to minimise volume to be conditioned
e. occupying a restricted area during extreme conditions.

Modifications were designed to demonstrate that providing cooling to a restricted area can address thermal comfort and peak load reduction aims. The modifications were chosen to improve conditions in hot weather; however, they were checked to ensure that they did not decrease the overall energy rating.

Rating tool

The temperatures and energy use in the case study houses were modelled using AccuRate software (Delsante 2005). The AccuRate engine forms the basis of software used for rating houses under the Australian Nationwide House Energy Rating Scheme (NatHERS) (DCCEE 2011), has been validated using BESTEST (Delsante 2004) and is widely used for residential building energy research (see, for example, Wang et al. 2010; Morrissey et al. 2011). When used in rating mode, AccuRate has default settings for many inputs including the hours of occupation, internal heat loads , heating and cooling set points and internal window coverings (Tables 4.2 and 4.3). The program calculates annual heating and cooling energy demand for the building design in the designated climate zone and an area-correction factor is applied to convert the total heating and cooling energy demand to a star rating.

When run in non-rating mode, AccuRate can be used to calculate temperatures in a free-running house (i.e. one with no heating and/or cooling applied). In these cases, some of the defaults still applied (e.g. hours of occupation assumed for different zone types) while others could be changed (e.g. internal window treatment).

Table 4.2: AccuRate zone types and occupancy assumptions

Zone type	Occupancy assumptions
Living room/kitchen	Conditioned from 0700–2400 hrs. Daytime occupancy. Cooking heat gains included.
Living	Conditioned from 0700–2400 hrs. Daytime occupancy. No cooking heat gains
Bedroom	Conditioned from 1600–0900 hrs. Night-time occupancy.
Other (daytime usage)	If heated and/or cooled, conditioned from 0700–2400 hrs. No occupancy heat gains.
Other (night-time usage)	If heated and/or cooled, conditioned from 1600–0900 hrs. No occupancy heat gains.

Table 4.3: AccuRate zone cooling set points

Location	Cooling set point
Darwin	26.5°C
Brisbane	25.5°C
Sydney	25.5°C
Adelaide	25.0°C
Melbourne	24.0°C

AccuRate weather data

AccuRate incorporates weather files for 69 climate zones with measured data derived from the Bureau of Meteorology (BoM). The weather data file in AccuRate is called up for a particular location when the postcode of the site is entered into the software. AccuRate uses data in the TMY (typical meteorological year) format. As the name suggests, data for the file are selected to represent typical weather conditions for the location. One consequence is that the weather files do not contain data that represent extreme events such as heat waves. However the weather files for Adelaide (South Australia,) Amberley (Queensland) and Richmond (NSW) all contained a 4-day hot period.

For Adelaide, the 4-day 'heat wave' period chosen for investigation had a maximum outdoor temperature of 44°C, it was more than 35°C for 25 hours of the 96 hours and there were three very hot nights (Figure 4.3). In terms of thermal comfort and building performance not only was this 4-day period uncomfortably hot, it followed a week with temperatures of more than 30°C for six of the seven days several of which were more than 35°C.

This period did not correspond to the current BoM definition of a heat wave for Adelaide (i.e. three days with a maximum greater than 40°C or five days with a maximum greater than 35°C). However, these temperatures would trigger high watch conditions under Adelaide's Extreme Heat Plan as the maximum temperature was ≥ 35°C for 3+ consecutive days and the minimum was ≥ 21°C for 3+ consecutive nights giving an average daily temperature (ADT) of 28°C (SA SES 2010).

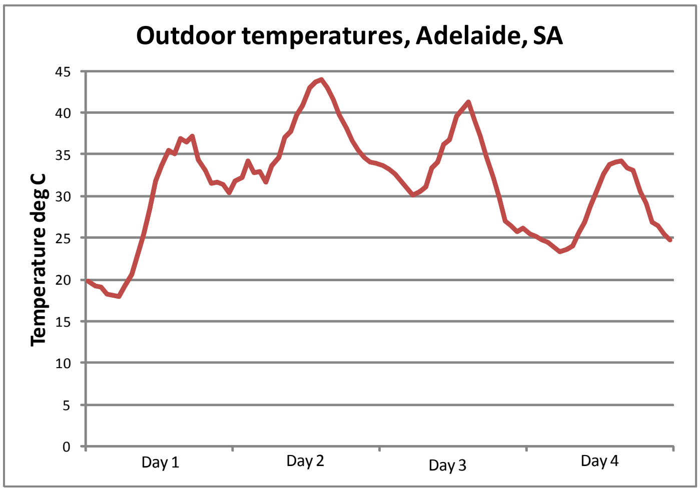


Figure 4.3: Outdoor temperatures during 4-day hot period from AccuRate Adelaide weather file

The climate data chosen to represent Brisbane came from the AccuRate climate file for Amberley, a suburb on the western outskirts of Brisbane. The 4-day period had a maximum outdoor temperature of 42.6°C, it was more than 35°C for 22 hours of the 96 hours and there were three nights with minimum temperatures in the high twenties (Figure 4.4).

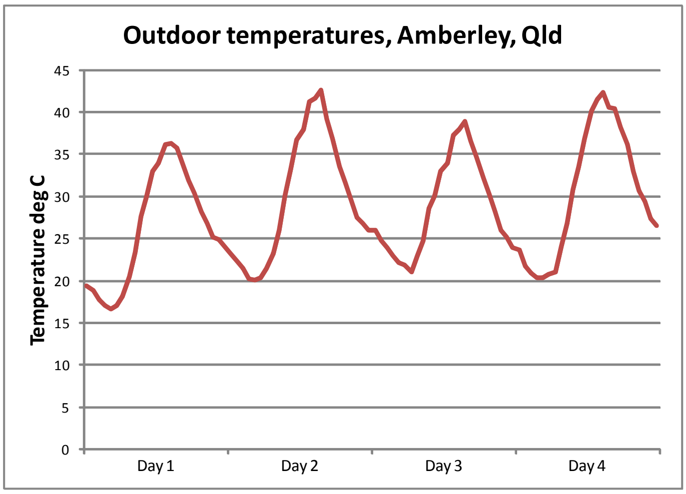


Figure 4.4: Outdoor temperatures during 4-day hot period from AccuRate Amberley weather file

The climate data chosen to represent Sydney came from the AccuRate climate file for Richmond. The 4-day period had a maximum outdoor temperature of 40°C, it was more than 35°C for 14 hours of the 96 hours and the minimum temperatures during the four days was 20.5°C (Figure 4.5).

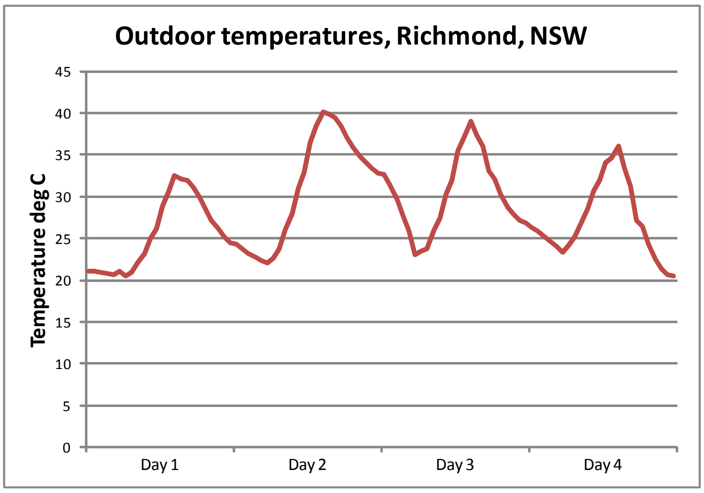


Figure 4.5: Outdoor temperatures during 4-day hot period from AccuRate Richmond weather file

Comfort temperature

The strategy for this research was to calculate internal temperatures and energy use for: (a) the base case; (b) the base case with retrofitted measures; and (c) a modified new design. The performance of different options was compared to a 'comfort' temperature. For this study, the upper limits of residential thermal comfort suggested by Peeters et al. (2009) were used, that is, bedrooms at 26°C, or 29°C if there was increased air movement (a ceiling fan), and 30°C for the living room/kitchen.

While thermal comfort in climate chambers and offices has been extensively researched (Fanger 1970; de Dear 2007), there are relatively few studies of appropriate comfort temperatures in a residential setting, although Oseland (1995) found that people have different thermal responses in these three settings (climate chamber, office, home). People have a wide range of adaptive strategies at their disposal in their homes and are likely to accept a wide range of temperatures as comfortable. They are responsible for paying for energy which may also increase the range of acceptable temperatures (Peeters et al. 2009). This finding was corroborated by findings from this project focusing on adaptive comfort as described in an earlier chapter.

Furnishings and activity in a residential setting may be considered closest to that of an office. Occupants may often be considered sedentary although in fact a range of activities may be undertaken.

Bedrooms

It is difficult to survey people when they are sleeping. The review of the comfort temperature for sleeping by Lin and Deng (2008) highlighted the difference made by the level of bedding. When the participants are covered, a range of 20–22°C is suitable whereas for uncovered participants, the range is 28–32°C. In a similar study for hot, dry climates, a range of 27–30°C was proposed. Looking at temperatures and the quality of sleep led to the conclusion of an overall comfort temperature for sleeping in the range of 21–32°C.

Cooling energy

Cooling energy demand for the base design was modelled using AccuRate's default settings with a set point temperature of 25°C for cooling in Adelaide and with the living room/kitchen including heat gains from cooking and conditioning between 0700–2300 hours and with bedrooms conditioned between 1600–900 hours. For the modified design, the 'cool retreat' was continually conditioned (from 0–2400 hours).

4.3.2 Case Study Results

The five case studies and the results of the thermal analyses are provided in the following notes. In each case, there is a brief description of the dwelling followed by the thermal analysis of the base case, retrofitted dwelling and modified version. The analysis is based on the hourly data for the heating and cooling load as provided by the AccuRate tool. Peak data present the peak cooling demand and do not specify the air conditioning electrical peak demand as elaborated in Section 5.5; however, the data demonstrate the relative impact of the design changes.

Base Case

Case study 1 was a small, single-storey 2-bedroom house, typical of new public housing for people on low incomes and for retirement home or assisted accommodation for the elderly in Australia.

Public housing presents a particular problem in terms of thermal comfort during heat waves. Public housing tenants may be in one or more of the categories of people vulnerable to heat waves (e.g. the elderly or those with disabilities or who are socially isolated). Often there are inadequate resources for major upgrades to the building stock and occupants may not be able to afford to install and operate cooling. Air conditioners are provided in public housing only in limited cases (e.g. in SA, they are installed for people with certain disabilities such as multiple sclerosis [DFC 2010]).

In all three locations, the maximum temperature in bedroom 1 was lower than that for living room/kitchen reflecting the smaller window to floor area ratio, smaller area of the external wall and the orientation of the windows.

Retrofitted measures

Figures 1.2, 1.3 and 1.4 present the impact on internal temperatures of applying a number of retrofitted measures to the base case. Most of these measures have little impact on the lower temperatures (i.e. < 30°C) although both improved glazing and external blinds reduce the length of time at higher temperatures in the living room/kitchen zone.

Applying a combination of all of the retrofitted measures had a significant impact on the cooling energy and the peak load during the 4-day study period.

Modified design

The design modifications were aimed at alleviating major heat gain problems (west-facing window to dining room was removed, shading added to northern windows) and at creating a ‘cool retreat’ in one room. This strategy would be suitable for situations where a single person or a couple occupies one bedroom and the other is used as a ‘spare room’; a common situation in Australia. In 2007, more than three-quarters of dwellings were reported to have more bedrooms than were needed to accommodate the occupants (ABS 2007).

The measures selected were those that would have the most impact for minimal cost, creating a space that had a low peak load and required minimal cooling to maintain comfort during the very high temperatures of the heat wave period. In Adelaide, the cooling energy was 13% of the base case; in Richmond, it was 9%; while in Amberley it was only 4% of the base case.

Case 1: Small house (single storey) 78 m^2

Version: Base case

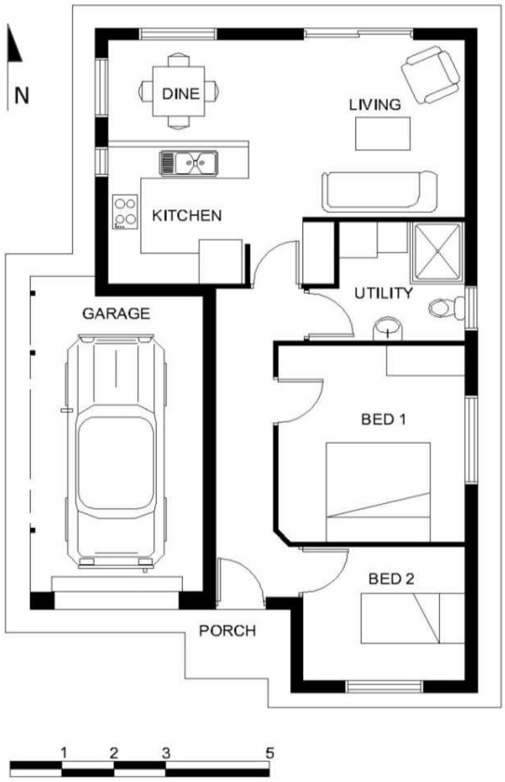


Fig 1.1: Case study 1: base case

Construction

Floor: concrete-slab-on-ground, tiles to wet areas, vinyl elsewhere

External walls: brick veneer + R2 bulk insulation

Windows: aluminium-framed, single glazing: window area = 16.7 m^2

Internal walls: plasterboard on studs

Ceilings: plasterboard + R3 insulation

Roof: metal sheeting

Table 1.1: Maximum temperature and % of hrs within comfort temperatures during 4-day heat wave

		Max temp	% hours within comfort
Adelaide, SA	Living room/kitchen	38.8°C	33% hours < 30°C
	Bedroom 1	35.7°C	9% hours < 26°C
Amberley, Qld	Living room/kitchen	36.7°C	64% hours < 30°C
	Bedroom 1	32.9°C	27% hours < 26°C
Richmond, NSW	Living room/kitchen	35.2°C	68% hours < 30°C
	Bedroom 1	32.8°C	28% hours < 26°C

Table 1.2: Total cooling energy and peak demand for 4-day heat wave: Living room/kitchen & Bedroom 1

	Energy	Peak demand
Adelaide, SA	483 MJ	5.6 kW
Amberley, Qld	299 MJ	4.8 kW
Richmond, NSW	385 MJ	4.8 kW

Case 1: Small house (single storey) 78 m^2	**Version:** Retrofitted measures

ADELAIDE, SA

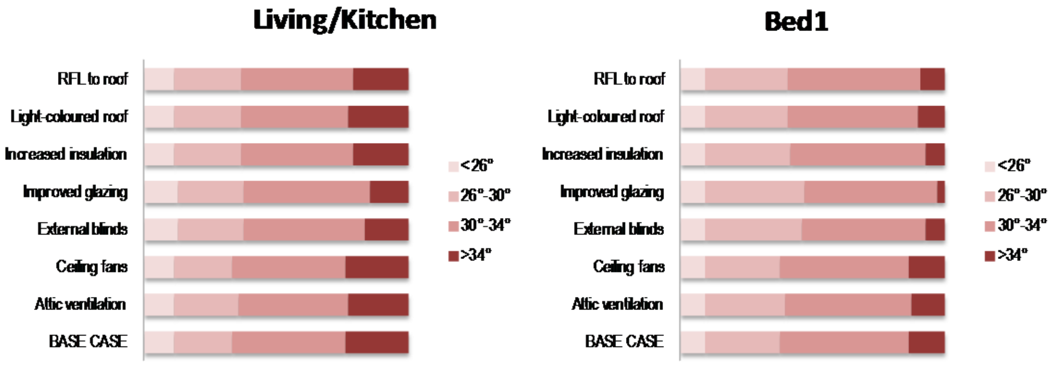


Figure 1.2: Proportion of time at temperatures during 4-day heat wave

Table 1.3: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	**% hours above comfort**
Living room/kitchen	35.6°C	53% hours < 30°C
Bedroom 1	33.5°C	49% hours < 29°C

Table 1.4: Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	**Peak demand**
Living room/kitchen + Bedrooms	259 MJ	3.1 kW

AMBERLEY, Qld

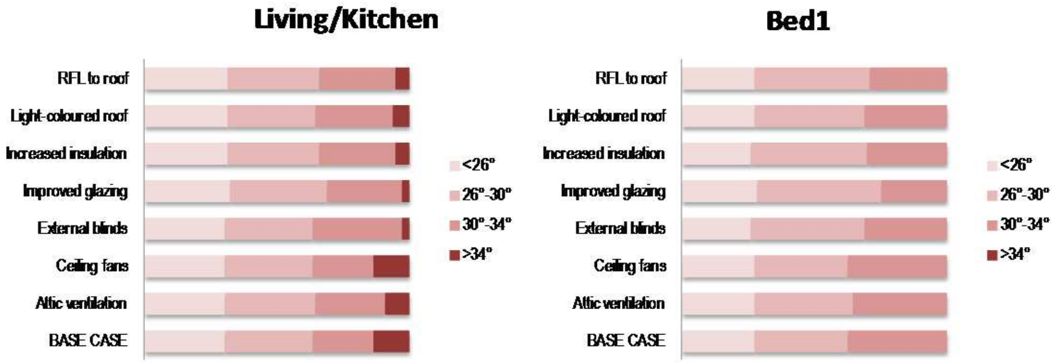


Figure 1.3: Proportion of time at temperatures during 4-day heat wave

Table 1.5: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	**% hours above comfort**
Living room/kitchen	33.0°C	78% hours < 30°C
Bedroom 1	31.5°C	82% hours < 29°C

Table 1.6:Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	**Peak demand**
Living room/kitchen + Bedroom 1	111 MJ	3.1 kW

Case 1: Small house (single storey) 78 m^2

Version: Retrofitted measures

RICHMOND, NSW

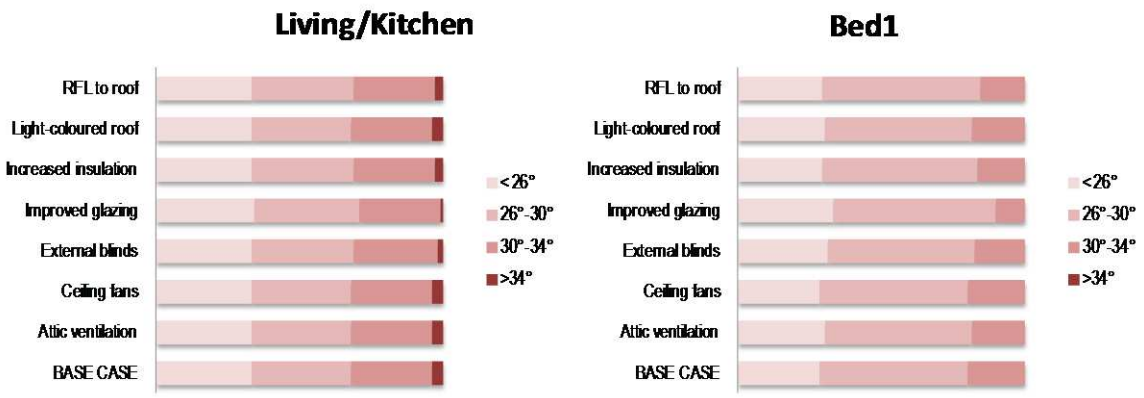


Fig 1.4: Proportion of time at temperatures during 4-day heat wave

Table 1.7: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	% hours above comfort
Living room/kitchen	32.3°C	86% hours < 30°C
Bedroom 1	30.1°C	97% hours < 29°C

Table 1.8: Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	Peak demand
Living room/kitchen + Bedrooms	190 MJ	4.4 kW

Case 1: Small house (single storey) 78 m^2

Version: Modified design

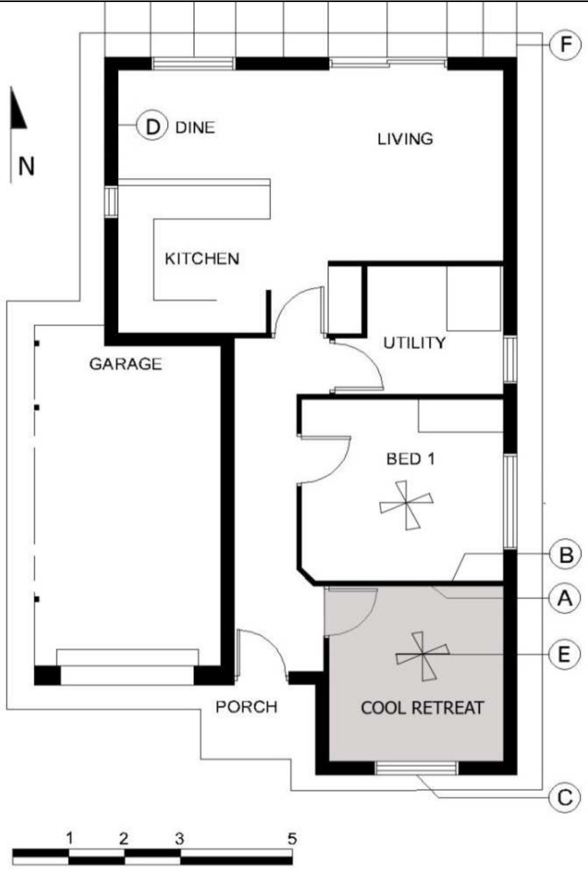


Figure 1.5: Case study 1: modified design

Summary of modifications

A: Internal layout: internal layout adjusted slightly to increase area of spare room/cool retreat

B: Insulation to internal wall: insulation to the internal walls of the cool retreat.

C: Reduce window area: reduce size of window in cool retreat.

Shade to window: external blind to cool retreat window.

Improve glazing: low SHGC film to cool retreat window.

D: Remove window: remove west-facing dining room window (a source of large heat gain).

E: Ceiling fans: install ceiling fans to Bedroom 1 and cool retreat.

F: Seasonal shade to north: removable shadecloth or deciduous vine to living and dining rooms.

G: Light-coloured roof

Table 1.9: Modified design: max. temp and % of hrs within comfort during 4-day heat wave (no cooling)

		Max temp	% hours within comfort
Adelaide, SA	Living room/kitchen	36.1°C	43% hours < 30°C
	Bedroom 1	34.9°C	28% hours < 29°C
	Cool retreat	34.5°C	36% hours < 29°C
Amberley, Qld	Living room/kitchen	33.6°C	71% hours < 30°C
	Bedroom 1	32.8°C	54% hours < 29°C
	Cool retreat	32.4°C	69% hours < 29°C
Richmond, NSW	Living room/kitchen	33.8°C	78% hours < 30°C
	Bedroom 1	31.3°C	74% hours < 29°C
	Cool retreat	31.1°C	81% hours < 29°C

Table 1.10: Modified design: total cooling energy and peak demand for 4-day heat wave: Cool retreat

	Energy	Peak demand
Adelaide, SA	64 MJ	1.0 kW
Amberley, Qld	11 MJ	0.9 kW
Richmond, NSW	34 MJ	1.0 kW

Case 2: 3-bedroom home

Base case

Case study 2 is a 3-bedroom brick veneer home of a design that is common in new housing estates. The open plan kitchen/meals/family room adjoins an alfresco eating area that is under the main roof of the house.

Bedrooms 2 and 3 have west-facing windows. Without cooling, these rooms get very hot with maximum temperatures of more than 40°C during the 4-day study period. The cooling energy required for the bedrooms and the kitchen/meals/family room/hall is 647 MJ with a peak load of 11 kW during the 4-day period.

Retrofitted measures

A number of retrofitted measures were applied one at a time to the base case to gauge their impact (see Figure 2.2). None of the individual measures resulted in a change in the number of hours at the lower temperatures (< 30°C); however, improved glazing and external blinds lessened the number of hours at the highest temperatures (> 34°C).

When the measures were combined, the maximum temperature reached, without cooling, was reduced by 2–3°C for all habitable rooms. If cooling was applied to the bedrooms and kitchen/meals/family room, the combined measures would lead to a 31% reduction in cooling energy and a significant reduction in the peak load demand from 11 kW (base case) to 4 kW.

Modified design

The modified design incorporates a basement beneath the wet areas (laundry, bathroom and part of the hall). Depending on the composition of the household, the basement-level room could be used as a storage room, playroom, teenage retreat or second living area and then, in the event of a heat wave, as a cool retreat.

The section of floor above the basement is lightweight removing the need for services in the slab. The basement walls adjoining the ground are cavity concrete block. There is a small courtyard to the east allowing light and ventilation to the lower level.

During the 96 hours of the heat wave period, the cool retreat only exceeded 30°C for one hour and was at 29°C or more for two hours.

Case 2: 3 bedroom project home (single storey) 150 m^2

Version: Base case

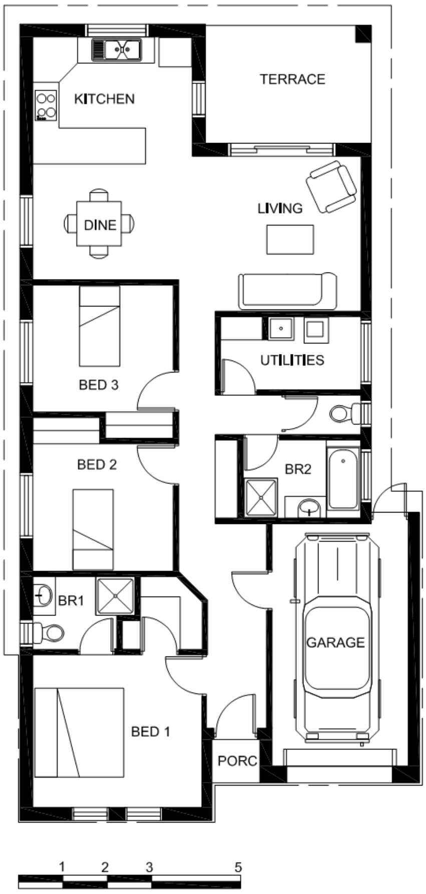


Figure 2.1: Case study 2: base case

Construction

Floor: concrete-slab-on-ground, tiles to wet areas, carpet elsewhere

External walls: brick veneer + R2 bulk insulation

Windows: aluminium-framed, single glazing: window area = 22.2 m^2

Internal walls: plasterboard on studs

Ceilings: plasterboard + R4 insulation

Roof: metal sheeting + reflective foil laminate

Table 2.1: Maximum temperature and % of hrs within comfort temperatures during 4-day heat wave

		Max temp	% hours within comfort
Adelaide, SA	Kitchen/meals/family	40.9°C	33% hours < 30°C
	Bedroom 1	38.9°C	14% hours < 26°C
Amberley, Qld	Kitchen/meals/family	38.0°C	60% hours < 30°C
	Bedroom 1	36.8°C	29% hours < 26°C
Richmond, NSW	Kitchen/meals/family	36.6°C	65% hours < 30°C
	Bedroom 1	35.0°C	30% hours < 26°C

Table 2.2: Total cooling energy and peak demand for 4-day heat wave: Kitchen/meals/family& Beds

	Energy	Peak demand
Adelaide, SA	645 MJ	10.2 kW
Amberley, Qld	473 MJ	9.3 kW
Richmond, NSW	554 MJ	9.2 kW

Case 2: 3-bedroom project home (single storey) 150 m^2	**Version:** Retrofitted measures

ADELAIDE, SA

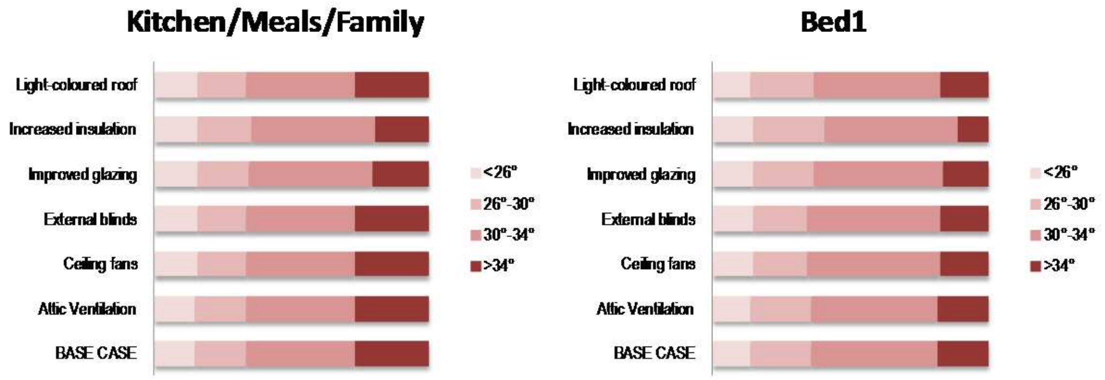


Figure 2.2: Proportion of time at temperatures during 4-day heat wave

Table 2.3: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	**% hours above comfort**
Kitchen/meals/family	38.5°C	40% hours < 30°C
Bedroom 1	36.9°C	35% hours < 29°C

Table 2.4: Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	**Peak demand**
Kitchen/meals/family+ Bedrooms	443 MJ	4 kW

AMBERLEY, QLD

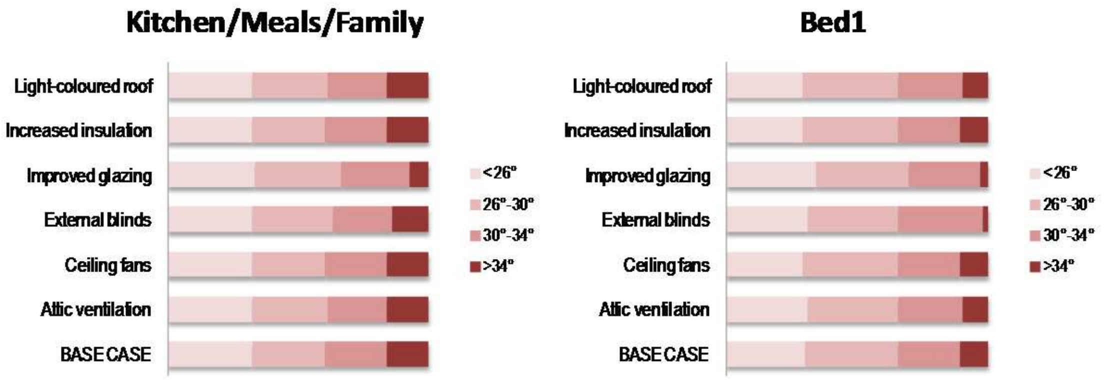


Figure 2.3: Proportion of time at temperatures during 4-day heat wave

Table 2.5: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	**% hours above comfort**
Kitchen/meals/family	35.2°C	68% hours < 30°C
Bedroom 1	32.7°C	65% hours < 29°C

Table 2.6: Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	**Peak demand**
Kitchen/meals/family + Bedrooms	259 MJ	7.2 kW

Case 2: 3-bedroom project home (single storey) 150 m^2	**Version:** Retrofitted measures

RICHMOND, NSW

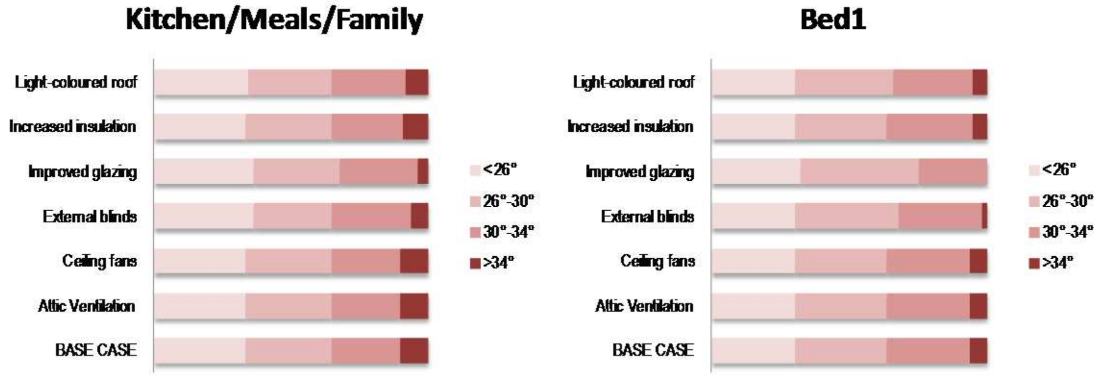


Figure 2.4: Proportion of time at temperatures during 4-day heat wave

Table 2.7: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	**% hours above comfort**
Kitchen/meals/family	34.7°C	74% hours < 30°C
Bedroom 1	32.1°C	68% hours < 29°C

Table 2.8: Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	**Peak demand**
Kitchen/meals/family+ Bedrooms	353 MJ	7.9 kW

Case 2: 3-bedroom project home (single storey) 150 m^2

Version: Modified design

Figure 2.5: Case study 2: modified design

Summary of modifications

A: Internal layout: internal layout is adjusted to create stairs to lower level and to include a door between kitchen /meals /family room and the hall.

B: Basement: Basement with cavity block retaining walls

C: Courtyard: to provide ventilation and natural light to basement cool retreat.

D: Shade to window: external blind to west-facing windows.

E: Improve glazing: low-e glazing to windows in habitable zones.

F: Ceiling fans: install ceiling fans to all habitable zones**.**

Table 2.9: Modified design: max. temp and % of hrs within comfort during 4-day heat wave (no cooling)

		Max temp	**% hours within comfort**
Adelaide, SA	Kitchen/meals/family	37.3°C	40% hours < 30°C
	Bedroom 1	38.3°C	32% hours < 29°C
	Cool retreat	31.2°C	99% hours < 29°C

Amberley, Qld	Kitchen/meals/family	36.0°C	69% hours < 30°C
	Bedroom 1	36.6°C	59% hours < 29°C
	Cool retreat	28.7°C	100% hours < 29°C

Richmond, NSW	Kitchen/meals/family	35.5°C	71% hours < 30°C
	Bedroom 1	34.7°C	59% hours < 29°C
	Cool retreat	28.2°C	100% hours < 29°C

Table 2.10: Modified design: total cooling energy and peak demand for 4-day heat wave: Cool retreat

	Energy	**Peak demand**
Adelaide, SA	15.3 MJ	1.6 kW
Amberley, Qld	10.8 MJ	0.7 kW
Richmond, NSW	37 MJ	1.4 kW

Case 3: 2-storey, 3-bedroom home

Base Case

This case study is a two-storey home designed for a narrow site. The entry/hall is open to the kitchen/dine/living and to the upper level via the stairway creating a large volume to be cooled. All the bedrooms are on the upper level and they recorded very high temperatures during the study period.

Retrofitted measures

A number of retrofitted measures were applied one at a time to the base case to gauge their impact (see Figure 3.3). None of the individual measures resulted in a change in the number of hours at the lower temperatures (< 30°C); however, improved glazing and external blinds lessened the number of hours at the highest temperatures (> 34°C).

When the measures were combined, the maximum temperature reached, without cooling, was reduced by 2–3°C for all habitable rooms. If cooling was applied to the bedrooms and kitchen/meals/family, the combined measures would lead to a 31% reduction in cooling energy and a significant reduction in the peak load demand from 11 kW (base case) to 4 kW.

Modified design

The modified design incorporates a number of changes to the internal layout within the constraints of the width of the original design and the provision of similar amenities. The garage is removed; two bedrooms and the study area are now sub-grade. These can be reconfigured to be summer sleeping and living areas. The design is modelled as free-standing but is adaptable for a terrace development.

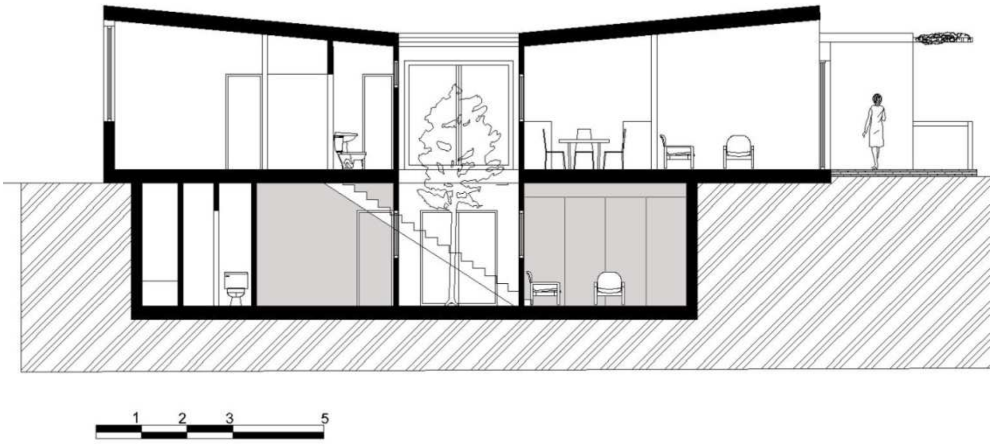


Fig 3.1 Section through modified design for Case 3

Case 3: 2-storey, 3-bedroom home (189 m^2)

Version: Base case

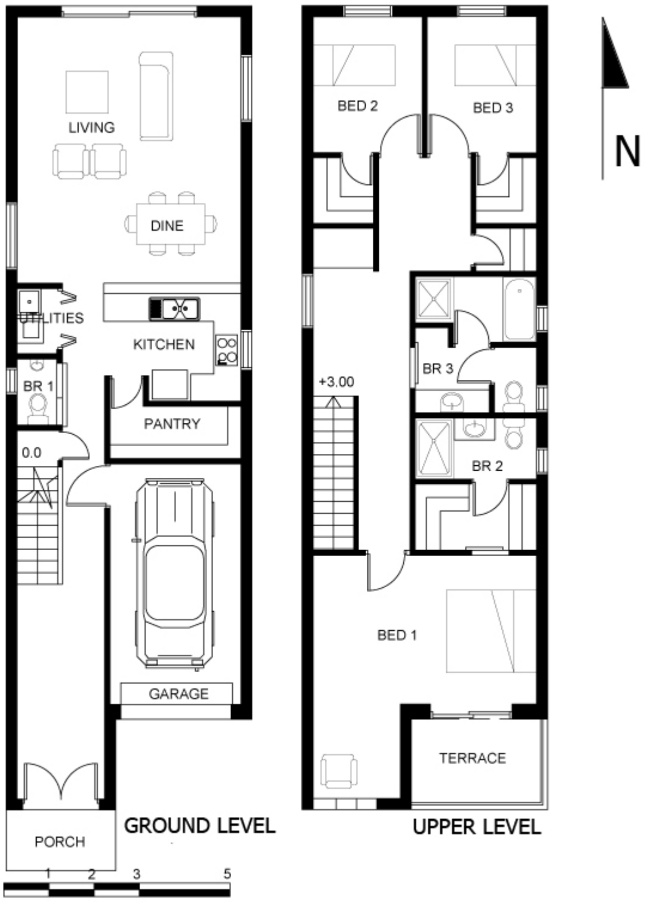


Figure 3.2: Case study 3: base case

Construction

Lower floor: concrete-slab-on-ground, tiles

Upper floor: timber – tiles to wet areas, carpet elsewhere

External walls: brick veneer + R2 bulk insulation

Windows: aluminium-framed, single glazing: window area = 23 m^2

Internal walls: plasterboard on studs

Ceilings: plasterboard + R3 insulation

Roof: metal sheeting

Table 3.1: Maximum temperature and % of hrs within comfort temperatures during 4-day heat wave

		Max temp	% hours within comfort
Adelaide, SA	Living/dine/kitchen	37.9°C	34% hours < 30°C
	Bedroom 1	43.4°C	15% hours < 26°C

Amberley, Qld	Living/dine/kitchen	34.5°C	68% hours < 30°C
	Bedroom 1	39.9°C	33% hours < 26°C

Richmond, NSW	Living/dine/kitchen	34.9°C	64% hours < 30°C
	Bedroom 1	39.1°C	27% hours < 26°C

Table 3.2: Total cooling energy and peak demand for 4-day heat wave: Living/dine/kitchen & Beds

	Energy	Peak demand
Adelaide, SA	963 MJ	18.8 kW
Amberley, Qld	598 MJ	15.7 kW
Richmond, NSW	914 MJ	18.1 kW

Case 3: 2-storey,3-bedroom home (189 m^2) | **Version:** Retrofitted measures

ADELAIDE, SA

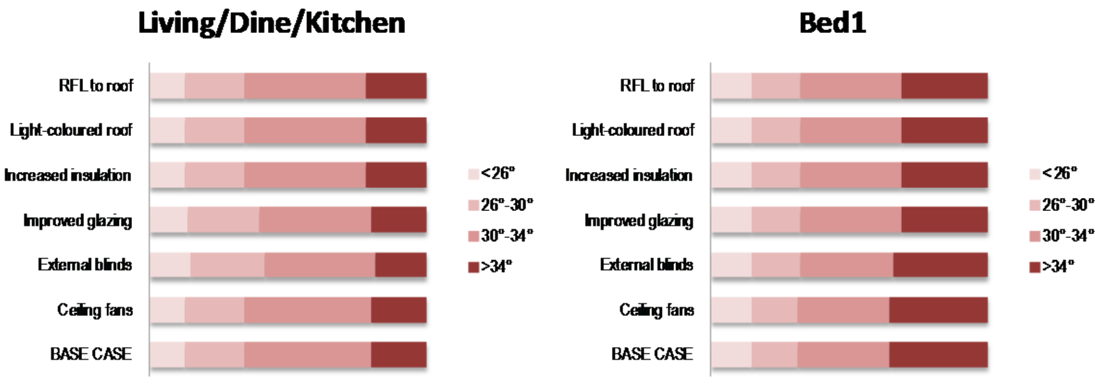


Figure 3.3: Proportion of time at temperatures during 4-day heat wave

Table 3.3: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	% hours above comfort
Living/dine/kitchen	35.6°C	50% hours < 30°C
Bedroom 1	40.5°C	34% hours < 29°C

Table 3.4: Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	Peak demand
Living/dine/kitchen + Bedrooms	641 MJ	13.9 kW

AMBERLEY, QLD

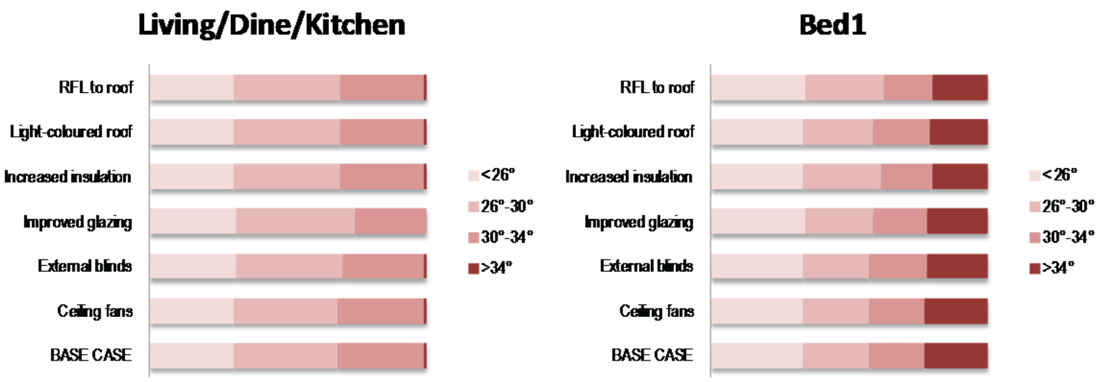


Figure 3.4: Proportion of time at temperatures during 4-day heat wave

Table 3.5: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	% hours above comfort
Living/dine/kitchen	32.9°C	80% hours < 30°C
Bedroom 1	36.2°C	63% hours < 29°C

Table 3.6: Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	Peak demand
Living/dine/kitchen + Bedrooms	364 MJ	11.7 kW

Case 3: 2-storey,3-bedroom home (189 m^2)	**Version:** Retrofitted measures

RICHMOND, NSW

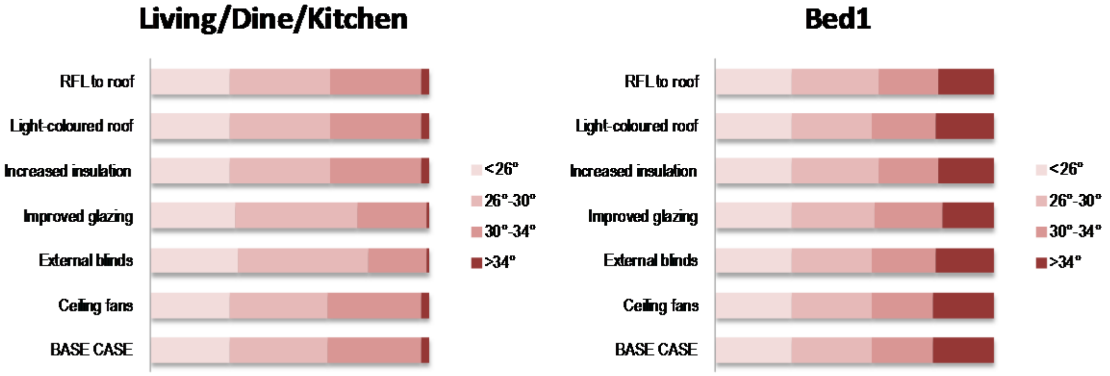


Figure 3.5: Proportion of time at temperatures during 4-day heat wave

Table 3.7: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	**% hours above comfort**
Kitchen/dine/living	31.7°C	88% hours < 30°C
Bedroom 1	36.5°C	57% hours < 29°C

Table 3.8: Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	**Peak demand**
Kitchen/dine/living + Bedrooms	552 MJ	13.9 kW

Case 3: 2-storey, 3-bedroom home (189 m^2)

Version: Modified design

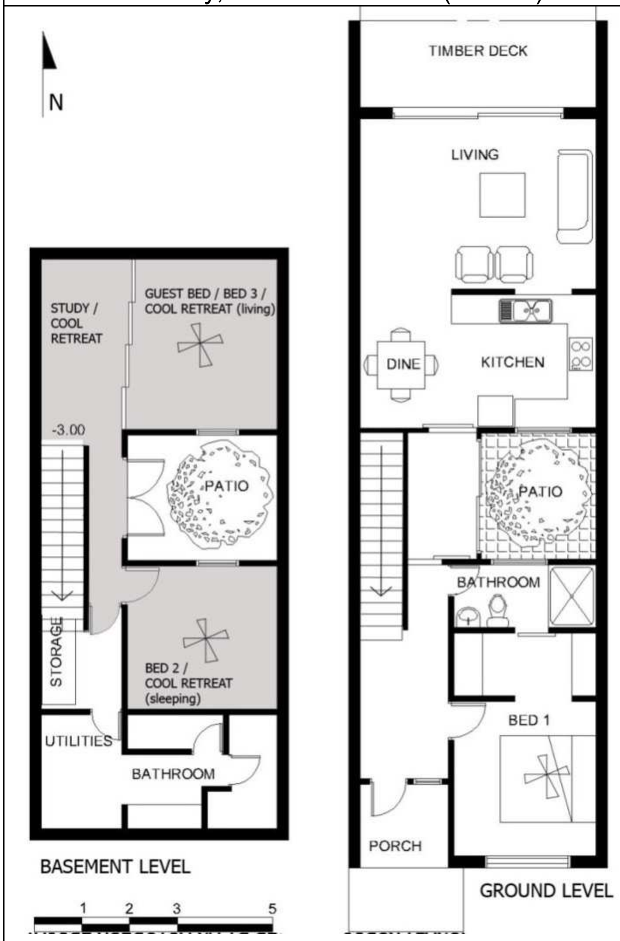


Figure 3.6: Case study 3: modified design

Summary of modifications

Area reduced: removing garage (assumed shared carport/ garaging) and rationalising circulation reduces overall area

Volume increased: ceiling height raised from 2.7 m to 3.0 m

Ground coupling: Bedrooms 2 and 3 and study, below grade with internal courtyard (patio) for light and ventilation

Material changes: Concrete blockwork to retaining wall, suspended concrete floor to upper level

Increase insulation: R2 bulk insulation to internal walls, R4 to ceiling of upper level, R2 to ceiling of lower level

Glazing: Glazing area slightly increased (25 m^2). Timber-framed single-glazed windows and glazed doors; U = 5.75, SHGC = 0.69

Shade to window: external venetians to cool retreat window

Table 3.9: Modified design: max. temp and % of hrs within comfort during 4-day heat wave (no cooling)

		Max temp	% hours within comfort
Adelaide, SA	Living/dine/kitchen	37.2°C	42% hours < 30°C
	Bedroom 1	40.8°C	31% hours < 29°C
	Cool retreat	31.4°C	96% hours < 29°C

Amberley, Qld	Living/dine/kitchen	34.1°C	71% hours < 30°C
	Bedroom 1	38.1°C	57% hours < 29°C
	Cool retreat	28.6°C	100% hours < 29°C

Richmond, NSW	Living/dine/kitchen	34.4°C	76% hours < 30°C
	Bedroom 1	37.1°C	56% hours < 29°C
	Cool retreat	27.0°C	100% hours < 29°C

Table 3.10: Modified design: total cooling energy and peak demand for 4-day heat wave: Cool retreat

	Energy	Peak demand
Adelaide, SA	58 MJ	2.9 kW
Amberley, Qld	14 MJ	1.0 kW
Richmond, NSW	25 MJ	1.5 kW

Case 4: 2-storey,3-bedroom apartment

Base case

This case study design is typical of the medium-height, medium-density apartment development that is forecast to increase in many Australian cities in the future. The 2-storey apartment is on levels 3 and 4 of a 4-storey development. The internal layout is open plan and the lack of internal zoning and a large area of west-facing glass contribute to a high cooling load. Bedrooms on the upper level are particularly uncomfortable during the 4-day heat wave with temperatures reaching over 40°C and with very few hours less than 26°C.

Retrofitted measures

A number of retrofitted measures were applied one at a time to the base case to gauge their impact (see Figure 4.2). For the living room/kitchen/dine, both the external shading and improved glazing increased the number of hours that were less than 30°C. The other retrofitted measures had no discernible impact on the internal temperatures.

For Bedroom 1, on the upper level, changes to the roof/attic space (changing the roof colour, adding foil and increasing attic ventilation) very slightly reduced the hours above 34°C. Adding external blinds increased the amount of time under 30°C.

Modified design

The major modification for this case study were changing the orientation so that the living area faces north, instead of facing west where the windows received large heat gain during the hottest time of the day. The change in orientation had a significant impact on performance during hot weather (and also during cooler weather).

The modifications created a cool retreat in the study/guest bedroom and adjacent dining room. Dividing this area from the kitchen separated the cool retreat from heat gains associated with cooking and from the opening between the lower and upper levels. The area to be cooled was considerably reduced. The upper floor plan was unaltered.

These changes created a cool retreat that, without cooling, was less than 30°C for almost half of the heat wave hours and, with cooling, would require only 15% of the base case cooling and would reduce the peak load requirement from 16.3 kW to 2.8 kW.

Case 4: 2-storey,3-bedroom apartment (159 m^2)

Version: Base case

Figure 4.1: Case study 4: base case

Construction

Floor: suspended concrete slab, insulation when there is a neighbour above, tiles to wet areas, carpet elsewhere

External walls: tilt-up concrete panel, reflective cellular insulation, plasterboard internal lining

Windows: aluminium-framed, single glazing: window area = 25 m^2

Internal walls: plasterboard on studs

Ceilings: plasterboard + R4 insulation

Roof: metal sheeting

Table 4.1: Maximum temperature and % of hrs within comfort temperatures during 4-day heat wave

		Max temp	**% hours within comfort**
Adelaide, SA	Living room/kitchen/dine	39.0°C	20% hours < 30°C
	Bedroom 1	41.9°C	3% hours < 26°C
Amberley, Qld	Living room/kitchen/dine	37.1°C	48% hours < 30°C
	Bedroom 1	39.6°C	3% hours < 26°C
Richmond, NSW	Living room/kitchen/dine	35.4°C	51% hours < 30°C
	Bedroom 1	39.0°C	7% hours < 26°C

Table 4.2: Total cooling energy and peak demand for 4-day heat wave: Living room/kitchen/dine & Bedroom 1

	Energy	**Peak demand**
Adelaide, SA	1051 MJ	16.3 kW
Amberley, Qld	861 MJ	14.9 kW
Richmond, NSW	1018 MJ	15.4 kW

Case 4: 2-storey,3-bedroom apartment (159 m^2) | **Version:** Retrofitted measures

ADELAIDE, SA

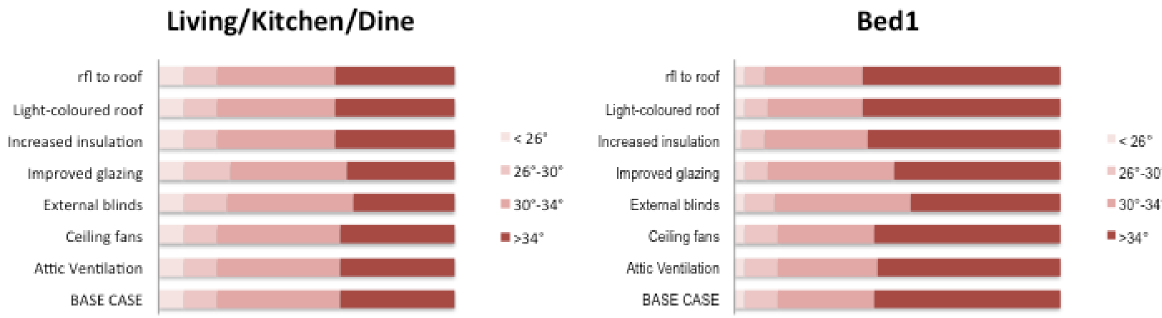


Figure 4.2: Proportion of time at temperatures during 4-day heat wave

Table 4.3: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	% hours above comfort
Living room/kitchen/dine	37.7°C	28% hours < 30°C
Bedroom 1	39.2°C	10% hours < 29°C

Table 4.4 Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	Peak demand
Living room/kitchen/dine + Bedrooms	698 MJ	12.5 kW

AMBERLEY, QLD

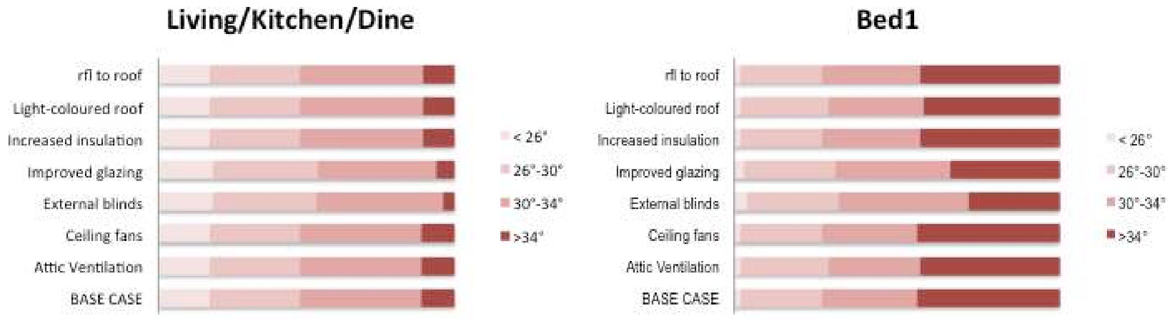


Figure 4.3: Proportion of time at temperatures during 4-day heat wave

Table 4.5: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	% hours above comfort
Living room/kitchen/dine	33.9°C	67% hours < 30°C
Bedroom 1	36.2°C	26% hours < 29°C

Table 4.6: Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	Peak demand
Living room/kitchen/dine + Bedrooms	451 MJ	11.9 kW

Case 4: 2-storey,3-bedroom apartment (159 m^2)	**Version:** Retrofitted measures

RICHMOND, NSW

Figure 4.4: Proportion of time at temperatures during 4-day heat wave

Table 4.7: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	**% hours above comfort**
Living room/kitchen/dine	33.8°C	65% hours < 30°C
Bedroom 1	36°C	28% hours < 29°C

Table 4.8: Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	**Peak demand**
Living room/kitchen/dine + Bedrooms	695 MJ	12.8 kW

Case 4: 2-storey, 3-bedroom apartment (159 m^2)

Version: Modified design

Figure 4.5: Case study 4: modified design

Summary of modifications

Orientation: change orientation by 90°. Living room faces north.

A: Internal wall: add wall between the kitchen/living room and the cool retreat. Insulate internal walls adjacent to cool retreat.

D: Window: reduce window area to upstairs living and cool retreat (total = 23 m^2), low-e glazing to windows + external venetians

E: Floor covering: tiles to lower level floor

F: Ceiling fans: to cool retreat and bedrooms

G: Roof: light-colour, foil to roof

Table 4.9: Modified design: max. temp and % of hrs within comfort during 4-day heat wave (no cooling)

		Max temp	% hours within comfort
Adelaide, SA	Living room/kitchen	37.7°C	11% hours < 30°C
	Bedroom 1	39.4°C	13% hours < 29°C
	Cool retreat	35.8°C	29% hours < 29°C

Amberley, Qld	Living room/kitchen	34.1°C	57% hours < 30°C
	Bedroom 1	34.8°C	46% hours < 29°C
	Cool retreat	30.9°C	84% hours < 29°C

Richmond, NSW	Living room/kitchen	33.8°C	46% hours < 30°C
	Bedroom 1	35.7°C	35% hours < 26°C
	Cool retreat	31.9°C	77% hours < 26°C

Table 4.10: Modified design: total cooling energy and peak demand for 4-day heat wave: Cool Retreat

	Energy	Peak demand
Adelaide, SA	129 MJ	1.9 kW
Amberley, Qld	31 MJ	1.8 kW
Richmond, NSW	104 MJ	2.3 kW

Case 5: 2-bedroom apartment in multi-storey apartment block

Base case

Case study 5 is a 2-bedroom apartment in a multi-storey apartment block with seven levels of accommodation. It is in on the third floor and has apartments on either side, and above and below. The apartments all have a similar design with the main window area on one face. In this case, the apartment faces north-west.

The apartment has high ceilings and a large window area (window to floor area ratio = 32%).

Retrofitted measures

A number of retrofitted measures were applied one at a time to the base case to gauge their impact (see Table 5.2).

Modified design

Modifications significantly improved annual performance as well – taking the rating from 6 stars to 7.1 stars

Case 5: 2-bedroom apartment in multi-storey block (82 m^2)

Version: Base case

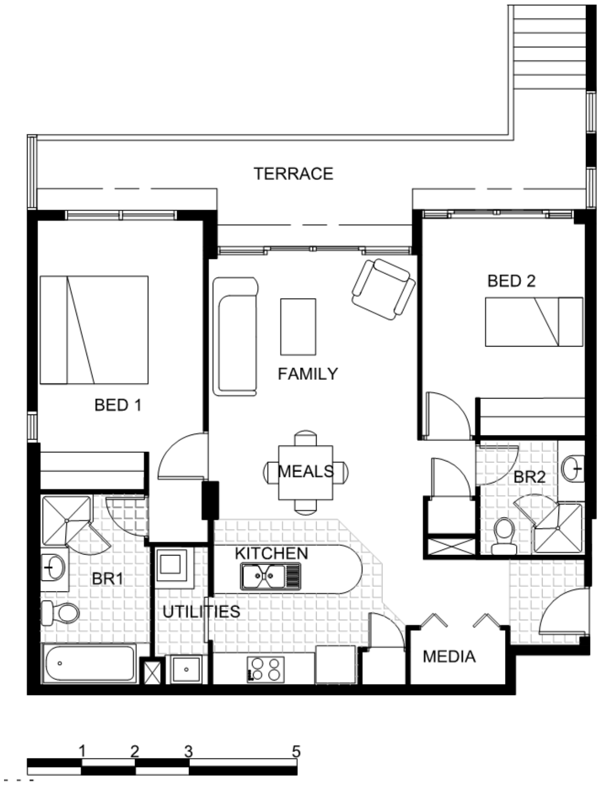


Figure 5.1: Case study 5: base case

Construction

Floor: suspended concrete slab, tiles to wet areas & living/dining/kitchen, carpet to bedrooms

External walls: pre-cast concrete

Windows: aluminium-framed, single glazing: window area = 23 m^2

Internal walls: plasterboard on studs

Party walls: aerated concrete panel with plasterboard either side

Ceilings: plasterboard

Table 5.1: Maximum temperature and % of hrs within comfort temperatures during 4-day heat wave

		Max temp	**% hours within comfort**
Adelaide, SA	Living/dine/kitchen	39°C	21% hours < 30°C
	Bedroom 1	39.1°C	5% hours < 26°C
Amberley, Qld	Living/dine/kitchen	34.1°C	64% hours < 30°C
	Bedroom 1	34.5°C	14% hours < 26°C
Richmond, NSW	Living/dine/kitchen	34.7°C	55% hours < 30°C
	Bedroom 1	35.7°C	15% hours < 26°C

Table 5.2: Total cooling energy and peak demand for 4-day heat wave: Living/dine/kitchen & Bedrooms

	Energy	**Peak demand**
Adelaide, SA	700 MJ	10.7 kW
Amberley, Qld	442 MJ	9.3 kW
Richmond, NSW	664 MJ	11 kW

Case 5:2-bedroom apartment in multi-storey block (82 m^2)	**Version:** Retrofitted measures

ADELAIDE, SA

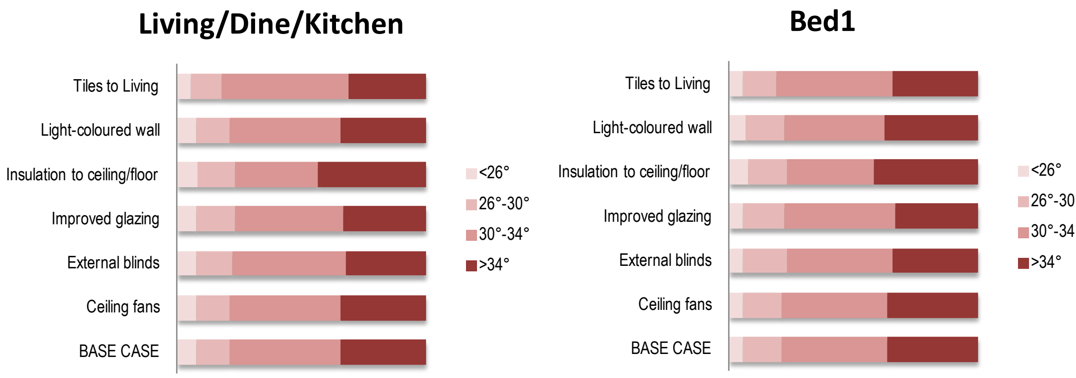


Figure 5.2: Proportion of time at temperatures during 4-day heat wave

Table 5.3: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	**% hours above comfort**
Living/dine/kitchen	37.8°C	24% hours < 30°C
Bedroom 1	37.6°C	18% hours < 29°C

Table 5.4: Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	**Peak demand**
Living/dine/kitchen+ Bedrooms	482 MJ	9.4 kW

AMBERLEY, QLD

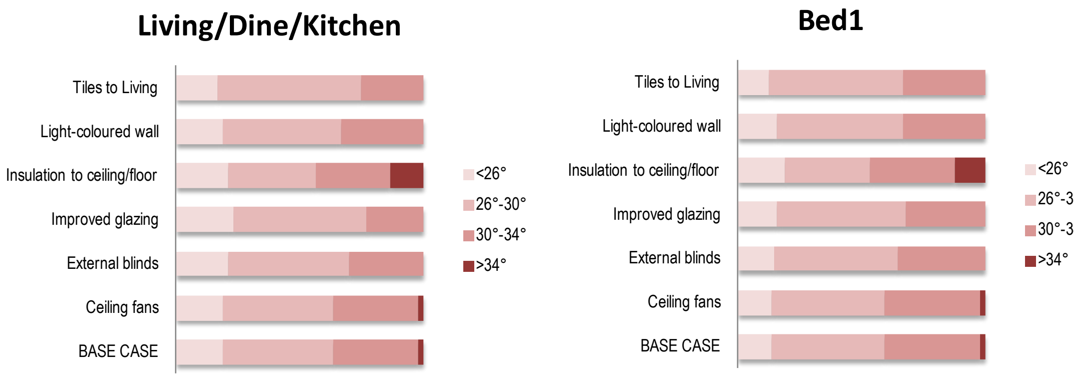


Figure 5.3: Proportion of time at temperatures during 4-day heat wave

Table 5.5: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	**% hours above comfort**
Living/dine/kitchen	31.7°C	93% hours < 30°C
Bedroom 1	31.4°C	70% hours < 29°C

Table 5.6 Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	**Peak demand**
Living/dine/kitchen + Bedrooms	177 MJ	7.9 kW

Case 5: 2-bedroom apartment in multi-storey block (82 m^2)

Version: Retrofitted measures

RICHMOND, NSW

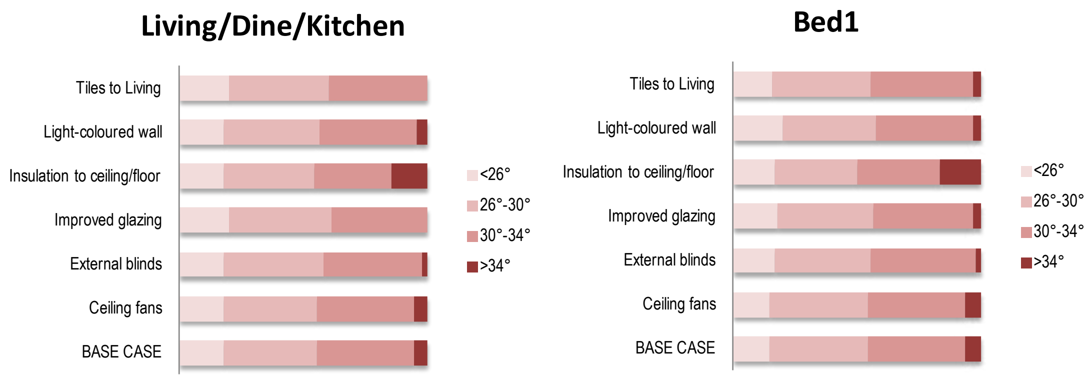


Figure 5.4: Proportion of time at temperatures during 4-day heat wave

Table 5.7: Combined retrofitted measures: max. temperature and % hrs within comfort during 4-day heat wave

	Max temp	% hours above comfort
Living/dine/kitchen	32.2°C	77% hours < 30°C
Bedroom 1	32.3°C	56% hours < 29°C

Table 5.8: Combined retrofitted measures: total cooling energy and peak demand for 4-day heat wave

	Energy	Peak demand
Living/dine/kitchen + Bedrooms	433 MJ	9.4 kW

Case 5: 2-bedroom apartment in multi-storey block (82 m^2)

Version: Modified design

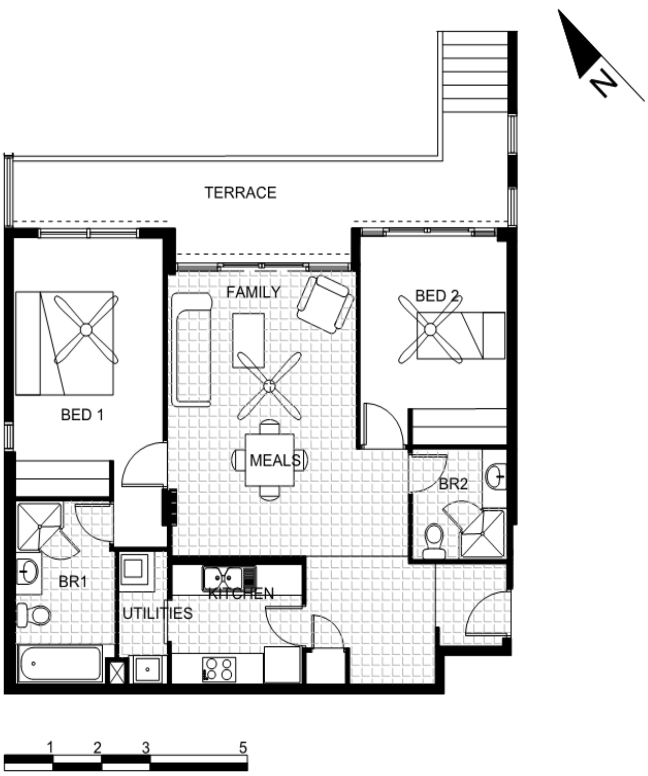


Figure 5.5: Case study 5: modified design

Summary of modifications

A: Internal layout: kitchen is reoriented and internal walls added to enable it to be separated from the living/dining room

B: Insulation to internal wall: insulation to the internal walls of the cool retreat.

C: Floor covering: replace carpet with tiles to cool retreat floor.

D: Ceiling fans: install ceiling fans to bedrooms and cool retreat.

E: Reduce window area: remove west-facing window in Bedroom 2

F: Improve glazing: low-e glazing to windows of bedrooms and cool retreat and external shutters to accessible windows.

Table 5.9: Modified design: max. temp and % of hrs within comfort during 4-day heat wave (no cooling)

		Max temp	**% hours within comfort**
Adelaide, SA	Bedroom 1	35.4°C	17% hours < 29°C
	Cool retreat	36.4°C	26% hours < 29°C
Amberley, Qld	Bedroom 1	30.5°C	76% hours < 29°C
	Cool retreat	29.7°C	91% hours < 29°C
Richmond, NSW	Bedroom 1	30.9°C	84% hours < 29°C
	Cool retreat	27.7°C	100% hours < 29°C

Table 5.10: Modified design: total cooling energy and peak demand for 4-day heat wave: Cool retreat

	Energy	**Peak demand**
Adelaide, SA	176 MJ	2.8 kW
Amberley, Qld	56 MJ	2.6 kW
Richmond, NSW	175 MJ	3.2 kW

4.4 *Overview of Building Design Solutions*

The following notes provide an overview of the results and outputs for the building design component of this research project. The overview is presented in three parts, namely base cases, retrofitted dwellings and modified versions of dwellings. Each part refers to the five case studies and makes specific comments about the three locations where relevant.

4.4.1 Base Cases

Case study 1 – Small house

In the Adelaide (SA) example, there was a limited proportion of time that the house was within the comfort range (33% for the living room/kitchen area and 9% for the bedroom) when the house was analysed in free-running mode during heat wave conditions and with no air conditioning. The maximum temperatures exceeded the comfort range. Bedroom 1 had slightly lower temperatures than the living room/kitchen area reflecting the smaller window to floor area ratio, smaller area of external wall and orientation of the windows.

The base case results for the thermal simulations for heat waves in Amberley (Qld) and Richmond (NSW) were similar to those of Adelaide although the temperatures were not quite as high and the proportions of time in the comfort range were greater.

Case study 2 – 3-bedroom home

The single-storey 3-bedroom brick veneer home was of a design that is common on new suburban residential developments.

Not surprisingly, the dwelling responded to heat wave conditions in a broadly similar way to Case 1 in terms of the proportions of time within the comfort range and the maximum temperature. The maximum temperatures were slightly higher for all locations compared with the case of the small house.

Case study 3 – 2-storey, 3-bedroom home

This case study was characterised by maximum temperatures exceeding the comfort range especially in Bedroom 1 located on the upper storey when it was analysed in free-running mode. For example, maximum temperatures of 43.4°C, 39.9°C and 39.1°C were estimated in Bedroom 1 for Adelaide (SA), Amberley (Qld) and Richmond (NSW), respectively.

Case study 4 – 2-storey, 3-bedroom apartment

Similar observations were made with respect to Bedroom 1 located on the upper floor with the percentage of hours at less than 26°C estimated as 3%, 3% and 7% for the three locations, Adelaide (SA), Amberley (Qld) and Richmond (NSW).

Case study 5 – 2-bedroom apartment in multi-storey apartment block

This case study generally showed similar trends to the previous four cases.

4.4.2 Retrofitted Dwellings

Case 1 – Small house

Most of the passive retrofitting measures modelled individually during the heat wave had little effect on the free-running temperatures in the house especially those temperatures at the lower end of the comfort range. However, improved glazing and external blinds had a noticeable effect on the upper end of the comfort range in all locations.

Combining all of the retrofitting measures caused a moderate reduction in the maximum temperatures during the heat wave conditions, for example, from 38.8°C and 35.7°C to 35.6°C and 33.5°C for the living room/kitchen and Bedroom 1 areas in Adelaide, respectively. The percentage of hours within the comfort range increased from 33% to 53% for the living room/kitchen area in Adelaide and from 68% to 86% in Richmond (NSW). However, continuous comfort conditions could not be maintained in any location for the duration of the heat wave conditions.

More significant were the energy consumption results for thermal simulations using active cooling when all retrofitted measures were combined. For instance, the cooling energy consumption for the living room/kitchen and Bedroom 1 areas decreased from 483 MJ to 259 MJ and the peak demand reduced from 5.6 kW to 3.1 kW in Adelaide (SA). Similar data for Richmond (NSW) were 385 MJ to 190 MJ for cooling energy and 4.8 kW to 4.4 kW for peak demand.

Case 2 – 3-bedroom home

Broadly similar trends were found for the 3-bedroom home. Continuous comfort conditions could not be maintained in any location for the duration of the heat wave when the home was analysed in free-running mode even when all retrofitting measures were in place. However, significant reductions in cooling energy and peak demand were observed in active cooling mode.

Case 3 – 2-storey, 3-bedroom home

Similar findings were evident for this case study, although the Bedroom 1 temperatures remained higher than those for the living/dine/kitchen area.

Case 4 – 2-storey, 3-bedroom apartment

Similar findings were evident for this case study, although the Bedroom 1 temperatures remained higher than those for the living room/kitchen/dine area.

Case 5 – 2-bedroom apartment in multi-storey apartment block.

This case study generally showed similar trends to the previous four cases.

4.4.3 Modified Version of Dwelling

Cooling energy and peak demand

The modified versions of the dwellings explored the concept of cool retreats: these would involve occupants modifying their behaviour patterns for the duration of the heat wave and restricting occupancy to a particular room or zone within the dwelling. The cooling energy used to maintain comfort conditions in the cool retreat was compared to that used for the base case. Substantial reductions in cooling energy and peak demand were demonstrated using thermal simulation with active cooling. For example, case study 1 (small house) required 13.3% of the whole house base case cooling energy to maintain comfort conditions in the modified Bedroom 2 cool retreat in Adelaide (SA). The corresponding peak demand for the cool retreat was 17.9% of that of the base case.

Case studies 2 (3-bedroom house) and 3 (2-storey, 3-bedroom house) showed greater proportional reductions in cooling energy consumption and peak demand in Adelaide (SA) amounting to approximately 6.5% and 15.5% of the base case, respectively. This indicates the effectiveness of basements in maintaining comfort conditions during heat waves.

Case study 4 (2-storey, 3-bedroom apartment) where a cool retreat was proposed for the lower level showed an approximately similar performance to that of case study 1.

Case Study 5 (2-bedroom apartment in multi-storey apartment block) was also modified using a number of measures including the use of internal walls to separate the kitchen from the living/dining area. The reduction in cooling energy and peak demand for the cool retreat was the least compared with the other case studies but the proportion of the base case was still very substantial at 25% and 26%, respectively.

For Amberley (Qld) and Richmond (NSW), the proportions of the base case cooling energy and peak loads used by the cool retreats were lower than that for Adelaide (SA) corresponding to slightly lower cooling requirements. Tables 4.4 to 4.6 summarise these results with the cooling energy shown in column 1 and peak load shown in column 4.

Table 4.4: Adelaide: cooling energy/cooling area and peak demand during 4-day heat wave

	Cooling during heat wave (MJ)	**Conditioned Area (m^2)**	**Cooling/m^2 (MJ/m^2)**	**Peak Demand (kW)**
Case Study 1				
Base Case	483	44.8	10.8	5.6
Cool Retreat	64	10.2	6.3	1.0
Case Study 2				
Base Case	645	87.3	7.4	10.2
Cool Retreat	15	17.6	0.9	1.6
Case Study 3				
Base Case	963	132.5	7.3	18.8
Cool Retreat	58	35.1	1.7	2.9
Case Study 4				
Base Case	1051	124.3	8.5	16.3
Cool Retreat	129	25	5.2	1.9
Case Study 5				
Base Case	700	75.4	9.3	10.7
Cool Retreat	176	30.2	5.8	2.8

Table 4.5: Amberley: cooling energy/cooling area and peak demand during 4-day heat wave

	Cooling during heat wave (MJ)	Conditioned Area (m^2)	Cooling/m^2 (MJ/m^2)	Peak Demand (kW)
Case Study 1				
Base Case	299	44.8	6.7	4.8
Cool Retreat	11	10.2	1.1	0.9
Case Study 2				
Base Case	473	87.3	5.4	9.3
Cool Retreat	10.8	17.6	0.6	0.7
Case Study 3				
Base Case	598	132.5	4.5	15.7
Cool Retreat	14	35.1	0.4	1.0
Case Study 4				
Base Case	861	124.3	6.9	14.9
Cool Retreat	31	25	1.2	1.8
Case Study 5				
Base Case	442	75.4	5.9	9.3
Cool Retreat	56	30.2	1.9	2.6

Table 4.6: Richmond: cooling energy/cooling area and peak demand during 4-day heat wave

	Cooling during heat wave (MJ)	Conditioned Area (m^2)	Cooling/m^2 (MJ/m^2)	Peak Demand (kW)
Case Study 1				
Base Case	385	44.8	8.6	4.8
Cool Retreat	34	10.2	3.3	1.0
Case Study 2				
Base Case	554	87.3	6.3	9.2
Cool Retreat	37	17.6	2.1	1.4
Case Study 3				
Base Case	914	132.5	6.9	18.1
Cool Retreat	25	35.1	0.7	1.5
Case Study 4				
Base Case	1018	124.3	8.2	15.4
Cool Retreat	104	25	4.2	2.3
Case Study 5				
Base Case	664	75.4	8.8	11.0
Cool Retreat	175	30.2	5.8	3.2

Total heating and cooling energy load and star ratings

A variety of measures were used to improve the performance of the base cases in heat wave conditions. These included changes to the fenestration including different glazing and shading. Such modifications have the potential to impair the thermal performance of the dwellings during the colder parts of the year. For this reason, the base cases and the cool retreat versions were analysed for the whole year rather than just the 4-day heat wave. A large proportion of the cool retreat versions of case studies 1 to 5 in the three locations required more heating energy to maintain comfort conditions in the cooler times of the year. However, in all versions, the reduction in cooling energy load more than compensated for the increase in heating energy. Tables 4.7 to 4.9 provide this information and also show the corresponding star ratings calculated by the AccuRate software for the base cases and cool retreat versions.

Table 4.7: Adelaide: NatHERS settings: annual heating, cooling and total energy demand and star rating*

	Annual Heating (MJ/m^2)	Annual Cooling (MJ/m^2)	Annual Total (MJ/m^2)	Star Rating
Case Study 1				
Base Case	39.9	46.6	86.4	6.4
Cool Retreat	42.2	25.1	67.5	7.1
Case Study 2				
Base Case	48.2	44.2	92.4	6.1
Cool Retreat	52	31.2	83.2	6.4
Case Study 3				
Base Case	49.1	45.4	94.5	6.1
Cool Retreat	55.9	19.5	75.4	6.8
Case Study 4				
Base Case	27.8	67.6	95.4	6.0
Cool Retreat	28.6	33.5	62	7.3
Case Study 5				
Base Case	37	56.9	93.8	6.1
Cool Retreat	10.8	44.5	55.3	7.6

Table 4.8: Amberley: NatHERS settings: annual heating, cooling and total energy demand and star rating*

	Annual Heating (MJ/m^2)	Annual Cooling (MJ/m^2)	Annual Total (MJ/m^2)	Star Rating
Case Study 1				
Base Case	5.4	55.6	61.1	6.4
Cool Retreat	5.6	33.3	38.3	7.9
Case Study 2				
Base Case	12.9	54.8	67.7	5.9
Cool Retreat	9.1	34.9	44.1	7.6
Case Study 3				
Base Case	14.5	48.8	63.4	6.2
Cool Retreat	10	25.8	35.8	8.2
Case Study 4				
Base Case	2.8	106.5	109.3	4.1
Cool Retreat	6.8	55.7	62.6	6.3
Case Study 5				
Base Case	7.3	76.4	83.8	5.1
Cool Retreat	0.1	62.2	62.3	6.3

Table 4.9: Richmond NatHERS settings: annual heating, cooling and total energy demand and star rating*

	Annual Heating (MJ/m^2)	Annual Cooling (MJ/m^2)	Annual Total (MJ/m^2)	Star Rating
Case Study 1				
Base Case	33.2	41.1	74.2	6.6
Cool Retreat	35.7	21.9	57.5	7.4
Case Study 2				
Base Case	43.8	40.2	84	6.2
Cool Retreat	48.3	25.9	74.1	6.6
Case Study 3				
Base Case	43.8	41.4	85.2	6.1
Cool Retreat	51.6	17.6	69.2	6.9
Case Study 4				
Base Case	21	68.2	89.2	5.9
Cool Retreat	24.7	37.7	63.3	7.2
Case Study 5				
Base Case	31.5	46.3	77.8	6.4
Cool Retreat	10.8	44.5	55.3	7.6

* Note: The simulations used mandatory NatHERS settings for zone types, temperature settings and hours of occupation and an area correction factor was applied to obtain the star rating. These assumptions varied from those used in the case study calculations.

4.4.4 Impact of Designs on Thermal Comfort and Required Cooling

Five dwelling designs in three locations in Australia were analysed for their thermal performance during 4-day heat wave conditions using thermal simulation software. In the base case versions, all dwelling designs in all locations indicated substantial periods of time when the internal temperatures exceeded the comfort range under free-running conditions (i.e. without active cooling).

A variety of retrofitting measures when applied individually had little effect on the free-running temperatures in the five dwelling designs. When the retrofitting measures were combined, a moderate reduction in maximum temperatures was found although continuous comfort conditions were not maintained. When the thermal simulation analyses were conducted with active cooling, the combination of retrofitting measures gave rise to significant reductions in cooling energy load and peak demand for electricity.

The dwelling designs were further modified to create cool retreats in certain rooms or areas in the dwellings. These modifications included basements for two of the dwelling designs. In all cases, the cooling energy used to maintain comfort conditions in the cool retreats was a small proportion of that in the whole house base case versions. The cool retreat seems to be an effective approach as evidenced by the general decrease of cooling energy demand across all case studies. Even though there is some increase in the energy consumption for heating purpose, the total energy consumption is lower in the cool retreat model. Basement cool retreats were particularly efficient at maintaining comfort conditions.

Whole year thermal analyses were also undertaken for heating and cooling energy loads for the base case and cool retreat versions of dwellings, and the reduction in the cooling requirement was found to exceed any increase in the heating requirement arising from the design modifications.

4.4.5 Impact of Designs on Construction Cost

A number of retrofitted options as well as options for new designs were investigated. Overall, the retrofitted and new design options applied standard building practices and materials which are in common use and, therefore are generally within the range of what can be considered affordable. Furthermore, for retrofitted options, these can be applied on an end-of-life basis and merely represent the appropriate choice for the householder.

Retrofitted options range from measures such as applying a light-coloured roof to changing the glazing. The first option is of no cost for re-roofed homes while replacing glazing is a relatively high cost. Belusko and O'Leary (2010) have conducted a cost analysis for applying minor building upgrades to increase the star rating of houses from 5 to 6, based on retail costs. Consideration was given to applying foils, adding insulation as well as upgrading the glazing. Based on this data, the cost of applying foils is less than $1,000, adding roof insulation less than $2,000 and upgrading living room glazing is less than $10,000.

The new house designs apply both technology solutions as well as changes to the design. Technology changes include applying a light-coloured roof, adding foils, and improving glazing and insulation. For new houses, roof colour represents no cost, while adding foils and improving insulation represents minor cost increases of less than $1,000. As highlighted by Belusko and O'Leary (2010), upgrading of glazing in the living zone is less than $5,000 for new homes. However, the cost of double glazing has been dropping in the pat months as more new suppliers of quality windows are entering the market.

These design changes applied the cool retreat concept. These changes can involve relocating the living room or adding a basement. The first option represents no additional cost whereas the latter can represent a very significant cost increase. Preliminary costings indicate a substantial increase of around 20% in the cost of new houses which include rooms in basements but these increases may be moderated under certain conditions such as on sloping sites, when built as semi-basements (i.e. half below grade), where there are planning height restrictions or where the houses are built in terraces enabling a large single excavation for the multiple basements. This concept requires further research and development as a possible design option for improving the performance of houses during heat waves.

Chapter 6 presents information on the likely amount of funds householders would be willing to spend to adapt to heat waves. Some low-income households were willing to spend up to $2,000 while most average households were willing to spend up to $5,000. These amounts cover most of the possible options for both new and existing households.

4.5 *Future Research*

The gaps and future research directions for the building design component of this report can be summarised as follows:

- The use of simulated future weather files for analysis of case studies. This would be to determine the thermal performance of case studies over several days during heat waves and over a whole year of future weather data.
- Cost–benefit analyses of the comprehensive retrofitting measures for existing dwellings over their remaining life cycles.
- Examination of other non-financial benefits for the retrofitting of existing dwellings, for example, reduced greenhouse gas (GHG) emissions using other software.
- Cost–benefit analysis of modified versions of case studies suitable for new dwelling construction. Included in this would be possible reductions in the size of air conditioning equipment. Other benefits still to be analysed include reductions in GHG emissions and the value of the semi-independence of electricity supply during peak demand periods.
- Consideration of supplementary building regulations which mandate the design and construction of cool retreats in dwellings for heat wave conditions in addition to the current energy-efficiency requirements.
- Investigation on the barriers to change in the Australian residential construction industry, which is required to move beyond techno-remedial approaches and develop future housing typologies.
- Determination of the most effective means to communicate optimal solutions to consumers and industry as opposed to the ‘minimum standards’ of the BCA.

5. COOLING ANALYSIS

Over the last few decades, cooling equipment has become a common feature of most households in Australia. The electricity usage and peak power demand from cooling equipment is related to the size and type of equipment, the selection and installation processes as well as the design of the building and household behaviour. The provision of improved distribution networks to cope with air conditioning has been the principal driver behind escalating electricity costs. With the onset of climate change, it is critical to assess how industry practice and current regulations are affecting the peak demand for cooling. In this chapter, the impacts of two of the most significant parameters, namely cooling equipment and roof construction, on cooling energy requirements are investigated. The assessment is focusing on a number of Australian locations including Adelaide, Melbourne and Brisbane.

5.1 *Cooling Equipment In Australia*

The demand for cooling has increased in recent times. Tables 5.1 and 5.2 show data analysed from the Australian Bureau of Statistics (ABS 2008) showing that, in 2008, 65% of all households had either a refrigeration-based or evaporative-based cooling system. Furthermore, based on 2005, the annual growth rate in the number of households with cooling equipment was found to be 2.1%. At the rate of this trend, it is likely that by 2020 virtually all households will have some form of cooling equipment. The data show that the principal cooling equipment is refrigeration-based, being either a ducted or a split-type system. The market share of evaporative cooling systems has shown a slight decline.

Table 5.1: Proportion of households with cooling system based on ABS (2008)

Proportion of Households	NSW	Vic	Qld	SA	WA	Tas	NT	ACT	Aust
With cooling system	57%	68%	62%	84%	79%	35%	91%	55%	65%
With refrigeration-based cooling	50%	49%	59%	62%	52%	34%	74%	35%	52%
With split or window/wall refrigeration cooling	35%	36%	53%	34%	30%	29%	61%	21%	38%
With ducted refrigeration cooling	15%	13%	6%	28%	22%	5%	13%	14%	15%
With evaporative cooling	7%	19%	3%	22%	27%	1%	16%	20%	12%

Refrigeration-based systems rely on the vapour compression refrigeration cycle. Electricity is used to drive heat out of the home: the performance of these systems is defined in terms of the thermodynamic performance defined by the coefficient of performance (COP). The COP is the ratio of the cooling effect and the electrical load used by the air conditioner. Typically, the COP of air conditioners is 2-3 which means that for every unit of electricity, 2–3 units of cooling are achieved. Evaporative cooling operates by humidifying hot dry air. The vaporisation of water absorbs heat from air thus cooling it. This air is pumped through the home achieving cooling. For hot dry summers as experienced in Adelaide and Melbourne, on a comparative basis, evaporative cooling achieves COP values of more than 20 (Saman et al. 2010). Furthermore, since these systems provide 100% ventilation, they reduce the amount of heat entering the home through walls and roofs, as cooled air absorbs this heat as it exits the building. This characteristic, known as displacement ventilation, results in less cooling being required compared to a refrigeration-based system which has to remove all the heat that enters the building to achieve thermal comfort (ASHRAE 2005). Despite these benefits, evaporative cooling has been replaced by refrigeration systems as the dominant form of air conditioning. Unlike refrigeration systems which can also be used for heating, a separate heating system is required alongside evaporative coolers. In addition, evaporative cooling is ineffective in humid regions or during days that are more humid. Multi stage evaporative cooling overcomes this issue, while maintaining the higher efficiency and 100% ventilation benefit of traditional evaporative systems (Bruno 2011). However, these systems have not been taken up on a large scale.

Table 5.2: Annual growth of proportion of households with cooling system based on 2005–2008 data (ABS 2008)

Proportion of Households	NSW	Vic	Qld	SA	WA	Tas	NT	ACT	Aust
With cooling system	1.4%	3.0%	1.8%	0.2%	3.7%	5.1%	0.0%	2.5%	2.1%
With refrigeration-based cooling	1.4%	3.0%	2.7%	1.0%	3.7%	5.2%	-0.1%	0.5%	2.4%
With split or window/wall refrigeration cooling	1.1%	2.3%	2.3%	0.1%	2.4%	4.5%	-0.8%	-0.3%	1.8%
With ducted refrigeration cooling	0.3%	0.7%	0.4%	0.8%	1.4%	0.7%	0.6%	0.8%	0.6%
With evaporative cooling	0.0%	0.0%	-0.9%	-0.8%	0.0%	-0.1%	0.2%	2.1%	-0.2%

Window/wall or single split-type systems which cool one room are installed in 38% of all houses and this is growing at 1.8% of households per annum. This growth is in single split systems as window/wall systems are generally existing older systems. Whole-of-house heating and cooling is either achieved by a ducted system or a multi-head system. These systems use considerably more energy than a single split system, as they condition the entire house. The ducted system, being generally of lower cost, is the dominant system. Although representing only 15% of all homes in Australia, ducted systems are growing nationally at 0.6% of households, are in 28% of homes in SA and of the cooling systems being installed are the fastest growing.

5.2 *Impact of System Efficiency, Design And Installation*

The cost of cooling and the impact on peak electricity demand is dependent on industry practice and regulations. The electricity demand from cooling equipment is a function of the COP of the system, system selection and installation practices.

The energy efficiency of cooling systems is regulated through the Minimum Energy Performance Scheme (MEPS) which rates the systems using stars and permits the use of systems above a predetermined rating. Evaporative cooling is currently not evaluated under this scheme, as these systems generally use a small amount of electricity. Modern evaporative systems use even less energy, and multi-stage systems tend to use more energy; however, they achieve higher levels of thermal comfort. Previous moves to develop an energy-efficiency standard for evaporative coolers have not been realised. However, the introduction of a star rating scheme would enable customers to take advantage of the benefits in cooling energy saving of evaporative systems. Research has shown that particularly during peak periods in hot dry climates, evaporative cooling can deliver significantly lower cost thermal comfort than refrigeration systems (Bruno 2011).

The star rating of air conditioning systems is based on the COP as measured at an indoor temperature of 27°C and an outdoor temperature 35°C operating at 100% output (AS/NZS 3823.2:2011). The rating only considers the unit itself and does not consider the energy-efficiency impact of ducting or using multiple heads, as found in whole-of-house systems. Furthermore, virtually all new systems are inverter-driven rather than operating at a fixed speed.

Inverter air conditioning involves the compressor within the system adjusting its rotational speed to match the load requirement. This process increases the COP of the system when operating below maximum capacity. As a result, energy savings can be achieved relative to the conventional fixed speed, with estimated savings of around 10% (Belusko 2010). However, the design of these units has resulted in some unexpected results during peak periods. Usually these systems have the ability to reach a cooling capacity of more than 150% of the rated capacity. Many systems are artificially 'clipped' to 130% to prevent this occurring. Traditional fixed speed air conditioners, during extreme peak periods, would simply not achieve the temperature set point, room temperatures would rise and the peak power demand from the air conditioner would remain constant. Inverter systems have a 'hidden' capacity and will increase power demand beyond the rated capacity. There is no regulation limiting this additional capacity.

The MEPS applies to all new systems sold in Australia. However, for ducted systems, no consideration is given to the impact of ducting on the star rating. The two major performance reduction factors in ducting are air leakage and heat transmission through the duct walls. Ducting is regulated by the Building Code of Australia (BCA). This regulation relates to the thermal resistance or R value of the insulation used in the duct. Since the BCA is only applicable to new homes, it is understood that the performance requirements of ducting are not applicable to new ducted air conditioning systems in existing homes. This is reflected by the fact that the volume of duct sales nationally is for ducts at a rating below that specified by the BCA, and this cannot be explained by the size of the evaporative cooling market. However, this may have changed in more recent times. Other considerations relating to ducting include the lack of regulation on the thermal rating of the duct itself, although there have been moves to develop a testing standard. Research has shown that the thermal rating is significantly below that determined by the thermal resistance of the insulation used (Belusko 2010). Follow-up research has shown that, in combination, these effects have resulted in a 39% increase in electricity usage in the case of Adelaide (Belusko 2012).

A more critical consideration relates to the installation of ducted systems. Sample measurements of leakage in residential systems have shown that leakage in ducted systems can typically be 30% (Palmer 2008) which translates to a minimum 30% increase in energy usage (Palmer 2008; Belusko 2012). There is currently no quality assurance process used in the residential sector to ensure that no leakage exists in newly installed systems. This is a common check used in commercial installations. Research has shown that, collectively, for a new installation in Adelaide, this can translate into a 40% and 80% increase in electrical energy usage of the air conditioner for new and existing homes. Consequently, for a new inverter system with significant losses due to poor ducting, peak electricity demand rises dramatically with the application of the 'hidden' capacity within these units.

Ultimately, the peak demand from an air conditioner is determined by its size. Air conditioner retailers generally size an air conditioner by applying a fixed load per square metre to the conditioned floor area. Generally, no consideration is given to the energy efficiency of the home. Given the desire to prevent customer dissatisfaction, the unit is usually oversized. As a consequence, there is an in-built increase in peak demand.

5.3 *Impact of Design Options on Cooling Energy*

The energy required to cool a building is defined by the ambient temperature, internal loads caused by equipment and people, and solar radiation. Of these, solar radiation has the most significant impact on peak cooling requirements (Athienitis & Santamouris 2002). When a person stands in full sun, the impact is equivalent to a 10°C temperature rise in the ambient temperature (Duffie & Beckman 2006). In Australian homes, solar radiation affects the cooling needs by entering the home directly through windows and indirectly by being absorbed by the roof and external walls. Effective shading can prevent solar gain through windows. The first energy-efficiency measure introduced into building regulations, through the BCA, was to insulate the roof. This was justified as the most economic measure, reflecting the benefit of reducing both heating and cooling requirements. Over the decades, the application of bulk insulation into the roof cavity and walls has represented the principal measure for reducing solar radiation-induced heat flow into houses.

In the last decade, consideration has also been given to the reflectivity of solar radiation from the roof and the impact of reflective foils. Less bulk insulation is required with roofs which reflect more solar radiation, such as light-coloured roofs and those who have had foils applied. There is little doubt that bulk insulation within the roof has significantly reduced the cooling energy use in Australian homes. However, existing practices and regulations do not fully account for the actual heat transfer processes that occur, and Australia remains behind most of the developed world in this area. The implementation of NatHERS and the application of the building modelling engine, AccuRate, represent a move away from a prescriptive approach and have allowed designers to consider the full range of options for reducing the cooling energy requirements in buildings.

According to the BCA, the thermal resistance or R value of bulk insulation is based on AS/NZS 4859.1:2002 which requires measurement of the R value at 23°C. However, no consideration has been allowed in the BCA for the degradation of the R value due to temperature. As stated in AS/NZS 4859.1:2002, the R value can degrade by 0.49%°C which, during peak summer, can represent a reduction of 14%. A fixed R value is also applied in AccuRate.

In both the European Union (EU) and US, thermal bridging through insulation is strongly regulated (ASHRAE Standard 90.1-2007, EN ISO 6946:1996). Thermal bridging occurs when heat can bypass the insulation through the timber or steel structure, significantly degrading its effective R value. Neither the BCA nor AccuRate have considered this effect, although this has been regulated for some time in the EU, the US and countries such as Turkey and China. The impact of thermal bridging has recently been introduced into AccuRate Sustainability which is based on the AccuRate engine.

The impact of poor installation of insulation cannot be overstated. As identified in the 1970s, gaps of 5% in roof insulation can degrade the R value by 50% (Verschoor 1977). To address this concern, regulations in the EU and US place considerable attention on the quality assurance of insulation installations. In the UK and France, thermography is a commonly used and often mandated tool for identifying gaps. In the US, filling of gaps using foam is a common practice. There is no quality assurance regulatory process or common industry practice for installation of insulation in Australia.

Experimental research has been conducted to evaluate the actual R value of installed bulk insulation in typical Australian roofing systems (Belusko et al. 2010, 2011). Table 5.3 presents the measured results, along with the values that are currently applied in AccuRate and the BCA. This research was based on two years of data, measuring the R value in an outdoor laboratory setting. As a comparison, a test was completed applying a continuous layer of insulation under the ceiling, which is a common practice in Europe, but not in Australia. The results clearly showed that the measured results of typical insulation practices in Australia are significantly lower than the expected results, unlike the continuous insulation approach.

Table 5.3: Measured ceiling to roof surface thermal resistance in typical timber roof attic system (m^2K/W)

Roofing system	Measured, heat flow down, (+/-10%)	Measured, heat flow up, (+/-10%)	AccuRate/BCA
R3 traditional bulk insulation	1.46	1.37	3.2
Continuous insulation R1.2	-	1.4	1.4

Overall, current regulations infer an insulating performance of bulk insulation in roofs, which is the most optimistic scenario and which, in practice, never occurs. The results in Table 5.3 demonstrate what the actual R value could be in situ. Such a significant difference can have major consequences during extreme heat wave scenarios where significantly more heat flows through the roof space.

It should not be inferred from the divergence between the actual and expected result that bulk ceiling insulation is ineffective, rather that the approach taken by regulations is incomplete, which is particularly relevant during heat waves. Therefore, it is proposed that a reliability-based approach be applied which aims to recognise the probability of these factors and applies solutions which reduces the risk of high heat flow through the roof in summer.

The amount of solar energy which the roof absorbs is strongly dependent on the reflectivity of solar radiation from the roof which is related to the roof colour. In southern Australia, the most popular roof colours for new houses for the last decade have been dark, with light-coloured roofs being least popular. In locations such as Brisbane and Darwin, light-coloured roofs have traditionally dominated; however, there is a concerning trend of dark-coloured roofs being used in some new homes. The amount of solar energy absorbed by the roof is a significant factor which determines the heat transmission into the dwelling during heat waves. The absorbed radiation is a function of the total solar reflectance (TSR) of the roof, which is the ratio of the reflected solar radiation to the total radiation incident on a surface. A typical grey- or black-coloured roof has a TSR of around 0.05 to 0.1, and a white roof has a TSR of around 0.9. Furthermore, recently produced radiation-reflecting paints are able to offer roof colours with significantly higher TSR values than traditional paints of the same colour. Overall, the defining parameter which determines the temperature rise of the roof surface compared to the ambient temperature is not the colour but the specified TSR.

Roof surfaces which absorb high amounts of solar radiation can readily reach temperatures of 80°C in hot weather. This temperature represents the driving force of the heat flow into the building. Roof surfaces which absorb low amounts of radiation can dramatically reduce this temperature, bringing it closer to the ambient temperature.

A mathematical model was developed of the heat flow through the roof during hot periods, applying the measured R values in Table 5.3. A comparison was made of a dark-coloured roof (TSR of 0.07), which absorbs 93% of solar radiation, and a lighter-coloured roof (TSR of 0.75), which absorbs 25% of solar radiation. It was demonstrated that the actual heat flow during this period could be reduced by a factor of 4, and converting the dark-coloured roof to a light-coloured was equivalent to adding insulation to a rating of R5 during hot periods. The dominant form of heat transfer in roofing systems in summer is through radiation. Reflective foils are very effective at reducing this heat flow. Both these features will essentially reduce the potential heat flow through the roof by reducing the overall driving potential, which also reduces the impact of thermal bridging, and reduces the temperature of the insulation itself, maintaining the R value. Overall, these features enhance the reliability of the roofing system at reducing the heat flow, particularly during extreme hot weather.

To demonstrate the significance of these steps, modelling was conducted in AccuRate of two energy-efficient homes representative of a typical house in 2030 with different roof insulation properties, in a variety of cities in Australia. According to ABS data, the dominant construction type in 2008 was brick veneer representing 44% of homes in 2008 and displacing all other types, growing at 0.2% per annum of households based on 1999 data (ABS 2008). Both houses were single storey, slab on ground, brick veneer homes with a star rating of 6 stars for Adelaide. House 1 was a 3-bedroom, single bathroom home with a single living area with a total floor area of 104 m^2, and a conditioned floor area of 96 m^2, 55.6 m^2 being the living zone. House 2 was a 4-bedroom, 2-bathroom home with two living areas with a total floor area of 211 m^2, and a conditioned floor area of 169 m^2, 101 m^2 being the living zone. House 1 had R2 insulation in the external walls and R3 in the roof. House 2 included foil in the roof, fans in the living zone, low emissivity (low-e) single glazed windows throughout the house, R4 insulation in the roof, R2 insulation within the external wall and R1.5 insulation in the internal walls. Both houses had a default TSR of 0.5 (50% absorption of solar radiation). Both houses where chosen as they were better designed for cooling, requiring more heating than cooling when rated in Adelaide. Therefore, any analysis would demonstrate the significance of the measures investigated. The analysis considered both the idealised and potentially more likely R values based on Table 5.3. For House 1, this R value was 1.4 and for House 2, this R value was 1.6. The R value for House 2 was determined by evaluating the thermal resistance of all bridging and gaps from the experimental data and applying this resistance with the R4 bulk insulation, using the parallel path heat flow analysis technique (ASHRAE 2005).

Tables 5.4 and 5.5 show the star rating of each house with different roof arrangements in different locations. Overall, it confirms the significant variation that can occur between the assumed and the more likely star rating of a building. Furthermore, the results show the impact of the TSR on the star rating.

Table 5.4: House 1, star rating for different roof configurations

	R3 without foil, TSR = 0.1	R1.4 without foil, TSR = 0.1	R1.4 with foil, TSR = 0.9
Adelaide	5.8	4.9	5.5
Brisbane	7.4	6.2	7.6
Melbourne	5.4	4.8	4.8
Hobart	5.2	4.8	4.4
Darwin	5.4	4.6	6.3
Sydney	6.9	5.5	6.8
Perth	5.7	4.4	5.9

Table 5.5: House 2, star rating for different roof configurations

	R4 without foil, TSR = 0.1	R1.6 without foil, TSR = 0.1	R1.6 with foil, TSR = 0.9
Adelaide	5.7	4.7	5.4
Brisbane	4.6	3.7	5.0
Melbourne	5.9	5.1	5.1
Hobart	5.9	5.3	4.9
Darwin	5.1	4.2	5.9
Sydney	5.2	4.1	5.1
Perth	4.9	3.9	5.1

Tables 5.6 and 5.7 show the total thermal loads for different roofing systems in different locations. For the purpose of investigation, the foil in House 2 was removed for the case study with a non-reflective roof (TSR = 0.1) containing insulation with an expected thermal resistance of R4. Hobart has limited cooling and is dominated by heating, showing that radiation-reflecting roofing and foil are inappropriate for this climate, and that what is more critical is having effective bulk insulation. Although the majority of homes in Darwin and Brisbane will continue to have light-coloured roofs and have a high TSR, the significant impact of ignoring the TSR cannot be overstated. For both houses in Darwin, an increase of 15% occurred between the expected and more likely roof scenarios. However, it should be noted that latent cooling in Darwin represents 50% of the cooling requirements, which means that any design measure will equally have a smaller impact and, therefore, such an increase could be argued to be relatively significant. Applying a roof with TSR = 0.9 and foil achieved a reduction in the load by 24% (average across both houses), and reduced the load to below the original expected load.

Table 5.6: AccuRate thermal energy data of House 1 with different thermal characteristics of the roof

Location	Annual thermal energy for each roof type, MJ			
		R3 without foil, TSR = 0.1 (expected)	R1.4 without foil, TSR = 0.1 (potentially more likely)	R1.4 with foil, TSR = 0.9 (potentially more likely)
Adelaide	Cooling	4830	6567	3530
	Total	11676	14772	12664
Brisbane	Cooling	2667	3401	2119
	Total	3616	4858	3463
Melbourne	Cooling	2181	2969	1526
	Total	15733	18524	18590
Hobart	Cooling	208	307	176
	Total	22409	25373	27715
Darwin	Cooling only	41214	47296	35464
Sydney	Cooling	2111	2947	1438
	Total	3622	5086	3772
Perth	Cooling	5197	7304	3478
	Total	8579	11794	8347

The results for Sydney and Brisbane were more dramatic due to the latent cooling requirements being significantly less. Between the ideal and the more likely scenario, an increase of cooling requirements of 39% and 28% was found, respectively, with a significant increase also in the total heating and cooling requirements. Applying a roof with TSR = 0.9 and foil achieved a reduction in cooling requirements of 49% and 38% for Sydney and Brisbane respectively, averaged across both houses. Furthermore, the more likely total heating and cooling requirements were 27% and 33% lower. In Adelaide and Perth, the increase in cooling requirements between what was expected and what was likely equated to 35% and 36% on average, respectively. Applying the heat flow reduction measures reduced cooling requirements in Adelaide by 44% and total requirements by 15% based on the most likely values. The values for Perth were 50% and 29% respectively, reflecting the greater significance of cooling in this city. In Melbourne, an average 34% increase in cooling requirements was determined when comparing the likely to the expected value. By applying foil and a roof with TSR = 0.1, a 46% reduction in cooling requirements was found: no change was determined in the total heating and cooling required, reflecting the dominance of heating in Melbourne.

Table 5.7: AccuRate thermal energy data of House 2 with different thermal characteristics of the roof

Location	Annual thermal energy for each roof type, MJ			
		R4 without foil, TSR = 0.1 (expected)	R1.6 without foil, TSR = 0.1 (potentially more likely)	R1.6 with foil, TSR = 0.9 (potentially more likely)
Adelaide	Cooling	10127	13448	7746
	Total	18063	23591	19840
Brisbane	Cooling	9000	11390	6875
	Total	10442	13709	9336
Melbourne	Cooling	4873	6424	3618
	Total	20850	25664	25716
Hobart	Cooling	905	1188	655
	Total	27665	32643	36653
Darwin	Cooling only	69524	79711	60801
Sydney	Cooling	6160	8490	4496
	Total	8349	11654	8429
Perth	Cooling	11682	15357	8185
	Total	15886	21309	15088

Overall, this analysis has demonstrated the significance of peak summer heat flow reduction measures through the roof. The results highlight how the cooling requirements can significantly vary depending on the actual thermal resistance of installed bulk insulation. The simulated measures would clearly limit the impact of this variation, significantly enhancing the reliability of the roof to mitigate against summer cooling. Furthermore, these measures would be likely to result in no increase in annual energy costs in the case of Melbourne, while energy cost savings for all other mainland cities could be achieved. These peak summer reduction measures are not applicable to Hobart, where cooling is a small component of heating and cooling requirements. Therefore, other measures for improving the reliability of bulk insulation in roofs were needed to achieve low heating requirements.

5.4 *Impact of Designs on A/C Electricity Demand*

Thermal loads translate to electrical energy consumption through the coefficient of performance (COP) of the air conditioner. To determine the corresponding electrical energy requirements of the measures previously presented, an analysis was applied to the energy data as provided by AccuRate. This analysis applied the COP as determined from the manufacturers’ data of a leading supplier of domestic air conditioners in Australia to determine the hourly electrical energy consumption of the air conditioner.

Figure 5.1 presents the COP as a function of the outdoor air temperature of a typical air conditioner based on the manufacturer’s data from a popular brand. These values will vary with different air conditioners depending on this star rating. The electricity consumption of an air conditioner is determined by a variety of other factors as discussed in the next section; therefore, this analysis is focused only on the impact of outdoor temperature. The figure contains different lines for each city, and this relates to the defined indoor thermostat setting as specified in AccuRate. The indoor air temperature also affects the COP. Overall, what the graph highlights is that during extreme conditions, the COP for heating is noticeably higher than the COP for cooling. Consequently, one unit of thermal energy required for heating in peak winter conditions requires less electrical energy than one unit of cooling energy during peak summer demand.

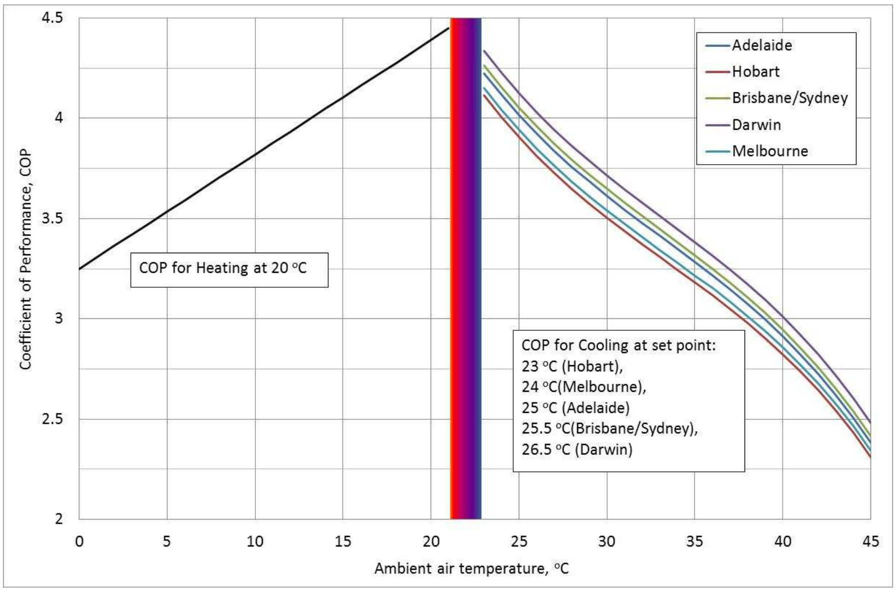


Figure 5.1: COP of a typical air conditioner as a function of outdoor air temperature at different indoor temperatures in different cities as per AccuRate set points

Overall, the graph also shows a reduction of the COP with increasing differences between the outdoor temperature and the indoor temperature, which translates to increased electricity consumption. Most Australian cities experience the peak demand in summer. As a consequence, this is the period when the air conditioner operates at its lowest performance. This issue is generally ignored in energy-efficiency ratings of buildings. Tables 5.8 and 5.9 show the electrical energy consumption of the air conditioner which corresponds to the data from Tables 5.6 and 5.7 for Houses 1 and 2, respectively.

Overall the annual electrical energy shows similar results and confirms the value of summer heat flow reduction measures. However, the impact on the more likely total heating and cooling savings is somewhat different to the values of the total reduction in heating and cooling energy requirements. In Adelaide, total savings are greater than the 15% reduction in total heating and cooling requirements, increasing to 22%. In Perth, the saving increases from 29% to 34%. In Sydney, the value increased to 30%. In Melbourne, rather than having no change, a saving of 4% was determined. In Brisbane, the saving was lower than that determined by the total heating and cooling requirements at 30%. In Darwin, the reduction in electrical demand was 24%, equal to the reduction in total cooling requirements. These electrical energy savings directly relate to achievable cost savings for heating and cooling. As expected, Hobart experiences a 10% increase in electrical energy consumption applying the heat flow reduction measures.

Table 5.8: House 1, annual electrical energy consumption of air conditioner for different roof configurations

Location	Annual electrical energy of each roof type, kWhrs			
		R3 without foil, TSR = 0.1 (expected)	R1.4 without foil, TSR = 0.1 (potentially more likely)	R1.4 with foil, TSR = 0.9 (potentially more likely)
Adelaide	Cooling	543	740	393
	Total	1036	1331	1049
Brisbane	Cooling	261	327	220
	Total	330	433	317
Melbourne	Cooling	233	317	162
	Total	1207	1436	1384
Hobart	Cooling	23	33	19
	Total	1657	1879	2036
Darwin	Cooling only	4042	4655	3488
Sydney	Cooling	203	277	147
	Total	311	433	313
Perth	Cooling	652	896	450
	Total	895	1218	798

The variation between energy and electrical energy savings can be best explained by analysing the annual COP of the air conditioner. Tables 5.10 and 5.11 show the annual COP based on the total thermal requirements and total electrical energy needed. The result represents the average COP of the air conditioner. As a result, locations requiring considerable heating have higher COP values than those requiring considerable cooling. The increased energy savings in Adelaide, Perth, Sydney and Melbourne reflect how heating can be done significantly more efficiently than cooling, dampening the increase in heating requirements produced by the heat flow reduction measures.

Table 5.9: House 2, annual electrical energy consumption of air conditioner for different roof configurations

Location	Annual electrical energy of each roof type, kWhrs			
		R4 without foil, TSR = 0.1 (expected)	R1.6 without foil, TSR = 0.1 (potentially more likely)	R1.6 with foil, TSR = 0.9 (potentially more likely)
Adelaide	Cooling	1102	1474	837
	Total	1674	2205	1703
Brisbane	Cooling	798	1018	621
	Total	901	1184	796
Melbourne	Cooling	495	663	362
	Total	1646	2049	1945
Hobart	Cooling	87	116	63
	Total	2060	2437	2701
Darwin	Cooling only	6731	7738	5931
Sydney	Cooling	552	769	402
	Total	708	994	680
Perth	Cooling	1405	1829	1005
	Total	1707	2255	1496

Table 5.10: House 1, annual coefficient of performance (COP) of air conditioner

Location	Annual coefficient of performance (COP) for each roof type			
		R3 without foil, TSR = 0.1 (expected)	R1.4 without foil, TSR = 0.1 (potentially more likely)	R1.4 with foil, TSR = 0.9 (potentially more likely)
Adelaide	Cooling	2.47	2.47	2.50
	Total	3.13	3.08	3.35
Brisbane	Cooling	2.84	2.89	2.67
	Total	3.05	3.12	3.03
Melbourne	Cooling	2.60	2.60	2.62
	Total	3.62	3.58	3.73
Hobart	Cooling	2.52	2.56	2.55
	Total	3.76	3.75	3.78
Darwin	Cooling only	2.83	2.82	2.82
Sydney	Cooling	2.25	2.92	2.71
	Total	3.23	3.26	3.35
Perth	Cooling	2.21	2.27	2.15
	Total	2.66	2.69	2.91

Table 5.11: House 2, annual coefficient of performance (COP) of air conditioner

Location	Annual coefficient of performance (COP) for each roof type			
		R4 without foil, TSR = 0.1 (expected)	R1.6 without foil, TSR = 0.1 (potentially more likely)	R1.6 with foil, TSR = 0.9 (potentially more likely)
Adelaide	Cooling	2.55	2.53	2.57
	Total	3.00	2.97	3.24
Brisbane	Cooling	3.13	3.11	3.08
	Total	3.22	3.22	3.26
Melbourne	Cooling	2.73	2.69	2.77
	Total	3.52	3.48	3.67
Hobart	Cooling	2.88	2.83	2.87
	Total	3.73	3.72	3.77
Darwin	Cooling only	2.87	2.86	2.85
Sydney	Cooling	3.10	3.07	3.10
	Total	3.27	3.26	3.44
Perth	Cooling	2.31	2.33	2.26
	Total	2.59	2.62	2.80

5.5 *Impact of Designs on Peak A/C Demand*

Using the energy data from AccuRate, it is possible to estimate the peak load requirements. AccuRate determines the thermal load hourly. However, these hourly loads are often very high as it is assumed that the capacity of the cooling equipment is infinite. As a result, the load data was evaluated based on a 3-hour running average which is more representative of the capacity of cooling equipment.

Tables 5.12 and 5.13 show the peak cooling thermal load and corresponding electrical load of the air conditioner, for each configuration. Overall, the impact of the roof configuration is similar to that of the annual energy requirements and electrical energy usage. Of particular interest is how the peak cooling demand for Hobart is greater than Sydney or Brisbane which highlights how Hobart can experience a short but relatively more severe summer. The increase in electrical peak demand comparing the expected to the more likely thermal resistance of the roof is most significant in Melbourne, at 26%, and least significant in Brisbane at 12%, averaging the result across both houses. The decrease that can be achieved applying the heat flow reduction measures based on the most likely thermal resistance of the roof, is maximum in Melbourne at 37% and minimum in Adelaide at 19%, with Sydney, Brisbane, Perth and Hobart achieving a reduction of 28%, 21%, 28% and 29% respectively.

Table 5.12: House 1, peak demand for each roof configuration

Location	Peak demand, kW	R3 without foil, TSR = 0.1 (expected)	R1.4 without foil, TSR = 0.1 (potentially more likely)	R1.4 with foil, TSR = 0.9 (potentially more likely)
Adelaide	Thermal	6.75	7.55	6.51
	Electrical	2.90	3.33	2.77
Brisbane	Thermal	3.36	3.86	2.36
	Electrical	1.17	1.33	1.00
Melbourne	Thermal	5.00	5.81	3.64
	Electrical	2.04	2.40	1.56
Hobart	Thermal	3.77	4.61	3.33
	Electrical	1.69	2.07	1.49
	Electrical	5.94	6.81	5.36
Sydney	Thermal	2.06	2.39	1.83
	Electrical	4.67	5.36	3.67
Perth	Thermal	1.86	2.17	1.64
	Electrical	6.08	7.03	5.28

The significance of the reductions in peak power demand can be considered in context of the growth in peak power demand. As discussed in Section 5.10, across Australia on average, 38% of peak power demand is attributable to air conditioning, and peak demand is forecast to increase 1–2.5% per annum. If it is assumed that half the houses in Adelaide Melbourne, Sydney and Perth have a TSR = 0.1, applying the heat flow reductions in which foil is added and the TSR of the roof is increased to 0.9, is equivalent to a reduction in the total peak power demand of 0.34%, 0.67%, 0.57% and 0.5% per annum in these cities, respectively. Applying these reductions from each city to the respective state, this reduction is equivalent to an estimated network capacity of 0.21, 1.3, 1.7 and 0.41 GW of electricity for each state, respectively. Homes in Darwin and Brisbane traditionally already have a high TSR. However if current trends continue such that the average TSR decreases, then over time, similar increases can be expected.

Table 5.13: House 2, peak demand for each roof configuration.

Location	Peak demand, kW	R4 without foil, TSR = 0.1 (expected)	R1.6 without foil, TSR = 0.1 (potentially more likely)	R1.6 with foil, TSR = 0.9 (potentially more likely)
Adelaide	Thermal	10.89	12.72	10.19
	Electrical	4.66	5.50	4.35
Brisbane	Thermal	6.44	6.72	5.33
	Electrical	1.97	2.17	1.81
Melbourne	Thermal	8.05	10.63	6.60
	Electrical	3.34	4.46	2.71
Hobart	Thermal	6.74	8.09	5.72
	Electrical	2.88	3.48	2.43
	Electrical	8.97	10.39	8.38
Sydney	Thermal	3.19	3.75	2.86
	Electrical	7.56	8.72	6.06
Perth	Thermal	2.69	3.36	2.28
	Electrical	9.58	12.03	7.92

A further consideration is the impact of ducted air conditioning. Current trends suggest that by 2020, 90% of houses in SA and WA will have air conditioning, a large proportion of which will be ducted. The research conducted by Belusko (2012), has shown that upgrading the ducting could achieve an average reduction in electricity usage of 45%. Applying this factor to the increases based on the current proportion of ducted systems (Table 5.1), the annual peak power reduction rate increases to 0.46%/yr and 0.63%/yr for Adelaide and Perth respectively. Therefore simply applying standard heat flow reduction measures as well as upgrading to quality ducting can significantly reduce the peak demand growth rate. These data, and the corresponding estimated reduction in network capacity are summarised in Table 5.16.

The sizing of air conditioners is a critical factor which affects peak electricity demand from air conditioners. Tables 5.14 and 5.15 presents the average design cooling load based on the thermal load averaged from each house. The recommended residential design load used in the air conditioning industry for Adelaide and Melbourne before the implementation of 5 star regulations was 120 W/m^2 (AIRAH 2007). In SA cooling load requirements applied by air conditioning retailers varies from 120 to 250 W/m^2. In contrast commercial buildings, which have specifically engineered air conditioning systems are sized to 150 W/m^2. These values contradict the expectation that with higher star rating houses, cooling demand should be reduced. By considering the 45% increase in demand that poor ducting can deliver, it can be seen that a significant portion of the sizing is related to additional heat flow through the roof and poor ducting.

Table 5.14: House 1, peak cooling load (W/m^2) based on living zone for each roof configuration

Location	R3 without foil, TSR = 0.1	R1.4 without foil, TSR = 0.1	R1.4 with foil, TSR = 0.9
Adelaide	121	136	117
Brisbane	60	69	42
Melbourne	90	105	65
Hobart	68	83	60
Darwin	107	122	96
Sydney	84	96	66
Perth	109	126	95

Table 5.15: House 2, peak cooling load (W/m^2) based on living zone for each roof configuration

Location	R4 without foil, TSR = 0.1	R1.6 without foil, TSR = 0.1	R1.6 with foil, TSR = 0.9
Adelaide	108	126	101
Brisbane	64	67	53
Melbourne	80	105	65
Hobart	67	80	57
Darwin	89	103	83
Sydney	75	86	60
Perth	95	119	78

A demonstration of these issues was implemented in Lochiel Park. Sizing of air conditioners was limited to 90 W/m^2, and foil and radiation reflecting roofing was recommended and widely adopted. Furthermore either multi head split systems or appropriate ducted systems were installed. These features were complemented by the

7.5 star rating requirement which ensured an efficiently designed building. As presented in Section 5.7, the peak power demand from air conditioning was well within this design limit, and average temperatures within the building during peak periods was well within thermal comfort conditions, as shown in Chapter 3.

Appropriate sizing of air conditioners for houses is currently being developed through an Australian Standard. The standard will apply appropriate methodologies as expressed in general engineering practice, sizing the system on the expected load of the house being planned. Adoption of this standard would prevent oversized air conditioners from being installed in homes.

Table 5.16 Summary of reduction in demand for various measures applicable to new and existing houses with air conditioning systems, implemented 2012–2030

	Demand reduction (annual peak reduction to 2030)			Demand reduction (GW)		
	TSR = 0.9, Foil (50% of homes)	TSR = 0.9, foil (50% of homes), improved ducting (all systems)	Adaptive comfort (80% systems)	TSR = 0.9, Foil (50% of homes)	TSR = 0.9, foil (50% of homes), improved ducting (all systems)	Adaptive comfort (80% systems)
SA	0.19%	0.42%	0.41%	0.21	0.34	0.3
Vic	0.36%	n/a	0.73%	1.34	n/a	1.9
NSW	0.31%	n/a	n/a	1.60	n/a	n/a
WA	0.27%	0.54%	n/a	0.41	0.61	n/a
Qld	n/a	n/a	0.75%	n/a	n/a	1.4

5.6 *Impact of Adaptive Comfort*

The potential for occupants adapting to the increased outside temperatures in comfort evaluation has been investigated using AccuRate for House 2. Adaptive thermal comfort provides the basis by which room temperatures can be higher than traditionally expected as thermal comfort is linked to adapting to external conditions. To investigate the impact on the cooling energy and peak power electricity demand that adaptive comfort could achieve, AccuRate was used with adjusted set points. The current set points are based on a fixed temperature condition of around 25°C. The adaptive comfort model defines the set point with reference to the average monthly ambient temperature, and therefore can be higher during summer. According to ANSI/ASHRAE Standard 55-2010 based on the upper limit of the range of 80% acceptability the set point is defined by:

$$T_{st} = 0.31\, T_{mm} + 21.3 \qquad (5.1)$$

where T_{st} is the set point, and T_{mm} is the mean monthly temperature.

The set point was determined for each summer month and found to only slightly vary. Therefore an average was taken and a fixed set point was applied in summer. Table 5.17 shows the current set points used in AccuRate and the set point based on adaptive comfort. These set points were applied to the typical roof configuration for House 2, in Adelaide, Brisbane and Melbourne, applying expected roof insulation thermal resistance. Table 5.18 presents the results determined for summer only, which, across the three cities load in summer represents 74%–80% of the total cooling thermal requirement. With adaptive comfort over summer the reduction in cooling electricity usage ranged from 68%–82%. Furthermore the reduction in peak electricity demand was 27%, 48% and 50% for Adelaide, Melbourne and Brisbane respectively. Therefore adaptive comfort represents a significant opportunity to offset future increases in cooling requirements. As a result if 80% of the houses in Adelaide, Melbourne and Brisbane applied this form of adaptation by 2030, this could achieve a peak demand reduction rate of 0.41%, 0.73% and 0.75% per annum. The impact on the required network capacity is presented in Table 5.16.

Table 5.17: Thermostat settings for summer applying adaptive comfort model

Location	Current set point used in AccuRate	Adaptive comfort set point
Adelaide	25.0	28.4
Melbourne	24.0	27.5
Brisbane	25.5	28.9

Adaptive comfort has generally related to unconditioned buildings and is currently applied in commercial buildings in which the set point can be controlled. The applicability of adaptive comfort in a residential air-conditioned home can only occur if the air conditioner is not able to achieve lower temperatures. Consequently, effective measures are needed to support positive adaptive comfort, whereas in the absence of these measures, there is a significant risk of negative adaptive comfort which actually raises comfort expectation and subsequent peak electricity demand.

Adaptive comfort can be directly applied in homes through two mechanisms, regulation of the sizing of air conditioning and smart grid control. Appropriate sizing through the use of the proposed Australian Standard, would prevent the shift to increased ‘air conditioning addiction’ resulting in lower temperatures within the home. The application of smart grid control is capable of either switching the air conditioner off for a few minutes or adjusting set points higher. In either case, room temperatures will increase. This smart grid approach can take advantage of adaptive comfort principles during extreme hot weather. Being applicable to the majority of the population, significant reductions in peak demand can be achieved, and can offset peak demand growth resulting from climate change.

Table 5.18: Summer results for House 2 applying adaptive comfort to typical roof arrangements with assumed roof R value

Location		Conventional Cooling	Adaptive Comfort
Adelaide	Thermal total, MJ	7513	2320
(R4, dark roof, no foil)	Electrical total, kWhrs	823	254
	Peak electrical, kW	4.7	3.4
Melbourne	Thermal total, MJ	4092	912
(R4, dark roof, no foil)	Electrical total, kWhrs	417	88
	Peak electrical, kW	3.3	1.7
Brisbane	Thermal total, MJ	5451	944
(R4, light roof, no foil)	Electrical total, kWhrs	782	138
	Peak electrical, kW	2.8	1.4

5.7 *Measured Air Conditioning Usage In Houses*

To investigate the actual energy used for cooling in homes as well as the peak power demand, a national monitoring program has been conducted. 16 homes in Adelaide, 15 in Brisbane and 20 in Sydney have been allocated for monitoring during the summer. Apart from the Sydney homes, all these homes are monitored alongside the comfort study presented in Chapter 3. Specifically in Adelaide, the 16 houses are part of the Lochiel Park development, 6 dwellings are typical detached houses, while the remaining 10 are low income units. In Brisbane 15 homes were found within Springfield Lakes, a new housing development. In Sydney 20 homes were found in the suburbs surrounding Beecroft.

As of the conclusion of this project, data from the six detached houses in Lochiel Park were available. To provide further analysis for Adelaide, previously monitored data from Mawson Lakes, a 10-year old development was included in this study. In Brisbane, 9 homes have had the air conditioning power monitoring fully commissioned. In Sydney 10 conventional homes have power monitoring, and a summary of these homes is presented in Table 5.19.

The Lochiel Park (LP) green village located in Adelaide, aims to reduce total energy and peak demand from the houses (Saman et al. 2011). All houses have a 7.5 minimum star rating. Strong recommendations were made to use radiation reflecting roofing and the use of foils in roofs. Furthermore, strict controls were placed on the selection of air conditioning, limiting the size to a design load of 90 W/m^2. Either high efficiency multi-head split systems or appropriate ducted systems were allowed for refrigeration cooling.

A year of monitored data is now available for total electricity usage for 22 typical detached homes which have refrigeration air conditioning, from July 2011 to Jun 2012. In addition the energy used for air conditioning, the air conditioning usage patterns and indoor temperatures were also monitored for 6 homes. 3 of these homes contained multi-head split systems and the other 3 contained a reverse cycle ducted system. Figure 5.2 shows the monthly total electricity usage of all 22 monitored homes with the monthly standard deviation, together with the average of the 6 homes. The data shows that the 6 homes are reasonably representative of the 22 homes.

Table 5.19: Summary of Sydney homes with A/C power monitoring

House No.	No. of Residents	Income	House Age	No. of Levels	No. of Bedrooms	House Type	A/C type
1	4	$110,000+	17	3	3	fibro cement	2 x split systems
2	3	$110,000+	30	2	4	brick veneer	Single split system
3	5	$110,000+	39	2	5	brick veneer	Single split system
4	3	$110,000+	52	2	3	double brick	Single split system
5	3	$110,000+	73	2	3	Double brick/brick veneer	2 x split systems
6	2	$110,000+	22	4	4	Brick veneer	Single split system
7	4	$110,000+	18	2	4	brick veneer	Ducted Reverse cycle
8	3	$110,000+	52	1	2	brick veneer	Single split system
9	4	$30–40,000	14	1	5	double brick	Ducted Reverse cycle
10	4	$110,000+	42	3	5	brick veneer	Ducted Reverse cycle

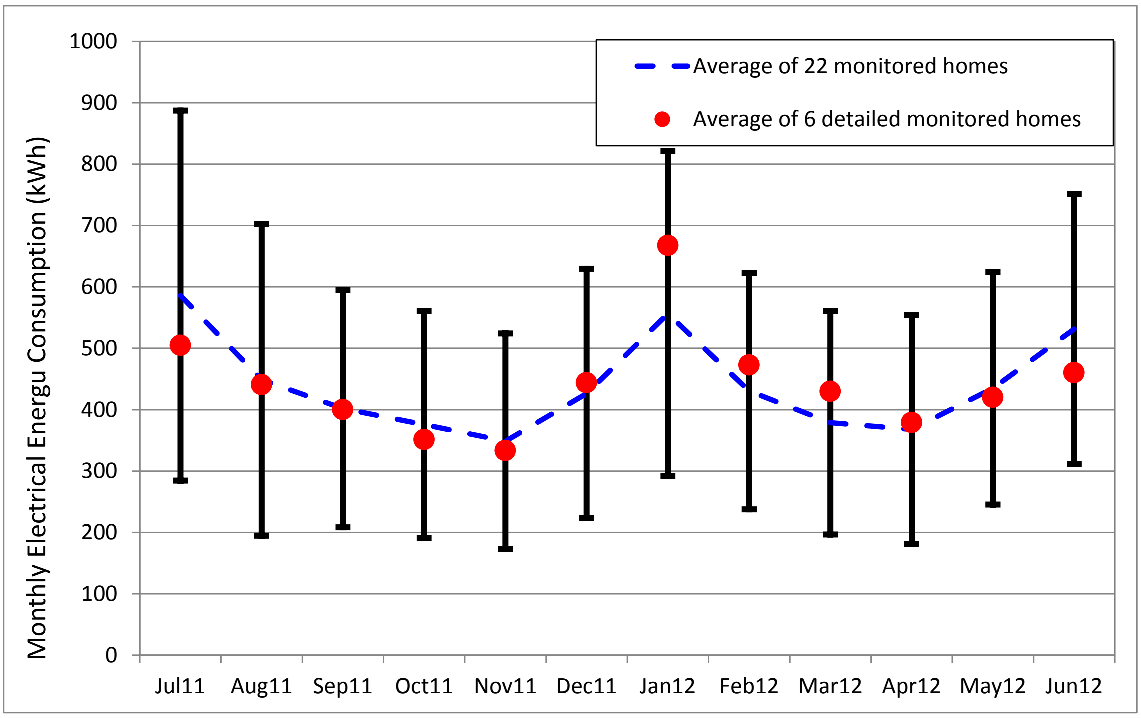


Figure 5.2: Total monthly electricity consumption of detailed homes with respect to all monitored homes in Lochiel Park

Table 5.20 shows the average cooling electricity usage of the 6 monitored houses for the summers of 2010/11 and 2011/12. The electricity usage can be compared to a study conducted in Mawson Lakes, a 10-year-old suburb in Adelaide. The study monitored the electricity usage of heating and cooling in 6 homes, of similar floor area to Lochiel Park, in a 3 star housing development (Saman & Mudge 2003). Overall, the electricity usage for cooling is considerably lower at 44% than that measured in Mawson Lakes. This demonstrates the benefits of the design options investigated.

Figures 5.3 and 5.4 show the representative peak electrical demand from the houses in Lochiel Park and Mawson Lakes as a function of the daily maximum ambient temperature of Adelaide. The analysis is based on identifying the daily peak air conditioning demand and corresponding total demand for a given day. The data from all the homes is subsequently averaged for each corresponding day. The graphs demonstrate how air conditioning is the dominant peak electrical demand for the household. At 40^{o}C the air conditioner represented 79% and 72% of the total household electrical demand at Lochiel Park and Mawson Lakes respectively. At 40^{o}C, the peak power electrical demand from Lochiel Park was measured at 3.8 kW vs 5.3 kW from Mawson Lakes, a reduction of 28%. This reduction demonstrates the effectiveness of the design options presented. From this demand and based on the conditioned floor area, the estimated cooling load was found to be less than 90 W/m^{2}. The average room temperature during peak conditions was found to be within accepted thermal comfort requirements. Therefore it can be assumed that the air conditioners were adequately sized and provided sufficient cooling to the households.

Table 5.20: Summary of two years of monitored data for six Lochiel Park houses

House	A/C type	A/C total electricity, kWhrs	A/C fraction of total electricity	A/C cooling electricity, kWhrs	Cooling fraction of A/C
L2OZ	Ducted	647	17%	261	40%
L3TS	Ducted	1122	26%	764	68%
L4FO	Ducted	1184	16%	906	77%
L6FS	Multi-split	1285	35%	218	17%
L26ST	Multi-split	1333	18%	678	51%
L23SS	Multi-split	1895	29%	576	30%
Average of Lochiel Park		1244	24%	567	47%
Average of Mawson Lakes		2336	28%	1278	55%

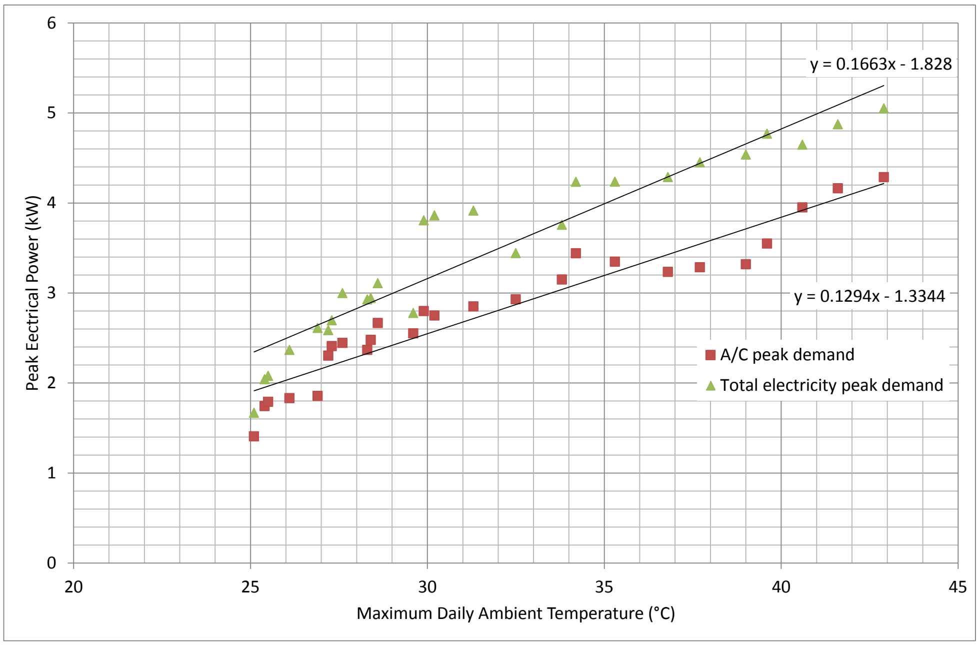


Figure 5.3: Average peak demand from six monitored houses at Lochiel Park compared to daily maximum temperature

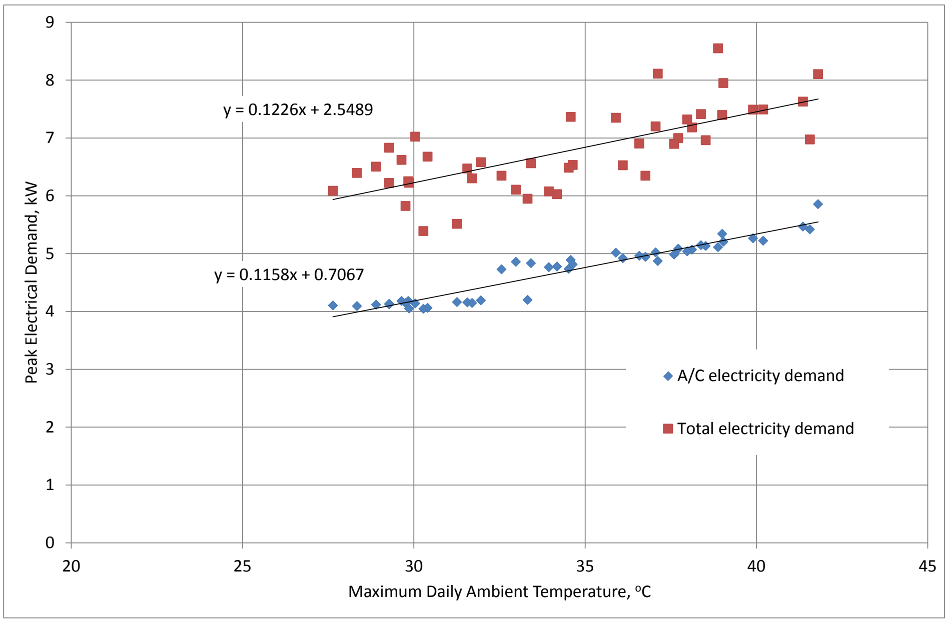


Figure 5.4: Average peak demand from six monitored houses at Mawson Lakes, Adelaide compared to daily maximum temperature

Figures 5.5 and 5.6 present the peak demand from the measured data taken from Sydney and Brisbane in this study, averaged across the homes for each day, as completed for Adelaide. Only data from Dec 2012–Jan 2013 were available for this study. Furthermore, only data for a few homes were suitable for analysis. The data for Brisbane considered six homes, all with split systems, as presented in Chapter 3. In Sydney only 2 houses had suitable data, and therefore the data presented can only be indicative. However the data included the hot day of 18 Jan 2013 when the maximum temperature reached 45.8°C. This data may not include the maximum total peak as this may not coincide with the peak from air conditioning. This difference can be due to other appliances and in the case of Sydney hot water was a major factor. Electric hot water demand was also measured in some of the homes, and it was identified that demand was occurring during peak air conditioning. Hot water demand is reflected in Figure 5.6 in the total demand value of 6.9 kW on the extreme hot day.

From the data measured, it is possible to determine the most likely time for peak air conditioning demand at extreme temperatures. However, due to the small data set, peak demand occurred over a wide range. From Lochiel Park, peak demand ranged from 1–5.30 p.m. with the typical peak demand occurring at 3 p.m. In Brisbane, the typical demand was at 4.30 p.m. ranging from 2–6.30 p.m. For Sydney, peak demand ranged from 4.30–5.30 p.m.

Overall the data across all cities is consistent, showing an increasing total and air conditioning peak demand with outdoor temperature. Furthermore, the data shows that air conditioning is the dominant peak electricity demand across all temperatures in all regions. Interestingly, ignoring Sydney, the increase in peak air conditioning demand, as reflected in the gradient of the line, is lowest in Mawson Lakes and greater in Lochiel Park and Brisbane. This highlights that with more energy-efficient housing, the peak to average demand from air conditioning increases. This factor is also greater in Brisbane due to the impact of humidity which results in a significant rise in cooling demand with temperature rise. This factor is not apparent in the Sydney data due to the low sample size.

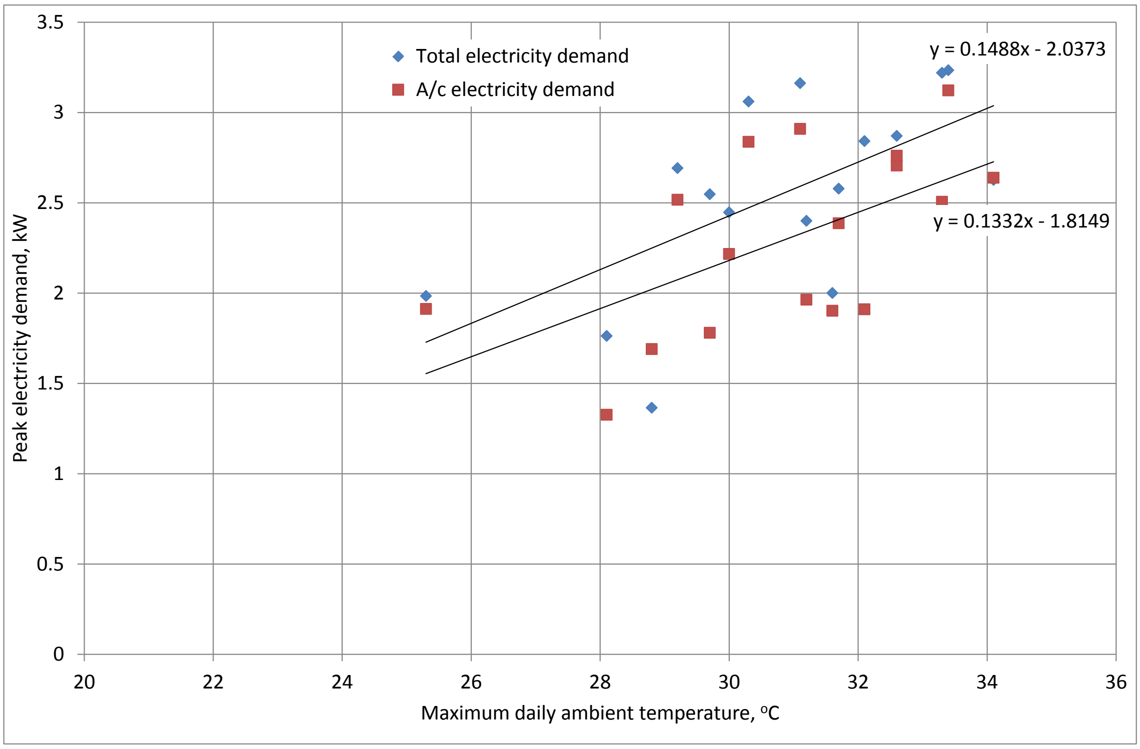


Figure 5.5: Average peak demand from six monitored houses in Brisbane compared to daily maximum temperature

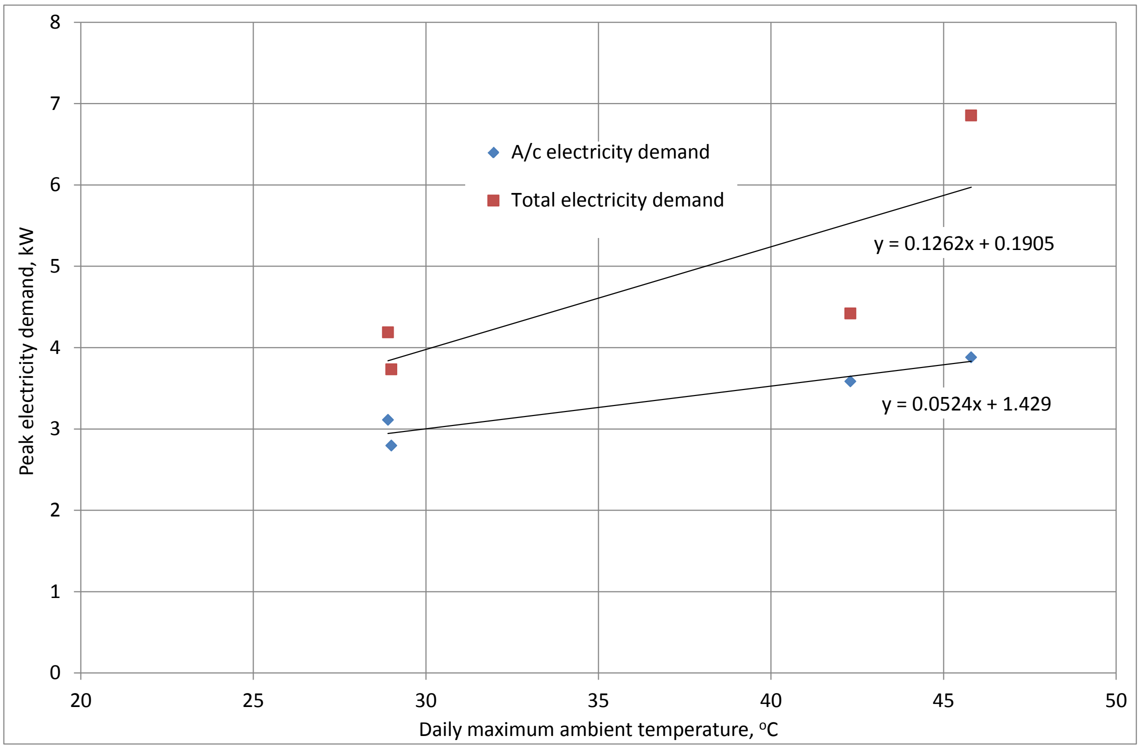


Figure 5.6: Average peak demand from two monitored houses in Sydney compared to daily maximum temperature

5.8 *Impact of Climate Change on Building Heating and Cooling Requirements*

The impact of anticipated climate change has been investigated using AccuRate for House 2. Applying the future TMY data developed in Section 2.1.7, it is possible to determine the likely increase in cooling energy requirements, electricity requirements and peak power demand. Tables 5.21–5.27 show the results for each city based on the typical TSR used in that city and applying the most likely thermal resistance of the insulated roof and not applying foil. The data shows the calculated thermal energy requirements for 2030 and 2070 using TMY of these years, and interpolates 2050 data.

Overall, the data reflects the warming across the country, with cooling thermal energy representing a larger portion of the total heating and cooling requirements. The cooling requirements for Adelaide change from representing half the total requirements today, to dominating the air conditioning needs with 79% of the heating and cooling requirements by 2050. In Perth cooling goes from 72% to 89% of total heating and cooling demand. In Melbourne, cooling goes from a small current need to 48% of total heating and cooling requirements by 2050. For Sydney and Brisbane, cooling represents more than 90% of heating and cooling requirements by 2050.

The total heating and cooling requirements generally increase with time for most cities. Dramatic increases occur in Sydney and Brisbane, with requirements increasing by 75% and 92% by 2050, respectively. Due to the drop in heating requirements, Adelaide experiences little change in total requirements, whereas Perth experiences a small increase, and Melbourne experiences a small decrease in heating and cooling requirements. As a result of reduced heating demand, the warming climate will likely significantly reduce the total heating and cooling requirements in Hobart with an estimated reduction of 32% by 2050. Darwin is likely to experience a significant increase in cooling requirements, going up by 51% by 2050.

Table 5.21: Impact of climate change in Adelaide on annual energy demand; House 2, TSR = 0.1, likely R = 1.6, no foil

	Current TMY	TMY2030	2050 est.	TMY2070
Cooling thermal, MJ	13448	16314	18706	21097
Total thermal, MJ	23591	22375	23792	25209
Peak cooling thermal, kW	12.7	12.4	12.7	13.0
Cooling electrical, MJ	5305	6438	7286	8133
Total electrical, MJ	7936	7993	8587	9180
Peak cooling electrical, kW	5.5	5.5	5.7	5.9
Annual COP	2.97	2.80	2.77	2.75
Peak COP	2.31	2.25	2.23	2.22

Peak cooling requirements generally increase in the cities shown. The most dramatic increases occur in Sydney and Brisbane. The significant increase in Hobart relates to the low current value. Interestingly Darwin, Adelaide, Melbourne and Perth experience small increases in peak cooling energy requirements. This can be attributed to these cities already experiencing extreme temperatures. As a result the increase in maximum temperatures expected with climate change in these cities, relative to the existing extreme temperatures is less significant than in other locations.

In summary, the results confirm that most of continental Australia will require cooling and heating will assume less significance in domestic heating and cooling requirements. Most cities will likely experience a total increase in heating and cooling demand, with decreases occurring in southern Australia where heating is dominant. Peak cooling requirements are likely to increase across the country.

Table 5.22: Impact of climate change in Brisbane on annual energy demand; House 2, TSR = 0.9, likely R = 1.6, no foil

	Current TMY	TMY2030	2050 est.	TMY2070
Cooling thermal, MJ	7105	10920	17476	24032
Total thermal, MJ	10110	13883	19379	24874
Peak cooling thermal, kW	5.1	7.2	7.6	8.1
Cooling electrical, MJ	2295	4188	6480	8773
Total electrical, MJ	3064	4933	6960	8988
Peak cooling electrical, kW	1.7	2.4	2.7	3.0
Annual COP	3.30	2.81	2.78	2.77
Peak COP	2.97	2.93	2.80	2.69

Table 5.23: Impact of climate change in Melbourne on annual energy demand; House 2, TSR = 0.1, likely R = 1.6, no foil

	Current TMY	TMY2030	2050 est.	TMY2070
Cooling thermal, MJ	6424	8961	10593	12225
Total thermal, MJ	25664	21956	21948	21940
Peak cooling thermal, kW	10.6	9.7	10.3	10.9
Cooling electrical, MJ	2387	3962	4772	5583
Total electrical, MJ	7375	7293	7674	8056
Peak cooling electrical, kW	4.5	4.7	5.0	5.4
Annual COP	3.48	3.01	2.86	2.72
Peak COP	2.38	2.07	2.05	2.03

Table 5.24: Impact of climate change in Hobart on annual energy demand; House 2, TSR = 0.1, likely R = 1.6, no foil

	Current TMY	TMY2030	2050 est.	TMY2070
Cooling thermal, MJ	692	1872	2217	2562
Total thermal, MJ	38780	27912	26505	25097
Peak cooling thermal, kW	6.0	7.9	8.1	8.3
Cooling electrical, MJ	244	758	913	1068
Total electrical, MJ	10291	7621	7300	6978
Peak cooling electrical, kW	2.6	3.8	4.0	4.1
Annual COP	3.77	3.66	3.63	3.60
Peak COP	2.32	2.07	2.05	2.03

Table 5.25 Impact of climate change in Sydney on annual energy demand; House 2, TSR = 0.1, likely R = 1.6, no foil

	Current TMY	TMY2030	2050 est.	TMY2070
Cooling thermal, MJ	8490	15753	19148	22543
Total thermal, MJ	11654	17233	20367	23500
Peak cooling thermal, kW	8.7	10.4	10.5	10.6
Cooling electrical, MJ	2767	7420	9272	11125
Total electrical, MJ	3577	7796	9581	11367
Peak cooling electrical, kW	3.4	4.8	5.0	5.2
Annual COP	3.26	2.21	2.13	2.07
Peak COP	2.60	2.17	2.10	2.04

Table 5.26: Impact of climate change in Perth on annual energy demand; House 2, TSR = 0.1, likely R = 1.6, no foil

	Current TMY	TMY2030	2050 est.	TMY2070
Cooling thermal, MJ	15357	18731	21955	25178
Total thermal, MJ	21309	21826	24542	27259
Peak cooling thermal, kW	12.0	11.6	12.1	12.5
Cooling electrical, MJ	6583	8084	9730	11377
Total electrical, MJ	8119	8877	10392	11907
Peak cooling electrical, kW	5.8	5.8	6.2	6.6
Annual COP	2.62	2.46	2.36	2.29
Peak COP	2.08	2.00	1.95	1.91

Table 5.27: Impact of climate change in Darwin on annual energy demand; House 2, TSR = 0.9, likely R = 1.6, no foil

	Current TMY	TMY2030	2050 est.	TMY2070
Cooling thermal, MJ	62007	80129	93689	107249
Total thermal, MJ	62007	80129	93689	107249
Peak cooling thermal, kW	8.3	9.8	10.7	11.6
Cooling electrical, MJ	21796	27163	32787	38411
Total electrical, MJ	21796	27163	32787	38411
Peak cooling electrical, kW	2.9	3.1	3.5	3.9
Annual COP	2.84	2.95	2.86	2.79
Peak COP	2.83	3.20	3.06	2.95

5.9 *Impact of Climate Change on Energy Costs*

Heating and cooling costs are determined by the total electricity usage of air conditioners. The overall trend with climate change is similar to the trend in heating and cooling requirements of the building, which shows that for most of Australia, refrigeration-based air conditioning will predominantly be used for cooling.

The modelled data should not be used to directly estimate running costs as actual costs are strongly dependent on household behaviour and the actual performance of individual buildings. However, the modelled data can provide useful relative changes in heating and cooling costs. Based on no change in electricity prices, in 2030, total costs in Melbourne and Adelaide are likely to remain unchanged with Perth showing a 9% increase, and Hobart showing a 26% decrease. In Sydney, Brisbane and Darwin an increase is costs of 118%, 61% and 25% respectively is anticipated. This data reflects how the warming climate will reduce heating demand and increase cooling demand. Again, based on no changes to electricity prices, relative to today, potential increases in running costs of 4%, 8%, 28%, 168%, 127% and 50% in Melbourne, Adelaide, Perth, Sydney, Brisbane and Darwin are anticipated in 2050. Hobart can expect a 29% reduction in total costs by 2050.

These results generally show a dramatic increase in costs above what the increase in total heating and cooling requirements would indicate. This increase is due to cooling being generally more expensive then heating. Furthermore, more cooling is done at higher temperatures when the air conditioner is less efficient.

In all cities there is an increase in peak cooling electricity demand, above current levels, which ultimately will increase electricity prices. However, the data shows there is a shift in electricity demand from winter to summer, with most of the energy usage occurring over shorter time frame. Consequently, the capacity factor of electrical infrastructure will reduce even further as the ratio of peak to average demand increases. Although, it is difficult to predict what impact this shift will have on winter/summer electricity prices, it is possible that the overall saving in winter electricity usage may not result in an equivalent reduction in electricity costs.

Overall, climate change will increase electricity prices. Therefore for southern Australia energy costs will rise due to increased prices rather than increased usage. For Sydney and northern Australia, costs will rise due to both dramatic increases in usage as well as prices.

5.10 *Impact of Climate Change on Peak Power Demand*

With higher summer temperatures due to climate change, there is a corresponding increase in peak power demand that can be expected from air conditioning. The modelled and monitored data can be used to estimate the potential increase in peak power demand.

Across Australia, growth in peak power demand across the National Electricity Market is project to range from 1–2.5% per annum over the next 10 years (AEMO 2012a). In South Australia the predicted medium scenario for growth in peak power demand is 1% over the next 10 years (AEMO 2012b). Estimated total peak power demand for each region is presented in Table 5.28 as stated in reports by the Productivity Commission (PC, 2012b), for the NEM, Power and Water Authority (PW, 2013) for the NT, and Western Power (WP, 2013) for WA.

Table 5.28: Estimated total peak electricity demand, additional growth rates and additional estimated peak demand due to climate change

	Estimated Peak Demand (2012), GW			Total demand growth rate due to a/c		Climate change induced additional demand (GW)	
	Total	Residential	A/c	2030	2050	2030	2050
SA	3.1	1.6	1.1	0.01%	0.03%	0.01	0.04
Qld	8.8	3.5	3.17	0.71%	0.44%	1.3	1.8
Vic	10	5.0	3.6	0.10%	0.12%	0.19	0.47
NSW	14	7.0	5.7	0.81%	0.43%	2.4	2.8
WA	4.1	2.1	1.5	0.01%	0.06%	0.01	0.10
NT	0.62	0.25	0.22	0.07%	0.16%	0.01	0.04

It is well established that domestic air conditioning is the major driver behind peak power demand, representing the majority of residential demand during peak periods (PC, 2012b). In Sydney 50% of the peak demand is attributable to residential use (AGL, 2012). Residential electricity usage represents 50% of the peak power demand in South Australia (Charles River Associates, 2004), while this value is 40% for Queensland (Topp & Kulys 2012). Given the age of the homes monitored at Mawson Lakes and in Brisbane, they can be argued to be representative of typical homes. As shown in Figures 5.4 and 5.5, air conditioning in Adelaide and in Brisbane represents 72% and 90% of household electricity usage during peak times, respectively. Applying appropriate estimated proportions for each region, Table 5.28 shows the estimated aggregated demand for residential air conditioning for each region, showing how air conditioning is estimated to represent 41% of total demand in NSW and 36% of total demand for all other regions. Therefore, on average, air conditioning represents approximately 38% of total peak demand, across Australia.

The increase in peak electrical cooling demand is presented in Tables 5.21–5.27for Australia's capital cities. Applying these increases to the total peak demand in each state of each city, Table 5.28 presents the estimated additional network capacity necessary to meet this demand due to climate change. For cities which already experience extreme temperatures, the increase in peak demand to 2030 is marginal with Adelaide, Melbourne, Perth and Darwin experiencing increases in peak demand of less than 5%, representing a negligible impact on the total growth of peak power demand. The contribution to the total growth in peak demand to 2050 is 0.16% and 0.22% for Melbourne and Darwin respectively, with negligible contributions in Adelaide and Perth. These results are directly a function of the projected increases in maximum temperature presented in Section 2.2.3. Table 2.10 shows how the cities of Perth, Adelaide and Melbourne experience the least increase in maximum temperature. The increase in the maximum temperature for Darwin is not reflected in a corresponding increase in peak demand due to the significant latent cooling which exists in the baseline peak electricity demand.

The cities of Hobart, Sydney and Brisbane experience the most dramatic increase in peak cooling electricity demand. The increase in Hobart is due to the base value being very low, and is most likely well below the winter peak. In Sydney and Brisbane, however, the increase in demand is 43% and 42%, by 2030 and 53% and 58% by 2050 respectively. This increase is reflected in the fact that these cities experience large increases in maximum temperatures (Table 2.10). Furthermore, as reflecting in the design temperatures shown in Table 2.7, these temperatures are applied to lower typical maximum temperatures than for cities such as Adelaide and Melbourne. In relation to the contribution to growth in total peak electricity demand this translates to annual rates of 0.71% and 0.81% for Sydney and Brisbane to 2030, and 0.58% and

0.59% for Sydney and Brisbane to 2050, respectively, and is presented in Table 5.28. Relative to the projected growth of 1–2.5% per annum, these growth rates are significant.

These increases in peak demand are reflected in the measured data. Section 5.7 shows how in all cities an increase in daily maximum temperature results in increased peak electricity demand. Furthermore the results for Brisbane demonstrate how, the peak electricity demand increases more per degrees Celsius in the daily maximum, than for Adelaide.

The increase in peak power demand in all cities will put extra pressure on the electricity grid and are likely to result in further increases in electricity tariffs. This outcome reinforces the likelihood of increased electricity costs to households with the onset of climate change, particularly in Sydney and Brisbane.

5.11 *Thermal Performance Evaluation of Houses*

An important measure of the applicability of the star rating to the actual energy used for heating and cooling relates to the actual quality of the insulation installation, and the amount of air leakage within the home. Many jurisdictions in the EU already require thermographic and air leakage testing of all new buildings. Eleven of the homes in south-east Queensland and two of the Townsville homes (plus two display homes in Townsville) were subject to thermal imaging and air infiltration tests.

Thermal imaging was conducted according to EnergyLeaks Quickscan EL 1 utilising a FLIR E50bx camera. Air leakage testing was conducted using a Retrotec 2000 fan, and in accordance with the following standards:

- ATTMA TS1 Issue 2 – Measuring Air Permeability of Building Envelopes
- BS EN13829:2001 Thermal Performance of Buildings
- BINDT – Quality Procedures and Explanatory Notes for Air Tightness Testing

In general, conducting these tests revealed poor levels of housing documentation. Many occupants did not have copies of their house plans (building documents) despite all homes being relatively new (generally less than six years old), and only three households could provide a copy of the energy rating certificate for the house or provide information on the expected thermal performance of the house (e.g. the star rating). All of the 15 houses subjected to thermography had issues that would make them non-compliant (minor to serious) with the current building regulations and impact negatively on the thermal performance of the building. Common issues included:

- Poor perimeter coverage (typically 300–600 mm around perimeter of internal ceilings), with particularly poor coverage in the corners of hip roof designs. (Note: BCA requires that all insulation covers at least 40% of the external wall top plate to give the desired thermal coverage to suit the dwelling) (Figure 5.7a and b)
- Patchy (or absent) ceiling coverage in general (Figure 5.7 c and d)
- Entry hallways, utility rooms (e.g. bathrooms, toilets, laundry) and bulkheads often not insulated correctly (Note: BCA requires bulkheads to be insulated as per ceilings) (Figure 5.7 e)
- Poor insulation around downlights, exhaust fans, manhole covers (Figure 5.7f)
- Doors and windows are weak spots thermally (Figure 5.7g and h)
- Poor/absent insulation of adjoining garages (with shared roof space with living areas)

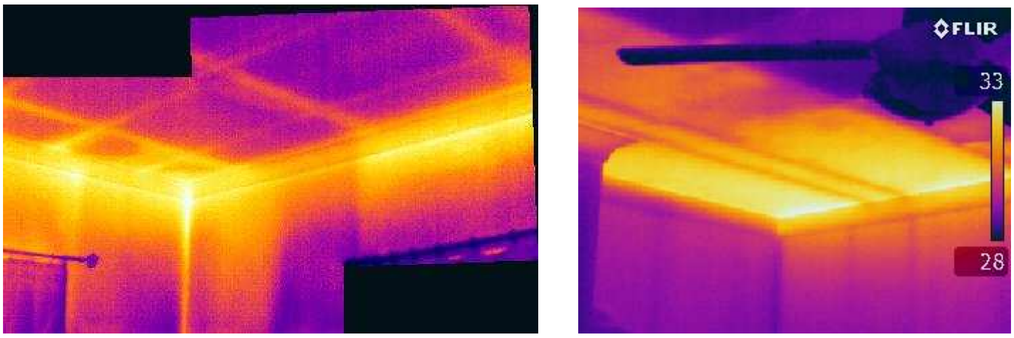


Fig (a): poor perimeter coverage

Fig (b): poor perimeter coverage

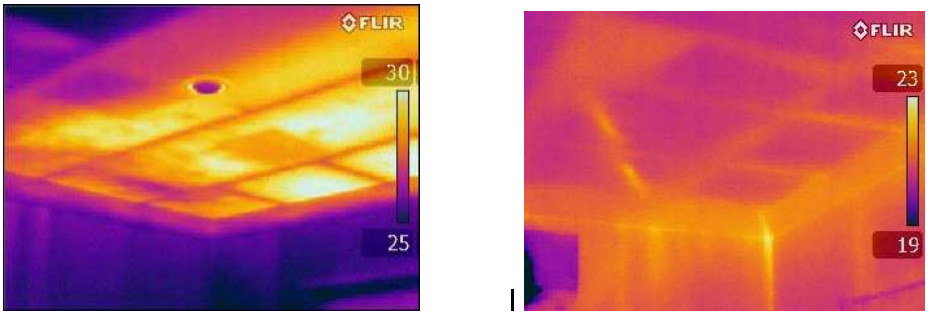


Fig (c): patchy ceiling coverage

Fig (d): patchy ceiling coverage

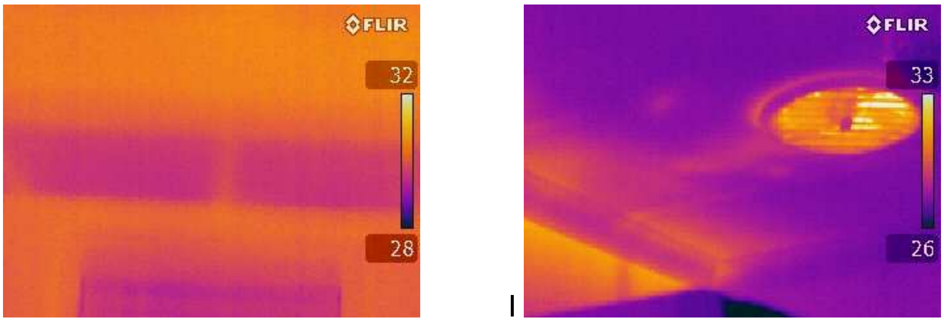


Fig (e): poor bulkhead insulation

Fig (f): absent draft stopper on vent

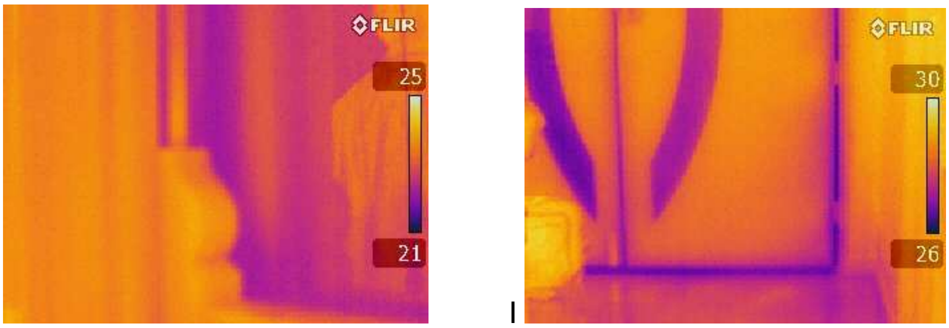


Fig (g): heat leakage around window frame

Fig (h): door leakage points

Figure 5.7: Typical thermal images showing gaps or missing insulation, and air leakage around doors and windows

Two of the homes revealed extensive and serious non-compliance issues that required house owners to seek restitution from the relevant builders (Figure 5.8).

Figure 5.8: Missing insulation as well as large air gaps around insulation, representing serious breaches of BCA regulations

Overall, these results show a significant inconsistency between expected and actual insulation installs. Consequently, without any quality control measures it is unreasonable to assume that the thermal resistance of roof spaces are as currently assumed.

5.12 *Conclusions*

The majority of homes in Australia have cooling equipment and this trend is likely to continue over time. In hot dry climates such as Adelaide, Perth and Melbourne, evaporative cooling is an effective and low cost provider of thermal comfort during heat waves. However, nationally, the dominant form of cooling equipment is reverse cycle air conditioning either as single split systems or ducted whole-of-house systems. Currently MEPS does not consider the performance of the whole of system efficiency in the case of ducted systems or the efficiency of evaporative systems. The separation of ducting thermal performance, which is in the BCA, and MEPS, has resulted in new systems being installed with ducting that is inferior to current regulations. In addition, no quality control assessment of ducting, can result in significant air leakage dramatically increasing energy consumption, particularly during peak periods. Currently, no consideration is given to the peak demand of inverter air conditioners, which can be significantly greater than the name plate due to its ‘hidden’ capacity.

NatHERS accredited software tools such as AccuRate, are very comprehensive and powerful building thermal models. Heat flow through the roof represents the dominant building load in peak summer. Assumed performance of insulated roof in these thermal models is unreliable, and research has shown that the thermal resistance or R value of the roofing system can be as low as half that of the R value of the bulk insulation. Analysis has shown that the increase in heating and cooling required by the building between the assumed and the potentially likely thermal resistance of the roof system was on average 34% across Australia. The application of roof heat flow reduction measures such as applying a high TSR roof and the use of foil in combination with the likely performance of insulation is able to deliver significant savings, reducing annual air conditioning electricity consumption by 18% on average across Australia. This saving directly translates to reduction in running costs.

The sizing of air conditioners is currently unregulated. Calculation of the design load considering the issues relating to ducting and heat flows through the roof identified how these factors are increasing the sizes of installed air conditioners. In addition to the natural bias of retailers to oversize air conditioners, larger systems are being installed in more energy-efficient homes, adding to the peak power demand problem.

AccuRate was used to identify the potential of reflective roofing with a high TSR and foils, operating in conjunction with bulk insulation on peak reduction in air conditioning demand. Significant reductions were identified and the estimated impact reduction in total peak power demand was identified.

The impact of adaptive comfort which complements demand side management of air conditioning was shown to be able to dramatically reduce electricity consumption for cooling by over 60%, as well significantly reducing peak power demand.

The future climate is likely to move all mainland cities into cooling dominated demand. Based on future TMY, the electricity usage for heating and cooling in Hobart is predicted to decrease over time. In all mainland cities, electricity usage is expected to increase with Sydney and Brisbane experiencing the most dramatic increases. All mainland cities can expect increased electricity costs.

With the onset of climate change, peak power demand will increase at higher rates than currently anticipated, particularly in Brisbane and Sydney. Furthermore, the usage levels of electrical infrastructure will skew away from winter which may affect electricity prices such that electricity savings during winter heating may not directly translate to equivalent cost savings. Consequently in all locations studied, apart from Hobart, electricity prices are expected to increase due to climate change. The measures to reduce peak power demand presented herein can reduce these trends.

6. BEHAVIOUR ANALYSIS

6.1 *Behaviour during Heat Waves*

This section of the project addressed the socio-behavioural factors that influence how Australians currently respond to heat waves in order to identify the factors that enable particular household types to respond effectively to increases in temperature or that inhibit them from doing so.

Three studies were undertaken: (1) telephone interviews with 15 key informants; (2) qualitative interviews with householders who were participating in the monitoring of indoor temperature and air conditioner use; and (3) an online survey of 500 individuals across three cities (Brisbane, Adelaide and Sydney).

These studies have suggested that most Australians cope reasonably well with heat waves and extreme heat, and most individuals know about an oncoming period of extreme heat days in advance. However, there is considerable risk for two groups who are particularly likely to be disadvantaged in their capacity to cope – elderly people and those on low incomes.

A consistent theme was that those with greater access to economic resources are better able to cope with heat waves. Specifically, wealthier individuals and their households are more likely to:

- Self-report a better capacity to cope with extreme heat and with fewer days on which they felt uncomfortably hot
- Have air conditioning per se, and when they have newer (< 5 years) units, they are likely to be more efficient and effective
- Have ducted air conditioning (which was experienced as the most effective type of air conditioning by survey respondents), or air conditioning per se
- Be living in better designed homes that are more efficient to heat and cool (as opposed to older houses, or public housing in which many lower income people reside).

Survey respondents were most likely to report a good capacity to cope with heat waves and extreme heat when they lived in houses:

- they owned (outright or with a mortgage)
- that were single family detached dwellings
- that had central ducted air conditioning.

Air conditioning is clearly central to Australians' strategies to manage their comfort at home during heat waves. In the online survey, comfort and the ability to sleep well were the two major drivers of air conditioning use: comfort was also a key driver of air conditioner use for participants in the householder interviews. Socio-economic differences were highlighted. Wealthier individuals were more likely to cite personal comfort as a reason to use air conditioning, whereas older people and those on low incomes were more likely to cite health reasons.

The householder interviews provided further insight into the decision-making processes concerning the use of air conditioners. Most householders reported a staged approach to managing their comfort in response to hot weather, starting with passive strategies (e.g. lightweight clothing, using blinds/curtains or increasing ventilation) and moving to the use of air conditioning as a final step or 'last resort'. Furthermore, air conditioner use was more common for householders after a few days of hot weather, when the indoor temperature had become uncomfortably high for an extended period.

From the online survey, it was observed that individuals who had air conditioning, especially ducted systems, were more likely to report a good capacity to cope with extreme heat and had had very few days on which they were uncomfortably hot at home over the past five years. Using air conditioning is the most common current and anticipated future response to heat waves, and the strategy that is most commonly considered with regard to future changes to respondents' homes.

The key conclusions from the three studies can be summarised as follows:

- There is a willingness to change behaviour in the home, but not to spend money.
- Lower income and elderly individuals are at highest risk, and should be a priority for interventions and assistance.
- There is substantial scope for low cost/no cost behaviour change in households.
- There is an unmet need in the general community with regard to understanding that heating and cooling are major sources of energy consumption and energy costs.

Recommendations regarding initiatives and programs that should be considered by government can be summarised as follows:

- Increase community education and awareness of cost-effective strategies to manage comfort and health during heat waves
- Provide targeted financial support to encourage particular improvements to housing design, and to support groups at increased risk of negative outcomes during heat waves (i.e. those on low incomes and elderly people)
- Introduce and effectively implement improvements to the Building Code of Australia.

6.2 *Behavioural Studies*

6.2.1 Study 1 – Key Informant Interviews

Telephone interviews were conducted with 18 subject matter experts in March 2012 (Table 6.1). The interviews were designed to gain insight into how diverse community groups cope during a heat wave. Specifically, interview questions addressed the types of strategies used to cope during a heat wave; the prevalence of air conditioning; the factors which affect the use of air conditioners; perceptions of comfort; the factors that hinder the achievement of a comfortable home temperature during a heat wave; the effect of electricity prices on coping; how heat waves affect individuals who undertake paid work; how travel plans and the use of non-household child care are affected during a heat wave; suggestions for house design to increase comfort during a heat wave; and suggestions for government support to increase safety and comfort during a heat wave. Interviews varied in length from approximately 13 to 56 minutes. On average, interviews ran approximately 32 minutes.

Table 6.1: Participants in key informant interviews

Name	Organisation	State	Area of Expertise
Cathy Weiss	Women's Health in the North	Vic	Women
Celine Buck	Helping Hand Aged Care	SA	Elderly
Tony Westmore	ACOSS	NSW	Low Income
Andrew Bishop	LMC	SA	General community
Sylvia George	Helping Hand Aged Care	SA	Elderly
Kate Williams	Centacare	SA	Intellectual/physical disabilities
Damian Sullivan	Brotherhood of St. Laurence	Vic	Low income
Victoria Johnson	Brotherhood of St. Laurence	Vic	Low income
Lasath Lecamwasam	GHD	ACT	General Community
Tai Hollingsbee	GHD	Vic	General community
Belinda McClelland	Warrigal Care	NSW	Elderly
Mark Andrew	GHD	Vic	General community
Jonathan Daly	GHD	Vic	General community
Russell Pfitz	GHD	ACT	General community
Mark Thomas	Buzz Architecture	SA	General community
Lynette Pugh	Domiciliary Care	SA	Elderly
Christopher	Domiciliary Care	SA	Elderly
Ruth Barker	Mater Children's Hospital	Qld	Children

6.2.2 Study 2 – Online Survey

The online survey was conducted in April 2012. The sample comprised 1,514 Australian household financial decision-makers, aged 18 years and over in three capital cities (Sydney n = 505), Brisbane (n = 505) and Adelaide (n = 504). A representative sample (by age and gender within each state capital) was surveyed to obtain 500 household financial decision-makers in each city. Following the completion of the interviews, the data set was weighted to the household financial decision-maker by household size and city based on known incidence and projected to the number of households based on ABS household population estimates.

As Table 6.2 shows, the sample contained equal proportions of men and women and participants from younger, middle-aged and older age groups. The majority of participants (68.8%) had a vocational or tertiary level of education, and were employed. Most participants (65.8%) were partnered, with around one-third being partnered with children.

The most common type of home ownership was as an owner with a mortgage (41.9%), followed by renters (33.3%). Around one-fifth of respondents owned their home outright. The majority of respondents lived in single-family detached homes. The sample also contained respondents from the lower and upper ranges of household income.

The survey (see Appendix) comprised 22 questions primarily addressing behavioural responses to heat waves (current and future), comfort in heat waves and extremely hot weather, air conditioner use in hot weather, and views on electricity pricing mechanisms.

Table 6.2: Overview of online survey sample, per cent

	All	Adelaide	Brisbane	Sydney
Gender				
Male	46.8	43.2	45.5	51.8
Female	53.2	56.8	54.5	48.2
Age				
18-34	33.9	29.3	34.9	37.5
35-49	36.5	35.8	38.2	35.3
50+	29.7	34.9	26.9	27.2
Education				
Year 10 or lower	11.6	13.1	14.7	7.1
Year 11/12	19.6	21.8	22.0	14.9
TAFE/VET	27.1	30.3	24.8	26.4
University	41.7	34.9	38.6	51.6
Employment status				
Employed	71.0	63.4	71.9	77.8
Unemployed	4.6	4.6	4.6	4.6
Not in labour force	24.4	32.1	23.6	17.7
Home ownership				
Own outright	20.6	20.1	21.8	19.8
Own with mortgage	41.9	43.3	40.2	42.3
Rent	33.3	33.6	34.9	31.5
Other	4.2	3.0	3.2	6.3
Home type				
Single family	68.8	75.9	74.3	56.2
Semi-detached/attached	12.8	13.5	11.2	13.7
Apartment/unit	17.3	8.8	13.4	29.5
Household income				
< $40k	21.8	29.1	21.2	14.9
> $40k–$69,999	24.5	25.8	25.1	22.5
$70k–89,999	15.0	14.7	16.5	13.7
$90k+	38.8	30.5	37.2	48.9
Household type				
Couple with children	35.7	32.7	35.2	39.1
Sole parent	7.5	8.3	5.9	8.1
Sole adult	17.5	19.4	16.2	16.9
Couple without children	30.1	31.5	33.9	25.0
Multiple family members	9.2	8.1	8.7	10.9

6.2.3 Study 3 – Householder Interviews

Telephone interviews were conducted with 18 householders, from Adelaide, Sydney, Brisbane and Townsville who were participants in the comfort study in Chapter 3 (Table 6.3). Participants were recruited from a broader sample of participants who were taking part in the online comfort surveys and were having the temperature and electricity usage in their homes monitored. These interviews were designed to provide further insight regarding how Australians experience heat waves/very hot weather, how comfortable and safe household temperatures are achieved and the actions Australians use in their homes to respond to very hot weather and heat waves. Specific questions addressed air conditioner usage and household temperature during the most recent hot weather; strategies for maintaining personal comfort during very hot days/heat waves; air conditioner use during past heat waves; factors making it difficult to achieve and maintain a comfortable household temperature during heat waves/very hot days; possible changes to participants' houses that would increase their level of comfort during heat waves/very hot days; and participants' views on the kinds of government-provided information and assistance that would be useful. It was originally planned to conduct 20 householder interviews. The data reached saturation (no more new information or data) at 18 interviews; therefore, it was decided to conclude the data collection at that point. The duration of the interviews ranged from 10 to 20 minutes, with an average length of 14 minutes.

Qualitative data from the key informant interviews and householder interviews were analysed using content analysis techniques. These techniques involve analysing the data to identify recurrent and salient themes. This approach could be classified as 'qualitative description', in which the aim is not to build or test a theory, but rather to provide an in-depth account of events and experiences in everyday terms.

Table 6.3: Participants in householder interviews

Region	Gender	Age	Education	Occupation	Children in the home	Income $	Rent / own home
Adelaide	Male	25-29	TAFE	Chef	1 child (5 yrs)	30,000 - 60,000	Rent
Adelaide	Female	≥ 45	-	Unemployed	Nil	≤ 30,000	Rent
Adelaide	Female	N/A	N/A	N/A	N/A	N/A	Rent
Adelaide	Male	N/A	N/A	N/A	N/A	N/A	Own
Adelaide	Male	N/A	N/A	N/A	N/A	N/A	Rent
Sydney	Male	35-39	Higher degree	Research student	2 children (3, 5 yrs)	60,000-90,000	Own
Sydney	Female	≥ 45	TAFE	Admin asst.	Nil	≥ 90,000	Rent
Sydney	Male	≥ 45	Research degree	Academic	Nil	60,000-90,000	Own
Sydney	Female	30-34	Bachelor's degree	Postgrad student	Nil	30,000-60,000	Rent
Sydney	Male	30-34	Higher degree	Academic	Nil	≥ 90,000	Rent
Brisbane	Male	40-44	Higher degree	Sustainability consultant	Nil	≥ 90,000	Own
Townsville	Female	30-34	Bachelor's degree	Electrical engineer	Nil	≥ 90,000	Own
Brisbane	Female	≥ 45	School Certificate	Director	Nil	≥ 90,000	Own
Brisbane	Male	25-29	TAFE	Electrician	1 child (3 mths)	≥ 90,000	Own
Brisbane	Male	40-44	Bachelor's degree	Architect	2 children (8,11 yrs)	≥ 90,000	Own
Brisbane	Male	30-34	Higher degree	Commercial development manager	2 children (3, 6 yrs)	≥ 90,000	Own
Brisbane	Male	40-44		Flight data coordinator	2 children (10,7 yrs)	≥ 90,000	Own
Brisbane	Female	30-34	TAFE	Child care professional	2 children (7, 4 yrs)	30,000-60,000	Own

Note. N/A = this information was not provided by participants.

6.3 *Results and Outputs*

6.3.1 Current Views and Experiences of Heat Waves

This section provides an analysis of the major trends and key findings from the online quantitative survey, and the two qualitative studies (interviews of key informants and householders). The findings presented here have emerged from a process of comparison and triangulation between these three studies, to present the strongest evidence regarding Australians' current views on and experiences of heat waves and periods of extreme heat, their coping strategies and behaviours, and the policy, urban planning and design responses most likely to improve Australian households' capacity to cope with extreme heat.

In addition to describing general community responses to heat waves and extremely hot days, a special focus of this report was on two groups that key informants with expertise in this area had identified as particularly at risk of negative effects of heat waves – individuals on a low income and elderly people (many of whom are also on a low income).

This section is divided into three main themes: current views and experiences of heat waves, current and future behavioural responses to heat waves, and implications for policy and practice. Key findings from the three studies are reported with regard to these three themes. From the online survey, we provide an overview of findings for the combined sample (Adelaide, Sydney and Brisbane), followed by summary tables identifying prominent trends and contrasts. All contrasts referred to in the text have been tested by chi-square analysis, and all are statistically significant at the $p < 0.05$ level, unless specified otherwise. This quantitative analysis is complemented by a more in-depth and nuanced analysis on each theme as provided by the two qualitative studies (interviews with key informants and householders).

The online survey findings indicated that the most common view of climate change was that it was increasing the frequency and severity of heat waves (Figure 6.). The majority (58%) of respondents held a different view with most stating that climate change had no impact on heat waves or that they did not know the answer to this question. A small minority of respondents indicated that there was no climate change.

More detailed data are presented in the Appendix (Tables A1 and A2). In summary, consistent with well-established patterns in the literature, those most likely to agree that heat waves were linked to climate change included younger people (aged under 50 years), employed persons and those with a tertiary education.

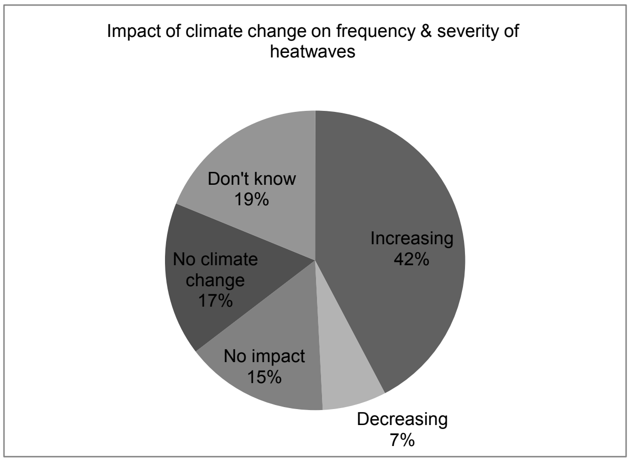


Figure 6.1: Perceived relationship between climate change and heat waves, online survey respondents

Although there were no direct questions exploring the connection between heat waves and climate change in the householder interviews, participants were asked to describe their regional climate and the factors that influenced their decision to not use air conditioning. The cost rather than concern for the environment or climate change was the most common response. Of those that cited climate change as a factor influencing their use of air conditioning, it was not in isolation from cost. Only one of the 18 participants explicitly linked climate change and heat waves. Most householders acknowledged that it had been a while since they had experienced a genuine heat wave, and overall, they were more likely to characterise heat waves, or very hot days, as an intrinsic aspect of the Australian climate rather than as a result of climate change.

We next turned to a discussion of how Australians experienced heat waves and extreme heat, focusing on the factors that were associated with self-report levels of comfort, and with knowledge about oncoming extreme heat days which was important in enabling effective household planning prior to periods of hot weather.

In the key informant interviews, some participants emphasised that the factors impacting on subjective feelings of comfort during heat waves were complex and multi-faceted. From a historical perspective, it was suggested that perceptions of a comfortable temperature were changing 'dramatically' and have changed since the arrival of affordable air conditioning. Key informants also observed that it was difficult to generalise about what the general community would consider a comfortable temperature inside their home. Physiological make-up (e.g. body mass index [BMI] and age) affected perceptions of comfort as this was related to metabolic rate and the ability to moderate body temperature. Furthermore, the incidence of obesity is increasing so over time a greater proportion of the general population would be adversely affected by their own physiology (i.e. carrying too much weight and not being physically fit).

Key informants with expertise on older people also emphasised that care needs to be taken when considering self-reported comfort and coping capacity of elderly people (i.e. those aged in their mid-70s and older). It is likely that many older people can psychologically tolerate higher temperatures to a greater extent than younger people, whereas younger people may have had more experience in air-conditioned environments (e.g. school, workplace and car). However, older people are often less able to physically tolerate higher temperatures and variations in temperature. An increase in temperature by a few degrees can place an elderly person at risk of heat stroke or associated heat stress issues.

The online survey addressed experiences of heat waves and extreme heat by asking two questions, one regarding the household’s capacity to cope, and the other about the number of days (per year) that respondents had felt uncomfortably hot in their home over the past five years.

As described below, the majority of respondents reported a good capacity to cope, good knowledge of oncoming heat waves and had experienced relatively few uncomfortably hot days. However, those who were more vulnerable to heat due to limited economic resources were less likely to cope well in heat waves or extreme heat.

The majority of respondents – around two-thirds – reported that their household’s ability to cope with heat waves was good or very good (Figure 6.).

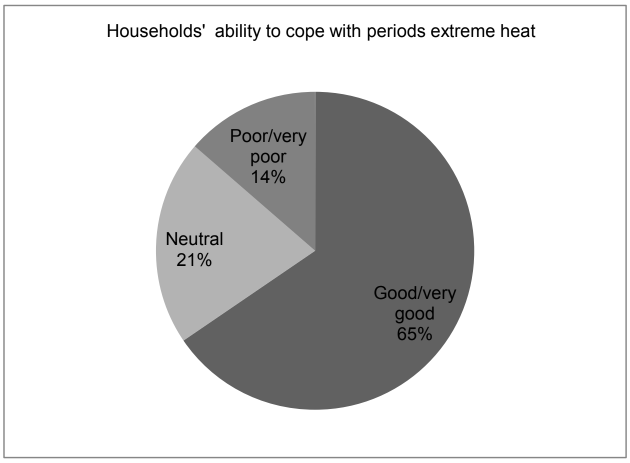


Figure 6.2: Rating of current household's capacity to cope with extreme heat, online survey respondents

Households who were more likely to cope well (good/very good ability) with extreme heat were those with greater financial and material resources (i.e. employed homeowners with a high ($90,000) income) (Table 6.4). Older people and those with partners were also more likely to report that their households coped well. With regard to housing design and location, respondents in single-family homes were more likely to report coping well with extreme heat, as were residents of Adelaide and Brisbane compared to those in Sydney.

The opposite pattern was evident for those households who were most likely to have difficulties coping with extreme heat (Table 6.5): these households had a lower level of education and lower income, were unemployed or were in sole-adult households (with or without children). Those who were renting, and those in semi-detached or apartment-type housing were also more likely to report a poor household ability to cope with extreme heat. Households with centrally ducted air conditioning were most likely to report coping well with extreme heat, although the majority of respondents with any type of cooling in the house reported that they coped well. Those with portable evaporative air conditioners were least likely to cope well and most likely to report that they had difficulties coping.

Table 6.4: Groups most likely to cope well with periods of extreme heat, online survey respondents, per cent

	Good/very good household capacity to cope (%)
50+ years	72.9
35–49 years	64.4
18–34 years	60.1
Employed	65.5
Not in labour force	66.9
Unemployed	57.4
Working 45+ hours per week	71.3
Working 35–44 hours per week	63.6
Working< 35 hours per week	66.4
Own home outright	78.2
Own home with mortgage	68.7
Rent	55.4
Other arrangement	55.1
Single-family home	67.4
Semi-detached/attached	64.4
Apartment/unit	61.9
Partnered without children	69.6
Partnered with children	67.2
Sole parent	59.3
Sole-adult household	61.8
Multiple family members	62.0
$90k+	74.1
$70k–$89,999	64.2
> $40k–$69,999	65.2
< $40k	59.0
Adelaide	71.5
Brisbane	71.4
Sydney	61.0
Central ducted A/C	80.0
Window/wall unit	68.2
Electric/ceiling fans	66.0
Evaporative/portable	57.3

Table 6.5: Groups most likely to have difficulty coping with extreme heat, online survey respondents, per cent

	Poor/very poor household capacity to cope (%)
Unemployed	18.4
Not in labour force	14.8
Employed	13.0
Rent	21.7
Other arrangement	8.7
Own home with mortgage	10.0
Own home outright	8.2
Semi-detached/attached	18.7
Single-family home	12.2
Apartment/unit	14.4
< $40k	16.0
> $40k–$69,999	13.6
$70k–$89,999	17.7
$90k+	11.3
Sole-adult household	17.4
Sole parent	15.3
Multiple family members	14.9
Partnered with children	11.9
Partnered without children	11.2
Evaporative/portable	14.6
Electric/ceiling fans	11.8
Window/wall unit	10.7
Central ducted A/C	6.0

Key informants with expertise on disadvantaged groups emphasised that lower income individuals may be more likely to live in homes that are hot, but are not likely to differ in their tolerance to heat in general unless there are health issues or young children are present. They observed that low-income households tended to use less energy even though they were more likely to have less energy-efficient appliances. Thus, these individuals might be prepared to live in slightly hotter environments owing to concerns about energy costs. In summary, an individual's financial status does not influence their perceptions of home comfort but perceptions about what could be done to achieve comfort was likely to be influenced by income.

Contrary to expectations, in the online survey, the presence of a household member with a disability or health issue that may be affected by the heat was not associated with the household's reported ability to cope with extreme heat. Rather, socio-economic factors were the strongest and most consistent predictor of coping capacity.

The online survey contained two additional indicators of household capacity to cope with heat waves or extreme heat: firstly, the number of days that were uncomfortably hot (per year, in the past five years) and, secondly, the likelihood of knowing about oncoming hot weather ahead of time. Responses to these two online survey items are discussed below.

Just under half of respondents reported very few uncomfortably hot days (0–4 days). On the other hand, one-third of respondents reported an average of 11 or more days per year where they felt uncomfortably hot at home (Figure 6.). Those most likely to report many (11+) of these days were women, those in rental or other accommodation, those in semi-detached/attached housing, households with lower incomes (< $70,000) and respondents residing in houses with a window/wall unit air conditioner (Table 6.6).

Respondents who reported the least number of uncomfortably hot days were men, homeowners (outright or mortgage), those residing in single-family homes or apartments/units, households on higher incomes ($90,000+) and houses with ducted air conditioning (Table 6.7).

The survey next addressed whether the respondents knew about oncoming hot weather: the majority of respondents (63.1%) knew that very hot days were approaching (almost always/frequently know) (Figure 6.). This was the case across all socio-demographic groups and household types. Those respondents most likely to have knowledge of oncoming hot days were older people, those not in the labour force or working part-time and Adelaide residents (Table 6.8).

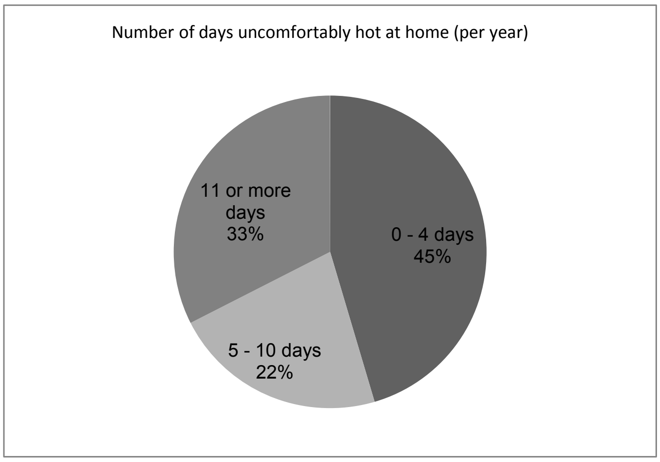


Figure 6.3: Number of days respondents felt uncomfortably hot (per year) in last five years, online survey respondents

Table 6.6: Groups with many (11+) uncomfortably hot days at home per year, online survey respondents, per cent

	11+ days uncomfortably hot per year (%)
Women	35.2
Men	29.9
Rent	41.2
Other arrangement	34.6
Own home with mortgage	28.5
Own home outright	25.4
Semi-detached/attached	42.5
Single-family home	31.8
Apartment/unit	29.2
< $40k	36.1
> $40k–$69,999	34.9
$70k–$89,999	30.8
$90k+	27.6
Window/wall unit	35.1
Evaporative/portable	32.1
Electric/ceiling fans	31.7
Central ducted A/C	25.2

Table 6.7: Groups with few (0–4) uncomfortably hot days at home, online survey respondents, per cent

	0–4 days uncomfortably hot per year (%)
Men	47.8
Women	43.0
Own home outright	49.7
Own home with mortgage	48.9
Rent	38.4
Other arrangement	47.2
Apartment/unit	48.7
Single-family home	45.3
Semi-detached/attached	38.5
$90k+	49.4
$70k–$89,999	46.8
> $40k–$69,999	44.4
< $40k	44.7
Central ducted A/C	56.2
Electric/ceiling fans	47.6
Evaporative/portable	45.3
Window/wall unit	42.6

Those least likely to have knowledge of oncoming hot days were younger people, employed persons, renters or mortgagees, residents of Sydney or Melbourne, those living in households with multiple family members or those who were sole parents (Table 6.9).

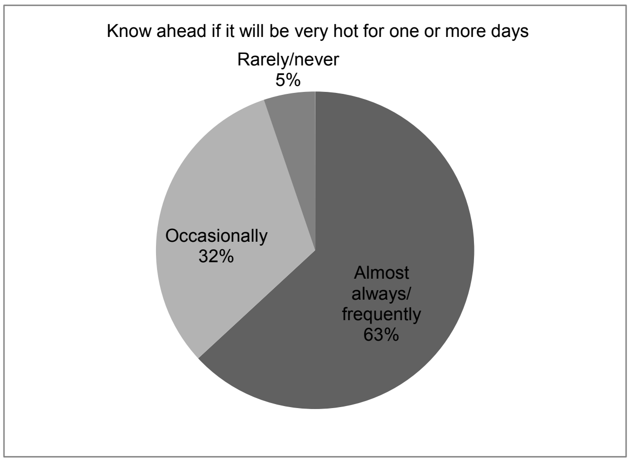


Figure 6.4: Know ahead of time if it will be very hot for one or more days, online survey respondents

Table 6.8: Groups most likely to know ahead of time about oncoming very hot days, online survey respondents, per cent

	Almost always/frequently know ahead of time (%)
50+ years	69.9
35-49 years	60.1
18–34 years	60.4
Not in labour force	73.3
Employed	60.4
Unemployed	58.5
Working < 35 hours per week	64.9
Working 35–44 hours per week	59.0
Working 45+ hours per week	58.0
Adelaide	84.2
Brisbane	61.9
Sydney	57.3

Table 6.9: Groups least likely to know ahead of time about oncoming very hot days, online survey respondents, per cent

	Rarely/never know ahead of time (%)
18–34years	6.9
35–49 years	4.9
50+ years	3.4
Employed	5.7
Not in labour force	3.6
Unemployed	3.0
TAFE/VET education	7.8
Year 10 or less	4.2
Year 11/12	3.8
University education	4.3
Working 35-44 hours per week	7.0
Working < 35 hours per week	3.6
Working 45+ hours per week	4.7
Rent	7.1
Own home with mortgage	5.6
Other arrangement	1.6
Own home outright	1.7
Sole-adult household	9.0
Multiple family members	6.6
Partnered without children	2.3
Partnered with children	3.7
Sole parent	4.1
Sydney	6.0
Brisbane	5.6
Adelaide	1.6

Consistent with the survey results, participants in the householder interviews reported that they coped well with heat waves and periods of extreme heat. However, it is important to note that a number of the householders were immigrants or visitors to Australia who had not yet experienced a heat wave in the time that they had resided in Australia. As highlighted by the key informants, it is difficult to generalise about what the general community would consider a comfortable temperature inside their home. The householder interviews provided further insight into whether and how householders adjust their subjective feelings of comfort during heat waves. Specifically, householders were asked to think about their usual desired household temperature and whether, during a heat wave or a string of very hot days, they were willing to put up with a hotter house temperature—or whether they attempted to bring the household temperature down to their usual desired household temperature. Most householders agreed that they were willing to put up with a hotter house temperature, because they expected it to be hot during summer. Furthermore, a number of the householders stated that once the use of air conditioning was required, due to extreme discomfort, they tended to set the air conditioner temperature at a higher set point than they would ordinarily prefer. The following quotes were typical of the responses to this question:

> *When you get home you just want to relax a bit and having a quite uncomfortably hot house isn't* [but] *you don't need to have the house as cool as sometimes you want to make it* (Male, Adelaide).
>
> *When we do turn the air conditioning on, we don't have it like really, really cold. We normally set it at 25, 26 degrees. So at least it's not, you know, really, really super cooling the house down. It's keeping it at a, I suppose a higher comfort level rather than you know, just being comfortable* (Male, Brisbane).

In general, the householders were able to modify their subjective comfort levels to a certain point, after which they would resort to the use of air conditioning. Furthermore, in relation to householders who were immigrants or visiting Australia, it was noted that they had a diminished level of tolerance for a hotter house temperature. One householder, originating from New Zealand, put it this way:

> *My temperature tolerance would be a lot lower than my wife. She's from here* (Male, Brisbane).

Householders also highlighted concerns around the community's broad reliance on air conditioning, particularly in the workplace and child care centres, resulting in a diminished tolerance for hotter temperatures in the home. Householders noted that they had not had air conditioning in their homes or cars as children, and therefore had a higher tolerance for hotter house temperatures than their young children, as one householder explained:

> *I've got two kids so when – in the afternoon like when I pick them from the child care and the child care the temperature is so set, like maybe 22 or something I feel really cold there but they are there since morning so when they come in* [to a house with no air conditioning on] *and they feel a bit cranky … So when you are used to a set temperature and then it automatically comes from the other place [*air-conditioned child care centre] *it's really hard to adjust* (Male, Sydney).
>
> *Most people over 35 I know, they never had air conditioning in their houses as children and we just went outside and we got on with it … I think it's a psychological constraint* [for children], *if you have air conditioning* (Male, Brisbane).

6.3.2 Current and Future Behavioural Responses to Heat Waves

We turn now to a discussion of how Australians respond to heat waves with regard to the strategies they use to cool their homes and manage their comfort at home.

Many of the key informants observed that the general community is quite heterogeneous, hence strategies vary according to different groups within the community. Strategies to cope with heat waves also depend on economic means, personal circumstances and housing (i.e. type of home and quality of the construction in terms of insulation).

Consistent with the survey findings (described below), many key informants observed that use of air conditioning is common in Australian houses, particularly newly built homes. Some key informants also observed that other strategies such as ventilation of the home at night are also common, but the effectiveness of this approach is substantially influenced by house design. Although diverse strategies exist, the use of an air conditioner was often identified as the most common strategy if an individual has access to an air conditioner and can afford to use it. Key informants also observed that environmentally conscious individuals would be less inclined to use air conditioners and would consider other options such as ceiling fans, ventilation, shading, and using thermal mass within their home. For some individuals the most common strategy is to use fans and drink water.

Some key informants indicated that the likelihood of taking action to keep oneself cool during a heat wave depends on self-awareness, the ability to control one’s environment, and the ability to stay still, hydrated and keep in the coolest room of the house for example. Affluent individuals who have enough time and enough control over their environment are likely to have the largest capacity to respond to heat waves.

Key informants with expertise on elderly people emphasised their vulnerability to extreme heat, and the difficulties many elderly people experience in coping well in the heat. They observed that some elderly individuals, such as those that live alone, are likely to be most vulnerable as a result of a cumulative effect where their nutrition and hydration can be impacted which consequently affects their decision-making ability and their cognitive ability to plan. Furthermore, elderly individuals who are experiencing mental decline would have less understanding of their temperature needs (e.g. dressing too warm). Furthermore, key informants emphasised that elderly individuals are likely to have difficulty in both accessing and understanding information regarding air conditioner use. Furthermore, the cost of operating an air conditioner can lead to avoidance of air conditioning.

With regard to low income individuals, key informants with expertise on disadvantaged groups observed that there is substantial diversity with regard to household coping strategies as low income individuals are not a homogenous group. A Brotherhood of St Lawrence study with 85 low income individuals showed common strategies to cope with a heat wave include closing up the house and shading windows during mornings of hot days. Other strategies included using fans and wetting clothes. A small number of individuals used air conditioners. During the day, if reasonable and possible, some low income individuals would leave their home for a shopping centre, cinema or friend's home. However, this is unlikely to be a frequent strategy especially for those that have limited mobility.

According to key informants, the effect of children on coping strategies during heat waves varies. Some parents of young children are quite concerned with ensuring their young children’s comfort and safety and would cool the home. Conversely, a very low income single parent, particular a very low income single mother, might only use an air conditioner if it is absolutely necessary, if it all, because of concerns regarding energy bills. Depending on the age of the children, having children can be linked to residing in a bigger house, which is often linked to more issues with energy management (e.g. keeping the house closed during the day). Larger families have a greater energy demand and can be experiencing ‘energy hardship’ or be at risk of doing so. This phenomenon is not limited to low income families.

Consistent with the views expressed by key informants, the results from the online survey also indicated that individuals use a wide range of strategies to cope with a heat wave. As discussed below, the online survey included three separate questions regarding respondents’ behaviours to manage their comfort during heat waves: (1) current strategies; (2) anticipated future strategies; and (3) the three main strategies they current use. Not surprisingly, there was considerable overlap between responses to these items. Here we discuss responses according to three broad categories – strategies to manage the temperature within the home (including leaving the home to spend time at another location), behaviours to manage bodily health and comfort and strategies to manage activities external to the home such as the car travel (Table 6.10).

Considering both the current responses reported and the top three main strategies used, the three most common responses to manage comfort in the home were using:

- An air conditioner
- Ceiling or pedestal fans
- External blinds or curtains.

The three most common responses to manage bodily comfort were to:

- Drink plenty of water
- Avoid strenuous activity
- Stay indoors or in the shade during the hottest part of the day.

The three most common strategies to manage activities external to the home were to:

- Plan the day to avoid the heat
- Avoid/reduce car trips
- Pay bills online or over the phone to avoid going out.

These patterns of common behaviours are mirrored in the anticipated future behavioural responses to heat waves (Table 6.11). Anticipated future responses in the home centred on the use of air conditioners and fans. Future expectations of managing bodily health/comfort centred on drinking water, adjusting activity levels and staying inside, whereas future strategies to manage external activities centred around planning activities and reducing car travel.

Table 6.10: Current behavioural responses to heat waves, online survey respondents, per cent

Strategies and behaviours	Current responses	Three main current responses
None	1.8	2.0
Managing comfort in the home		
Use your air conditioner	59.6	47.0
Use ceiling or pedestal fan	56.8	30.9
Use external shades or draw curtains to reduce the heat from the sunlight	43.9	15.8
Move to a cooler room in the house	43.1	10.1
Adjust the setting of air conditioner to cope with heat wave	34.7	9.8
Leave secured door/window open	33.0	9.5
Go to an air-conditioned building in the local area (shopping mall, community centre, swimming pool, etc.)	32.4	6.7
Use awnings, shadecloths or external blinds on the sides of the house facing the sun	26.8	7.1
Use an evaporative cooling portable unit	6.4	2.2
Managing bodily health/comfort		
Drink plenty of water	78.5	46.7
Avoid strenuous activity	49.0	11.5
Stay indoors or in the shade during the hottest part of the day	66.1	23.6
Wear a hat, loose clothing, sunglasses and sunscreen if going out is unavoidable	48.5	7.0
Take cool showers or splash yourself with cold water several times a day	40.8	12.9
Eat little and often, and try to eat more cold food	20.7	1.9
Go to a swimming pool	22.9	6.8
Avoid alcohol, tea, coffee and sugary or fizzy drinks	13.3	1.9
Sit in your car with the air conditioning on	7.6	1.4
Managing activities outside the home		
Plan the day in a way that allows you to stay out of the heat	42.7	10.5
Avoid time in the car / reduce the number of trips in the car	24.0	2.6
Pay bills online or over the phone to avoid going out	21.2	1.0
Spend more time in the workplace where it is cooler*	15.5	3.6
Buy extra items ahead of the hotter weather to make sure there is enough food to last	8.1	0.9
Spend more time working from home*	5.0	1.2

Note. Persons not in the labour force or unemployed excluded from this data.

A similar pattern was also observed with regard to the changes respondents would consider adopting for their home in order to better cope with future heat waves. The most common strategies considered were related to air conditioning (purchasing/upgrading/servicing) and purchasing of additional fans (Table 6.11).

Consistent with the survey results and the interviews with key informants, the householder interviews indicated that individuals employ a variety of strategies to manage their comfort during heat waves and periods of very hot weather. For those householders that have air conditioning in their homes, use of air conditioning was a uniformly accepted strategy employed during extremely hot days to maintain personal and household comfort. Householders did, however, anticipate periods of extreme hot weather and heat waves and employed a number of strategies to maximise their household comfort levels. For example, householders attempted to keep their homes comfortable by using cross ventilation techniques, shading windows and keeping the house closed. Other strategies were employed in order to manage personal comfort levels such as wearing appropriate, lightweight clothing and bed clothing, staying in the coolest part of the house, reducing activity, staying hydrated and eating lighter meals, planting ivy to cover western facing walls, planting trees to soften the impact of the sun, going swimming and avoiding oven use.

Table 6.11: Future behavioural responses and changes to home would be considered to improve future capacity to cope with heat waves, online survey respondents, per cent

Strategies and behaviours	Future behavioural strategies	Future changes to home
None	2.0	19.8
Managing comfort in the home		
Use your air conditioner (install new A/C in future)	49.1	16.1
Use ceiling or pedestal fan (buy/install more fans in future)	42.3	29.9
Have air conditioner serviced before summer	-	20.9
Move to a cooler room in the house	31.5	-
Use external shades or draw curtains to reduce the heat from the sunlight	30.8	21.2
Adjust the setting of air conditioner to cope with heat wave	25.7	-
Leave secured door/window open	21.0	-
Go to an air-conditioned building in the local area (shopping mall, community centre, swimming pool, etc.)	23.4	-
Use awnings, shadecloths or external blinds on the sides of the house facing the sun (install in the future)	25.6	14.0
Use an evaporative cooling portable unit	6.6	-
Upgrade existing air conditioner	-	14.4
Install/upgrade roof insulation	-	12.0
Install awning/shade/cover over verandah/balcony or outdoor area	-	11.8
Move to smaller/more energy-efficient home	-	6.8
Managing bodily health/comfort		
Drink plenty of water	60.0	-
Avoid strenuous activity	36.1	-
Stay indoors or in the shade during the hottest part of the day	44.1	-
Wear a hat, loose clothing, sunglasses and sunscreen if going out is unavoidable	30.8	-
Take cool showers or splash yourself with cold water several times a day	30.3	-
Eat little and often, and try to eat more cold food	10.3	-
Go to a swimming pool	18.7	-
Avoid alcohol, tea, coffee and sugary or fizzy drinks	11.0	-
Sit in your car with the air conditioning on	3.7	-
Managing activities outside the home		
Plan the day in a way that allows you to stay out of the heat	33.7	-
Avoid time in the car / reduce the number of trips in the car	15.6	-
Pay bills online or over the phone to avoid going out	13.2	-
Spend more time in the workplace where it is cooler*	11.1	-
Buy extra items ahead of the hotter weather to make sure there is enough food to last	9.0	-
Spend more time working from home*	5.2	-

Note. Persons not in the labour force or unemployed excluded from this data.

From the householder interviews a clear pattern emerged with regard to the strategies householders use, and the order in which they tend to enact particular responses to manage their comfort. The most common pattern (from initial to later responses) was wearing appropriate clothing, pre-emptive shading of the house, ventilation, using fans and, finally, turning on the air conditioner.

> *In the first instance you'd start with what you're wearing. So, you try and wear clothes that match the temperature and then you move on to things like opening the windows and increasing the airflow. Then, things like turning on the fan, is nearly always the next choice* (Female, Adelaide).
>
> *If I'm at home I'll pull the curtains around after midday, say 1 o'clock, 2 o'clock at that time, so you won't get that [unclear] coming inside and other factors like - then there's another window on another side - sorry, you won't get that sun coming inside so I just try and I open - I usually open the window on the eastern side. So I'll try to change a little bit, just try to avoid using the air conditioning* (Female, Sydney).
>
> *Obviously before turning the air conditioning on that's what's happening. You know, windows open. If there's no flies, we leave the sliding doors open, or the front doors open … then obviously the fans going as well if there's no breeze, which tends to happen in the morning before the kind of sea breeze kicks in* (Male, Brisbane).

The householders' strategies to maintain household and personal comfort during heat waves or extreme hot weather reveal a good knowledge of their regional climate (when breezes are most likely to occur) and the pros and cons of the design features and aspect of their homes (which sides of the house absorb the most heat, which windows need to be opened to cross ventilate). As the previous quotes demonstrate, householders generally had a planned series of steps to maximise comfort, most often concluding with the use of air conditioning. As previously stated, air conditioners were predominantly used following successive hot days, at which point the household temperature becomes 'unbearably' uncomfortable, warranting the use of air conditioning.

We now turn to a more in-depth analysis of the use of air conditioning in Australian homes.

As discussed previously sections, using air conditioning is one of the main strategies that Australians use to cope with days of extreme heat and heat waves. Here we look at air conditioner use in more detail, examining the factors that promote or impede use within the Australian community in general, and for vulnerable groups (low income, elderly) in particular.

As noted previously, key informants emphasised that within the general community the use of home air conditioners is very common. Some key informants observed that there is a general expectation that air conditioners will be available in new homes, which was considered 'a major problem'. A high use of air conditioners results in a very large power load on the infrastructure, which can lead to brownouts (i.e. a drop in power evident via dimming or flickering of lights) in some older suburbs. Brown-outs were also anticipated by some key informants to become 'a major problem', particularly if house design does not change because there is a high reliance on mechanical means of cooling. High energy consumption is not only an issue for residents in terms of high costs but it is also an issue for the broader community in terms of the infrastructure that is needed to support the consumption.

Most participants in the householder interviews were also reliant on air conditioners as one of their main strategies to maintain a comfortable temperature in the home. As observed previously, the householders indicated that they mainly used air conditioning as a final response to uncomfortable heat, after putting into place other passive measures such as opening and closing windows, closing curtains and outside awnings, dressing appropriately. Householders indicated that the need for air conditioning was generally precipitated by a series of consecutive hot days, at which point their homes heat up to an uncomfortable temperature. Consistent with findings from the survey, and interviews with key informants, the use of air conditioning was common in the householders' anticipated future response to heat waves. It is important, however, to reiterate that most householders proactively engage in a variety of measures to increase their comfort during heat waves and extreme hot weather. As previously mentioned, the use of air conditioning was generally cited as a last resort and is used in combination with other passive measures, as one householder explains:

> *"I would say … about 35%* [of the time] *we'd use our air conditioning. Because the rest of the time we'll take the passive means or passive measure*s" (Female, Sydney).

According to the online survey, the most common types of air conditioning are window/wall units (around half of respondents), followed by electric/ceiling fans and central ducted systems. A substantive proportion of respondents – 18.2% – had no type of air conditioning in their home (Figure 6.5).

More detailed data regarding types of air conditioning by social demographic and housing characteristics is presented in the Appendix (Table A3). Two patterns are particularly worthy of commentary. First, the quality of air conditioning in the home varies considerably with economic resources. Central ducted air conditioning is more common for those with higher household incomes ($70,000+) and homeowners (outright or mortgage). Whereas those with lower economic resources are most likely to have no form of air conditioning in their home. That is respondents with low household income, who are sole parents or living alone and those who are renting. The second pattern concerns geographic location. Adelaide residents are most likely to have central ducted air conditioning, and least likely to have no air conditioning. Brisbane residents are most likely to have evaporative or portable units or electric/ceiling fans, whereas Sydney residents are most likely to have no air conditioning.

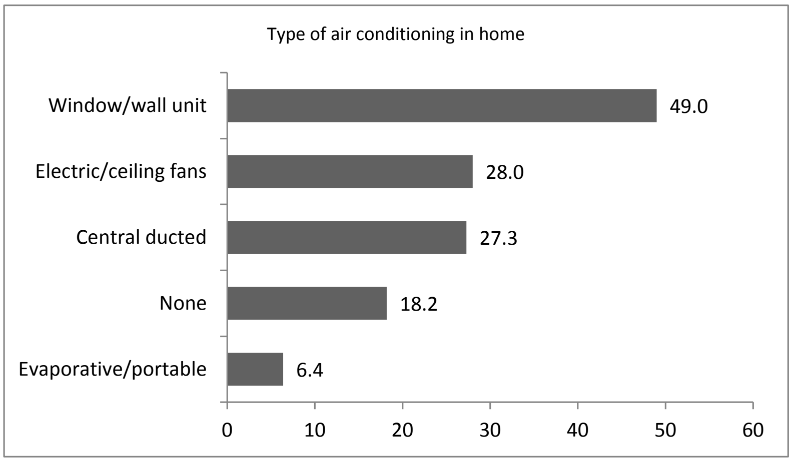


Figure 6.5: Type of air conditioning in home, online survey respondents, per cent

As Figure 6. shows, the majority of respondents with air conditioning had systems that were either less than five years old, or five to nine years old. There were few differences by social-demographic or housing characteristics (detailed data provided in

Appendix Table A4). Adelaide residents were least likely to have newer systems (< 5 years) and most likely to have systems that were 10 or more years old. Those on lower incomes ($40,000) were most likely to have older systems (10+ years). Those in rental accommodation and those in apartments/units or semi-detached/attached housing were most likely to have newer systems (< 5 years), whereas homeowners (outright, no mortgage) and those in single family homes were most likely to have older systems (10+ years).

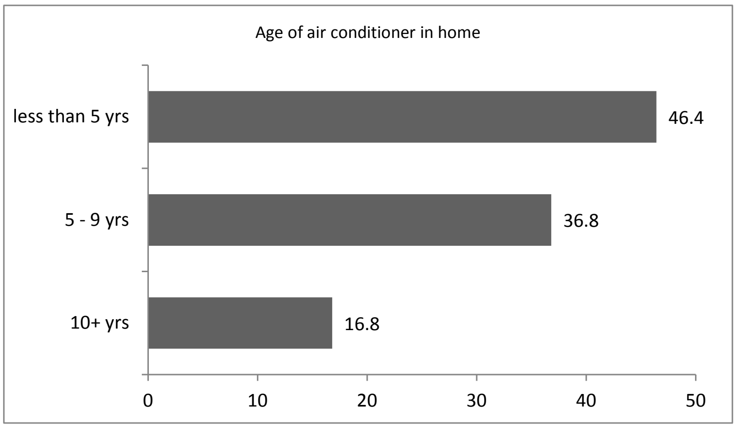


Figure 6.6: Age of air conditioning in home, online survey respondents, per cent

Given the prevalence of air conditioning in Australian households, and the heavy reliance on air conditioning as a coping strategy during heat waves, it is important to understand the factors that drive or limit use. The next section addresses this question drawing on data from the three studies.

Key informants observed that the use of air conditioners has become quite habitual in Australian homes, and can be considered as a type of 'automatic' behaviour’ that may not be subject to mindful reflection and awareness. This is considered as occurring more so in the last 15-20 years, as in the past decade air conditioners have become more affordable to purchase. It was suggested by key informants that many people value air conditioners without considering their economic and environmental effects. Nonetheless, environmental attitudes and knowledge of the impact that air conditioners have on the environment was argued by some key informants to have reduced use of air conditioners to some extent. The importance of housing design was emphasised by key informants. Poor design is associated with higher use of air conditioning, whereas in homes designed to facilitate effective cooling by passive means air conditioning is less likely to be used.

Turning to the online survey, feelings of comfort and capacity to sleep better were the two most common reasons for using an air conditioner during heat waves. There were some differences by social-demographic characteristics and geographic location (detailed data in the Appendix Tables A5 and A6). Managing health/illness was more likely to be cited as a reason by older people (50+ years), those not in the labour force (many of whom are likely to be retired) and persons with a lower income (< $40,000). In contrast, comfort was cited as a reason by those likely to have more financial resources – employed persons and those with higher incomes ($70,000+) (sole parents were least likely to cite comfort as a reason to use air conditioning). High income respondents were also likely to identify reducing stress and improving sleep quality as drivers of use. The presence or absence of children in the household was not consistently associated with particular reasons for use. There were gender differences, with women more likely to cite reduction of stress and tiredness, and capacity to continue usual daily activities as reasons for air conditioner use. This most likely reflects the typical pattern of care and domestic work in Australian households, where women spend considerably more time on these tasks in the home.

There were also differences by geographic location. Adelaide residents were most likely to cite comfort, health and capacity to continue daily activities. Whereas Sydney residents were least likely to cite sleep, tiredness and stress as reasons to use their air conditioner, but were more likely to cite humidity (along with Brisbane residents) as a driver of air conditioner use.

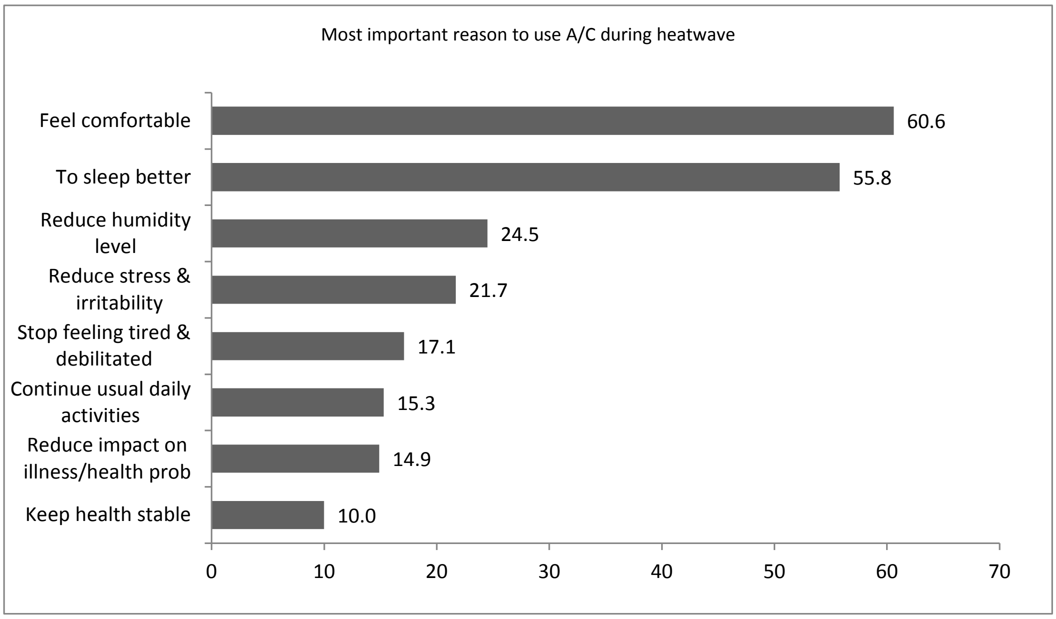


Figure 6.7: Most important reason to use air conditioning during heat wave, online survey respondents, per cent.

Note. Respondents could select up to three responses on this item.

Participants in the householder interviews were also asked to describe the factors that increase their use of air conditioning during heat waves or extremely hot weather. In contrast with the surveys and key informant interviews, the householders did not reveal any concerns that their use of air conditioning was habitual. As highlighted previously, the householders emphasised their efforts (through passive means) to avoid excessive use of their air conditioning. The majority of the householders (excluding those that do not have air conditioning in their homes) only used their air conditioning during heat waves or a series of very hot days. Householders indicated that at this point their homes heat up to an unmanageable temperature and as such air conditioning is required to achieve comfort.

It is important to acknowledge that the participants in the householder interviews are not likely to be representative of the general Australian population, as these participants were recruited from a sample of households already involved in the larger NCCARF study. Therefore, the sample is likely to be biased towards householders who have a high degree of awareness and concern about climate change in general, and their household use of energy in particular.

As noted earlier, whilst many of the householders were able to adjust their subjective feelings of comfort, withstanding hotter than normal household temperatures during heat waves, they did not expect their children to endure hotter temperatures. A number of householders indicated that they were more likely to use air conditioning if their children expressed discomfort:

> *It depends* [using air conditioning] *if I have my daughter, because she's four, and it depends how hot she gets, because I'm normally better at turning things on for her than me* (Female, Adelaide).
>
> *I have a daughter, so if she's really hot then I am just going to turn it on straight away and not worry about cost* (Male, Adelaide).

Consistent with the survey and key informant interviews, the predominant factor that increased householders' use of air conditioning was comfort. In contrast to the survey and key informant interviews, only two of the 18 householders indicated that they use the air conditioning during the night to aid sleep. Humidity was only mentioned once as a factor which increases participants' use of air conditioning.

Considering factor that limit or prevent air conditioning use, a strong and common theme across all three studies was cost. As Figure 6. shows, survey respondents reported that the financial cost of purchasing or running air conditioners were the main factors limiting or preventing use.

Many of the key informants acknowledged that cost has a significant impact on air conditioner use, particularly for low income individuals. Key informants with expertise on low income individuals observed that these individuals are more likely to reside in houses without an air conditioner, or to consider using air conditioning as a luxury only to be used when experiencing extreme heat. However, not all low income individuals are able to limit their air conditioner use due to cost concerns. Key informants with expertise in this area observed that low income individuals who have thermo-regulatory problems (e.g. because of MS, brain injuries or old age) give high consideration to maintaining the temperature of their home at a level that is not going to hinder their health. These individuals cool more often but experience difficulties with affordability. They continue to use their air conditioner as they are aware that their health will be significantly hindered if they do not. However, the need to use an air conditioner and knowing that the bill will be unaffordable creates significant stress, which also negatively impacts on their health.

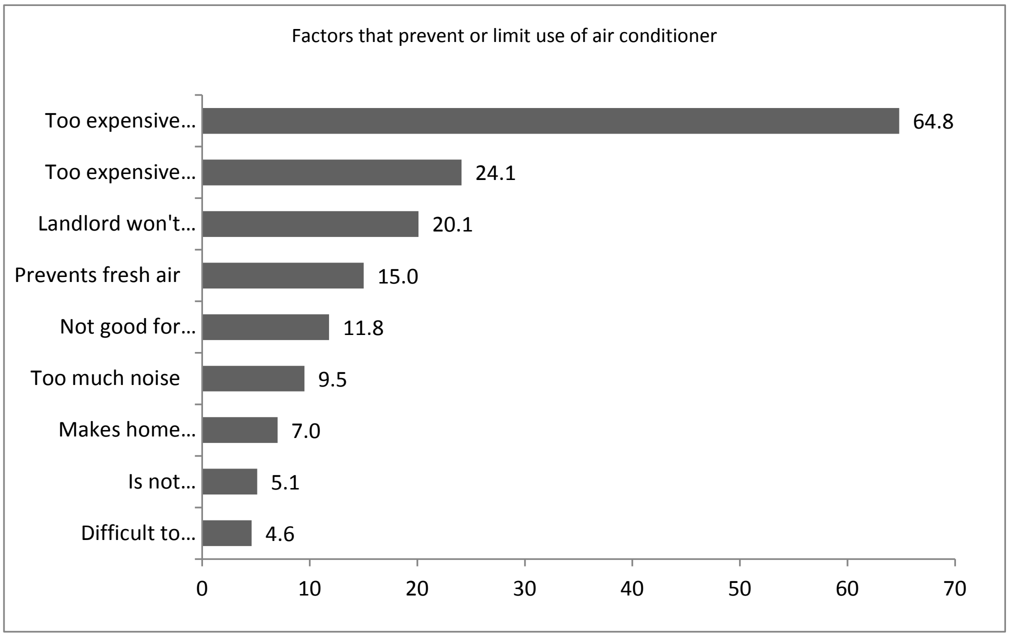


Figure 6.8: Factors that prevent or limit use of air conditioning during heat wave, online survey respondents, per cent

Note. Respondents could select up to three responses on this item.

Key informants with expertise on older people made similar observations; that older people are also likely to be very concerned about cost, and to perceive air conditioner use as a luxury rather than a necessity. As observed previously, many older individuals may be more psychologically tolerant to heat, as air conditioning was not available for much of their lives.

Some key informants observed that the relationship between actual cost and use is not straightforward. Specifically, cost is most likely to have an effect on use if people are have an accurate perception of air conditioner running costs. They observed that since cost has a delayed impact (i.e. substantial gap between use and payment of bills for use) individuals are often more concerned more about their immediate comfort during a heat wave than cost and hence use an air conditioner. Even if the individual is slightly concerned about costs, if the heat wave causes much discomfort and makes it difficult to cope then some key informants argued that cost might not be given much consideration.

Consistent with this argument, the online survey indicated that many Australians are not likely to have an accurate understanding of the costs of air conditioner use.

In the online survey only one third of respondents (34.3%) correctly identified heating and cooling as the largest contribution to household energy bills. The majority of respondents identified another type of appliance in the household (e.g. fridge, television, lighting).

Those least likely to understand the contribution of heating and cooling to electricity costs were younger people (< 34 years), unemployed persons, those with a low income (< $40,000) and those in rental and other arrangements. Adelaide residents were most likely to answer this item correctly, followed by Sydney residents, with Brisbane residents least likely to answer correctly (detailed data provided in Appendix Table A7).

Consistent with the survey and interviews with key informants, the householder interviews identified cost as the overwhelming factor which limits the participants' use of air conditioning. As indicated earlier in this report, environmental factors were only cited a small number of times and never in isolation from cost:

> *I think it's because of the electricity price I try to avoid to consume more energy and try to do more alternative things like use light clothes* (Female, Sydney)
>
> *The cost of it. Cost to run it. I will try everything else before I use the air conditioning. The air conditioning is the last resort* (Female, Brisbane).

Interestingly, when asked whether they were familiar with how much their air conditioners cost to run, the majority of householders said that it was a high cost. For those householders with air conditioning, cost was a factor in limiting their general use of air conditioning. However, during heat waves or days of extreme heat, comfort trumps cost for most householders.

6.3.3 Exploring Possibilities for Behavioural Change in the Home, and Policy Change Related to Electricity Pricing

In this section we move from describing how Australians experience and respond to heat waves and days of extreme heat, to a discussion of how these responses might be changed to support and facilitate more effective coping. The findings so far emphasise the importance of economic resources and financial costs, both in terms of groups who are most likely to have difficulties coping with heat waves, and also the factors that are perceived to influence the use of air conditioners.

We start by examining two issues related to financial costs - householders' willingness to invest money on home improvements designed to increase comfort during heat waves, and online survey respondents' views regarding alternative energy pricing mechanisms.

Key informants emphasised that the key factor affecting the achievement of a comfortable home temperature is house design. As described previously, there are range of lower and higher cost modifications that can be made to homes to improve comfort during heat waves. Key informants with expertise with regard to low income and elderly groups made similar observations regarding these individuals' capacity to improve their houses. As observed previously, these individuals are more likely to be residing in older, poorer quality and more poorly designed homes (with regard to heating and cooling). Key informants in the area of low income individuals also observed that many people are aware of the benefits of making long-term investments in their home to enhance its coolness in hot weather (e.g. the benefits of insulation and air conditioning) but in many cases would not be able to afford these investments. Furthermore, those in rental accommodation often face difficulties with keeping their home cool as they are not able to make modification to their homes, and many low income individuals are in rental or government/community housing.

Online survey respondents were asked how much they were willing to spend on their home to improve capacity to cope with heat. Around half of respondents were willing to spend up to $2,000 (Figure 6.). A substantial proportion of respondents – 30% – were not willing to spend any money. Very few respondents (around five per cent) were willing to spend $5,000 or more, therefore we limit our analysis to willingness to spend up to $5,000.

Consistent with the observations made by the key informants, those most likely to state they were not willing to spend any money were those with a low income (< $40,000) and groups more likely to have limited economic resources, specifically older respondents (50+ years) and unemployed persons. Consistent with this pattern, those with higher incomes ($70,000+) were more likely to report a willingness to spend $2,000–$4,999.

Those in rental accommodation were least likely to say they were not willing to spend any money, whereas homeowners with a mortgage were most willing to spend a modest amount of money ($2,000–$4,999).

Brisbane residents were also most likely to state they were not willing to spend any money, and least likely to be willing to spend between $2,000–$4,999. Detailed data are provided in Appendix Table A8.

Householder interviews also addressed possible changes to their homes that participants would consider in order to increase comfort. Their suggestions included increasing shade on the sides of the house that have contact with the sun (including walls and windows), tinting windows, whirly birds, ceiling fans and planting trees. It is interesting to note, that although the householders were asked to consider the ways that their homes could be changed to increase their comfort, they were more motivated to talk about the measures that they have already taken to adapt their homes to best deal with heat waves and extreme hot weather. As observed previously, this may reflect the likely 'selection effect' of sampling from what are most likely highly motivated and knowledgeable households.

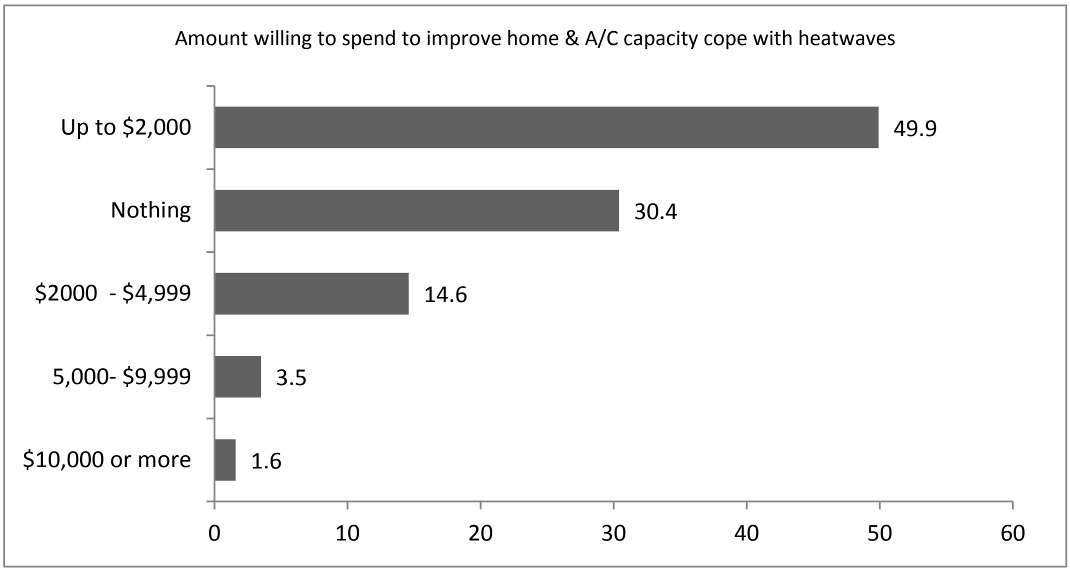


Figure 6.9: Amount respondents willing to spend to improve house and air conditioner capacity to cope during a heat wave, online survey respondents, per cent

One aspect of housing design that may be more feasible for a wide range of households is to adapt one part of the house to become a 'cool room', rather than make modifications to the whole of the house. This strategy was also supported by the key informants, they observed that this type of 'cool room' could have a concentration of good design features (e.g. shading and insulation). It is also cheaper to air condition one room rather than the whole house.

Online survey respondents were also willing to consider the idea of a cool room. The majority of respondents – 72.6% – indicated that they would be prepared to be confined to one part of the house.

Those more likely to consider being confined to one part of the house were older people (50+) and those not in the labour force. Those in semi-detached/attached homes were most likely to agree to being confined to one area during heat waves (detailed data in Appendix Table A9).

Turning now to systemic strategies to encourage and shape behaviour change, we now turn to the issue of electricity pricing mechanisms. Here we report on online survey respondent's views on various pricing mechanisms, and also key informants' views particularly with regard to the effect of particular pricing mechanisms on vulnerable or disadvantaged groups.

Many of the key informants observed that higher electricity prices would make individuals more cautious of spending money on air conditioning. They also observed that household income is likely to have a major impact on capacity to cope with increased electricity prices. Higher electricity prices were suggested to have a significant impact on lower and middle SES groups but are unlikely to have an effect on very wealthy groups who can afford the price increase. Key informants with expertise on low income households observed that many low income individuals are very concerned about current and future electricity prices. The cost of electricity can discourage individuals from cooling adequately. In their experience, many low income individuals try to minimise their energy use but find that their energy bills still rise in cost which they find 'frustrating' and some feel 'disempowered'. A lack of knowledge regarding strategies to reduce energy costs is also common. The key informants in this area reported that many low income individuals are struggling to manage financially at the current time, hence increasing energy prices are perceived as a 'threat'. These individuals and households often lack clear information on what they could do to maximise their comfort while minimising their energy use, and there is also a lack of awareness regarding air conditioners that are energy efficient (although cost is also a major barrier to purchasing effective and efficient cooling systems).

Similarly, key informants with expertise on older people observed that elderly individuals with low incomes were suggested to 'suffer…quite dramatically' if electricity prices were increased substantially. Specifically, it was suggested that increases in electricity prices are going to make it less likely that elderly individuals use air conditioners. Consequently, this could increase their vulnerability to health problems. Dehydration or overheating is also linked to falls. Key informants also suggested that future cohorts of older people may respond differently than those who are currently in this age bracket. ‘Baby Boomers’ are a unique generational cohort and they have a different view of themselves, finances and cooling equipment than current elderly individuals. Similarly, self-funded retirees are likely to have a different mindset compared to the current generation of retirees, with most better resourced to create their comfort. In addition, the current generation of adults has a high divorce rate, reduced number of children, and are more likely to have siblings who undertake paid work, which will affect their future access to support.

As observed previously, some key informants also observed that the association between increased electricity price and decreased use of air conditioners during heat waves is not likely to be straightforward for many households. Some key informants argued that price is unlikely to have a significant effect on individuals’ management of heat wave situations if they feel that their health or their children's health is threatened. If health is at risk and they have access to electricity they are likely to use the air conditioner regardless of whether the bill is affordable.

The online survey findings also concur with the views of key informants that Australian householders are sensitive to rises in electricity prices. As Figure 6. shows, two-thirds of survey respondents considered a 5–10% increase in electricity prices to be large.

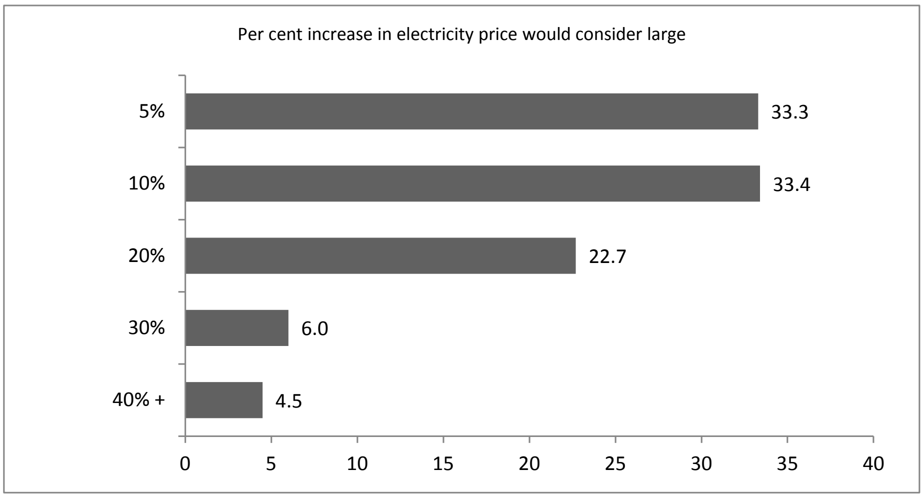


Figure 6.10: Percentage increase in electricity prices that respondents would consider to be large, online survey respondents, per cent

Beyond an increase in cost of use per se, there are a range of pricing mechanisms that can be used to encourage changes to the amount and patterns of household electricity use. The online survey canvassed respondents’ views on seven alternative pricing mechanisms (Table 6.12). There was a clear pattern in respondents’ support for energy pricing mechanisms; more predictable and consistent pricing regimes were clearly preferred (Table 6.12). A single flat price all year around was strongly supported ('a lot') by around one quarter of respondents, with an additional third reporting 'some' support. Only a minority of respondents – 15% – did not support a flat price mechanism at all.

Key informants with expertise in the areas of low income and older people also expressed concern about the potential of some pricing mechanisms to significantly impact on the capacity of vulnerable groups to cope with heat waves. They observed that individuals, who are at home in the afternoons and early evenings, when their homes are the hottest, use their air conditioners and use them in an expensive way. These individuals are more likely to be those who are not in the labour force – the elderly, those on a low income, unemployed persons or people with chronic health issues, illness or disability. With the introduction of 'time of use pricing' the economic penalty for using air conditioning during these times will worsen, creating additional economic strains and pressures to these groups who are already at risk of socio-economic disadvantage.

Table 6.12: Extent of support for energy pricing mechanisms, online survey respondents, per cent

	A lot	Some	A little	None
Single flat price all year around	26.5	34.1	23.6	15.8
Set price schedule prices for peak summer, peak winter and all other times	11.9	36.9	27.1	24.1
Variable hourly price between off-peak and on-peak on an intraday basis	10.5	32.7	29.9	26.9
Reduced prices if electricity retailer temporarily & marginally control A/C use	9.7	30.3	24.1	35.8
Variable monthly price between off-peak and on-peak and on a monthly basis	8.4	34.1	31.9	25.6
Peak penalty if exceed limit during peak periods, lower rate rest of year	8.8	31.2	23.2	36.8
Higher prices during peak periods & lower prices at other times	7.9	29.6	28.2	34.3

6.4 *Discussion*

The three studies provided complementary insights and findings into the factors that influence Australians attitudinal and behavioural responses to heat waves. The key points can be summarised as follows:

1. There is a willingness to change behaviour in the home, but not to spend money.

Air conditioners are central to most Australians' coping strategies for remaining comfortable during heat waves and very hot days. There were indications from the online survey of significant willingness to change behaviours and strategies. For example, around 30% of survey respondents reported they planned to purchase more fans in the future, and three quarters of respondents would consider creating a 'cool room' in the house, to which household members could retreat during hot weather. In contrast, there was very little support, from survey respondents (and some key informants) with regard to increasing financial costs to individuals and households.

2. Lower income and elderly individuals are at highest risk, and should be a priority for interventions and assistance.

The vulnerability of low income and elderly people (many of whom are on low incomes) to negative outcomes during heat waves and extremely hot days was emphasised by the key informants. Poor quality housing and a lack of financial resources increases the likelihood these individuals will experience significant discomfort during heat waves, and have restricted access to relief by using air conditioners in their own homes. Furthermore, both groups contain a higher proportion of individuals with health problems and illnesses that are exacerbated by heat, and in the case of older people are more susceptible to heat-related health problems.

3. There is substantial scope for low cost/no cost behaviour change in households.

Based on the online survey findings, it is likely that many Australian householders could implement additional strategies and behaviours in their homes that would increase their comfort and possibly decrease their reliance on air conditioners. For example, 56.1% of survey respondents do not use external shades or draw curtains, 56.9% do not move to a cooler room in the house, and 51% do not try to avoid strenuous activity during hot weather. The need for more effective public education and information strategies is discussed below.

4. Increasing general community understanding of heating and cooling as major sources of energy consumption and energy costs should be considered a priority.

In the online survey, 65% of householders were not able to correctly identify heating and cooling as the major sources of energy consumption in their homes. Key informants also emphasised that many groups, especially those who are older or are in low income groups, may also lack an understanding of factors that contribute to energy costs, and how to better manage their energy use.

The key informants also made a number of suggestions and recommendations regarding initiatives and programs that should be considered by government. In sum, the three main forms of support that the government could provide are:

5. Increasing community education and awareness of cost effective strategies to manage comfort and health during heat waves
6. Provide targeted financial support to encourage improvements to housing design, and to support groups at increased risk of negative outcomes during heat waves (i.e. low income and elderly people)
7. Introduce and effectively implement improvements to the Building Code of Australia.

We explore each of these recommendations in greater depth below.

6.4.1 Community Education and Awareness

The online survey findings and views of key informants indicate that the current information and awareness campaigns regarding behavioural coping strategies and housing modifications to facilitate better coping with heat waves are of limited effectiveness with regard to informing and influencing Australians' responses to heat waves.

Many of the key informants recommended that the Government more effectively educate the community on what a heat wave is and the temperatures that classify as a heat wave, the signs of distress or negative health impacts that should be monitored in elderly people, babies and individuals with poor health and how to respond to these signs accordingly. This information should also include advice regarding how to plan for heat waves and how to schedule activities during the day. Technological advice could also be provided. For example, individuals could be advised that evaporative air conditioners are effective cooling systems that are cheap to operate and maintain. Some key informants emphasised that the message that it is not necessary to have refrigerated air in order to be comfortable in hot weather is a key public message.

Householders' views on what governments can do to better support Australian's capacity to cope with heat waves concur with these key informant recommendations. Householders highlighted continued education and improvements to building design as the key policy area, specifically, educating the population with regard to personal coping strategies and strategies to minimise the impact of the heat on older homes and homes that have poor building design for heat waves. Several householders suggested a government-initiated review of these sorts of houses:

> *Maybe they can do like checklists with important points that influence on the comfort - on the high temperature inside your home so you can go with that checklist and have a review of your house* (Female, Sydney).

Some key informants also observed that general community campaigns are not likely to have an impact on particular groups. They suggest instead that visiting at-risk groups such as elderly and isolated individuals and individuals who do not speak English would be the most appropriate and effective approach to ensure they understand how to best manage their comfort, correct use of air conditioners (e.g. optimal temperatures, correction operation) and strategies to reduce health problems related to heat exposure.

Key informants with expertise related to child health recommended that government information campaigns need to emphasise the importance of ensuring children should not be left in locked enclosed environments (as this is the biggest risk for children) and could inform on the need for good ventilation in homes where children reside.

Beyond information campaigns, some key informants suggested that more direct and immediate feedback to households regarding energy use would both educate individuals regarding the high cost of heating and cooling, and also assist households to better manage their air conditioner use and hence save costs.

6.4.2 Targeted Financial Support

There was consensus amongst key informants regarding the importance of government grants and financial incentives to assist people to adapt their homes so that they can cope better in heat waves. For example, homeowners could be subsidised for installing more energy-efficient cooling or for making modifications to improve ventilation. Key informants with expertise on vulnerable groups also argued that government funded concessions on electricity bills are also an important and effective way of supporting individuals who have thermo-regulatory difficulties due to health conditions or illnesses. More could be done to raise awareness of these concession in states where they are available, and to improve access to these concessions more generally.

6.4.3 Housing Design

As noted previously, key informants emphasised that the key factor affecting the achievement of a comfortable home temperature is house design. Other studies in this project address issues of housing design in detail, so this section will not provide an extensive discussion. Some key informants argued that additional funding to support air conditioner use would not be addressing the fundamental problem of poor housing design. They recommended that the minimum requirements of the Building Code of Australia should be reviewed and revised.

Some key informants also noted the need to ensure building codes are designed that both ensure effective ventilation in the home whilst maintaining home security and taking into account other safety issues around the home. In Queensland, for example, a significant issue is children falling from windows and balconies. The use of window louvers can maintain ventilation and also prevent these types of accidents.

Further, one of the two householders that live in newly built homes with passive design features, that aim to achieve a comfortable household temperature without the use of air conditioning, suggested a government incentive scheme for passive control homes:

> *It's cheaper to have a badly designed house and put a $5000, $10,000 of air conditioning that's potentially going to use, 20% of that in electricity, through a yearly cycle than it is to design properly because* in turn there's no incentive for good solid [passive] design (Male, Brisbane).

Many key informants also argued that governments should increase investment in build affordable and energy-efficient households for vulnerable groups such as those with a low income or the elderly, who are most likely to be residing in low quality housing.

6.4.4 Future Research

This study provided an in-depth analysis of how Australians respond to heat waves and days of extreme heat, and the factors that impact on their use of air conditioning. Two areas of future research should be given particular priority.

First, the findings of this study suggest that there is still a lack of knowledge, and uptake of, low cost passive behavioural strategies in the home to increase comfort during heat waves and extremely hot days. A priority for future research should be large-scale community-based trials of campaigns/interventions to increase Australians' uptake of low cost strategies such as use of blinds, curtains, other types of shading and ventilation in the home. There is clearly a need for an evidence-based approach to improving community awareness of the financial cost of air conditioning, and alternative low cost strategies.

Second, more research is needed on groups that are particularly vulnerable or disadvantaged with regard to their capacity to cope during heat waves. This study focused mainly on two of these groups – low income and elderly people. There is a need for more in-depth research on these groups to provide high quality data on their experiences and responses to heat waves, and the programs and interventions that are most likely to increase their capacity to be comfortable and protect their health during heat waves and extremely hot days.

7. FRAMEWORK FOR REDUCING ADVERSE RISKS FROM HEAT WAVES

With the onset of climate change, heat waves are causing serious health risks for many Australians. As the current dominant response to heat waves is the use of larger capacity air conditioners by those who can afford them, electricity costs are escalating due to large investments being made to enlarge the distribution capacity, making cooling unaffordable to vulnerable groups, thus compounding these health risks. Apart from short term government and community organisation plans for coping with heat waves when they happen, no medium/long term plans or policies for coping with and responding to heat waves have been developed. It is proposed that a comprehensive framework be developed and implemented which can reliably help Australian households adapt to heat waves. Based on the outcomes of the multidisciplinary research carried out in this project, this section provides a first attempt to encompass proposed building and appliance regulations as well as a proposed program for changing household behaviour. It provides an initial overview of the proposed framework.

7.1 *Impact of Climate Change*

Predicted future changes in extreme temperatures during a Typical Meteorological Year (TMY) are presented in Table 7.1 for Australia's major cities. The Table clearly shows how not only are the number of warm and hot days increasing, but the number of cold days is also decreasing. Based on future TMY, the mainland cities will require more cooling with a corresponding reduction in heating needs (Table 7.2). This change has significant implications for the NatHERS house rating tool which provides energy star ratings for homes based on a current TMY reflecting current/ historical weather data. Given the lifespan of houses, consideration should be made to apply a TMY which reflects the anticipated climatic changes over the life of the building as described in Chapter 2.

Table 7.1 Change in the number of warm and cold days in the TMY.

Location	No. days, daily max ≥ 30°C			No. days, daily min ≤ 10 °C		
	Current	2030	2070	Current	2030	2070
Sydney	13	25	29	55	36	20
Adelaide	63	69	74	126	92	65
Melbourne	27	34	38	155	100	80
Brisbane	21	46	69	55	35	24
Perth	72	84	91	116	85	53
Darwin	303	344	354	0	0	0
Hobart	4	6	7	220	184	162

Table 7.3 presents the estimated change in the annual heating and cooling costs for each capital city, based on new house designs, existing air conditioning technology and no change to electricity prices. Significant increases in air conditioning costs are expected in Sydney and Brisbane with a decrease expected in Hobart, with some increase in other cities. However, the significant drop in heating demand will increase the peak to average power demand ratio, and prices may be adjusted such that heating cost savings may not be fully realised.

Table 7.2 Proportion of electricity usage for cooling relative to total air conditioning electricity usage for new homes.

	2012	2030	2050
Adelaide	67%	81%	85%
Brisbane	75%	85%	93%
Melbourne	32%	54%	62%
Hobart	2%	10%	13%
Sydney	77%	95%	97%
Perth	81%	91%	94%

Table 7.3. Increase in electricity running costs with climate change.

	2030	2050
Adelaide	1%	8%
Brisbane	61%	127%
Melbourne	-1%	4%
Hobart	-26%	-29%
Sydney	118%	168%
Perth	9%	28%
Darwin	25%	50%

At 38% of total peak power demand, air conditioning represents the single most dominant factor which determines peak electric power demand and the subsequent size and cost of electricity infrastructure to satisfy this demand. Table 7.4 presents the impact on peak power demand and infrastructure size increases necessary to cope with climate change in a business as usual scenario. Some increase is necessary in SA, Vic, WA and NT; however a more dramatic electricity infrastructure expansion is required in NSW and Qld. Consequently, with the absence of peak demand reduction strategies, increased air conditioning needs associated with climate change will be another elements contributing to increases in electricity tariffs on top of the projected trends.

Table 7.4 Impact of climate change on the peak power demand

	Total additional peak power annual growth rate		Current peak demand from a/c (GW)	Climate change induced additional demand (GW)	
	2030	2050		2030	2050
SA	0.01%	0.03%	1.1	0.01	0.04
Qld	0.71%	0.44%	3.17	1.3	1.8
Vic	0.10%	0.12%	3.6	0.19	0.47
NSW	0.81%	0.43%	5.7	2.4	2.8
WA	0.01%	0.06%	1.5	0.01	0.10
NT	0.07%	0.16%	0.22	0.01	0.04

7.2 *Improvements to Building Design and Regulation*

This project has demonstrated the viability of a number of approaches in enabling a reduction of air conditioning peak demand. Current regulatory framework includes no provision to support peak power mitigation from the residential sector. Building energy regulations only focus on evaluating the total energy requirements to meet thermal comfort. Rating and regulating the maximum peak power demand from building designs is needed. This could be implemented through a peak cooling star rating approach through NatHERS accredited software. In line with the move away from prescriptive measures, this approach enables relevant parties to implement a range of strategies for reducing the peak cooling demand from the building. Progressive increases in the peak demand minimum performance standards for new dwellings and renovations would directly reduce peak air conditioning demand over time.

For new dwellings, a new building design philosophy has been developed with a focus on making the home more comfortable during peak summer periods. This may lead to increased heating requirements. However, the total heating and cooling requirements for the building is reduced, and this approach reverses the current focus of energy efficient design, on reducing heating demand. The concept of including a cool retreat or internal living space, specifically allocated for use during heat waves, is presented, and provides the basis for future house design. These concepts were combined with various design options such as improved glazing or highly reflecting roof surfaces. It is concluded that these designs are well suited to a changing climate and can typically reduce peak cooling demand by approximately 67% for the region encompassing Qld, NSW, Vic and SA. If this philosophy is applied to all new homes in these states, based on a 2% house replacement rate, this would result in an annual total peak demand reduction rate of 0.2% to 2030 and 2050. This translates to a reduction in network capacity of 0.61 GW and 1.3 GW by 2030 and 2050 respectively equivalent to a number of central power generation plants.

Although a number of measures can reduce peak cooling demand, the single most effective options relate to reducing heat flow through the roof. Research and field measurements have shown that current regulations and installation practices relating to bulk insulation do not achieve the expected thermal resistance of roofing systems. Bulk insulation within the roof is a critical solution to reducing total and peak cooling demand in housing. Therefore consideration should be given to correctly rating insulated roofing systems in NATHERS and the BCA as well as implementing quality assurance systems, which would bring Australia in line with leading OECD regulations. Thermography is a common low cost tool used for assessing insulation in buildings. In the absence of these measures, de-rating the thermal R value of bulk insulation in roofing systems should be considered in any peak cooling analysis.

An effective and reliable measure of reducing heat flow through the roof is the application of roofing colours which deliver a high Total Solar Reflectance (TSR), as well as the use of reflective foils in combination with bulk insulation. This can be applied to both new and existing homes. Table 7.5 shows the potential benefit in reduction in the total peak demand in various states. This analysis is based on what is typically used in new homes in these states. The total potential reduction in peak power demand in the National Electricity Market (NEM) is 3.3 GW by 2030 which is comparable to the total increase associated with climate change of 4 GW.

Table 7.5 Summary of the reduction in electric power demand associated with roof heat flow reduction measures applicable to new and existing houses with air conditioning systems, implemented 2012 to 2030.

	Demand reduction (annual peak reduction to 2030)		Peak demand reduction (GW)	
	TSR = 0.9, foil (50% of homes)	TSR= 0.9, foil (50% of homes), improved ducting (all systems)	TSR = 0.9, Foil (50% of homes)	TSR= 0.9, foil (50% of homes), improved ducting (all systems)
SA	0.19%	0.42%	0.21	0.34
Vic	0.36%	n/a	1.34	n/a
NSW	0.31%	n/a	1.60	n/a
WA	0.27%	0.54%	0.41	0.61

The cost associated with retrofit or new house designs are within the general range of what is currently constructed. Some options such as changing roof colour, applying improved glazing or reorganising the house design represent negligible cost increase, particularly when carried out as a part of other renovation activities, whereas other options such as incorporating a basement as a cool retreat represents considerable additional costs. Overall, the opportunity to apply these options and minimise cost can be readily applied and assessed using a NatHERS peak and total star rating scheme. Furthermore, these costs need to be put in the context that inaction will likely result in dramatic increases in electricity running costs for air conditioning.

7.3 *Improvements in Air Conditioning Regulations and Practices*

In order to reasonably assess the energy and peak power demand, a new house assessment method for dwellings should go beyond just considering the building shell and incorporate heating/cooling appliances and other major appliances being used as the total and peak electricity consumption is not completely reflected in the energy or peak thermal energy requirement of the building design. Appliances can potentially be linked to their star rating as defined by the Minimum Energy Performance Standard (MEPS).

The sizing of air conditioners is another area which requires regulating, bringing the selection in line with current practices applied to commercial buildings. This will prevent oversizing by air conditioner retailers. This involves consideration for the location and the building design. For a single split air conditioner which conditions a single room, a suitable floor design load should be used based on the age or, if available the peak cooling rating. For whole of house cooling, an appropriate design calculation should be required considering the actual building design as well as the type of being selected. The standards should refer to the modified design temperatures, and appropriate indoor temperature set points, to prevent oversizing of the system. The maximum capacity of an air conditioner should not exceed the name plate specification, thus removing the ‘hidden’ capacity of some systems.

It is also appropriate that Minimum Performance Energy standards (MEPS) encompass the ducting component of air conditioners. Consideration should also be given to requiring quality assurance systems for ducted systems to prevent air leakage. Evaporative cooling is an effective cooling technology which requires significantly lower power for cooling compared to a refrigeration based system. MEPS need to incorporate evaporative cooling systems on an equivalent basis to other cooling equipment.

The general population have the capacity to adapt to meet thermal comfort needs during heat waves. This is enhanced within the home where the opportunity to adapt is greater. Consideration should be given to implement the principles of adaptive comfort in informing the selection of indoor set points in air conditioner calculations and standards. For each location, a suitable indoor set point should be specified, based on further field studies. This should become the basis for modelling the heating and cooling load requirements for buildings and the air conditioning sizing process, where applicable. This will further reduce the likelihood of over sizing of air conditioners. The adaptive comfort results demonstrate the viability of smart grid control of air conditioners during peak periods, where people can adapt to the minor increases in room temperature. The impact of raising the thermostat to that defined by adaptive comfort principles on the total peak demand is presented in Table 7.6. Further work is needed to enhance and fine tune this potential.

Table 7.6. Impact of adaptive comfort applied to 80% of systems on the total peak demand.

	Current Set point	Adaptive comfort summer set point	Demand reduction rate 2012 to 2030	Total demand reduction (GW)
SA	25	28.4	0.41%	0.3
Vic	24.0	27.5	0.73%	1.9
Qld	25.5	28.9	0.75%	1.4

7.4 *Improvements in Public Awareness*

Fundamentally the outcome of currents trends of relying more heavily on air conditioning is a function of human behaviour. There is a desire and need for improved public awareness to enable households to implement changes to their houses, to prepare for heat waves, as well as how to behave during a heat wave to better manage their comfort needs. Furthermore, improved public support for collective behaviour modification will also support necessary regulatory changes and industry practices, to adapt houses to heat waves.

Programs and policies aimed at population behaviour change should recognise and address differential capacity based on financial resources and health. Specifically, those on low incomes and more vulnerable individuals (e.g. elderly persons or those with chronic health conditions) are more likely be living in inferior quality homes and have less capacity to engage in particular adaptive behaviours and responses. General community education programs and changes to policy and practice are not likely to meet the needs of these groups. Rather, specific and targeted community-level interventions are needed.

7.5 *Recommendations*

Overall the proposed framework presented is based on an integrated approach to respond to heat waves. A combination of strategies including behaviour change, dwelling reconfiguration and the use of energy efficient air conditioning is required. These strategies can collectively reverse the current compounding health risks associated with climate change. In themselves each measure would achieve limited success due to the potential negative impact of other factors. However, the complementary nature of each component will deliver a framework for adapting households and diminish the risks associated with heat waves to individuals as well as reducing the need for augmenting the electricity infrastructure. On the basis of the research carried out in the project, the following actions are recommended for inclusion in a framework for adapting Australian households to heat waves:

- New TMY climatic data has been developed for 2030 and 2070. Climate data used in NATHERS and air conditioning design calculations must be adjusted to reflect a changing climate.
- Regulations for new buildings need to include a rating, through NATHERS, for the maximum peak power demand from building designs.
- The most effective methods for reducing the cooling demand for existing dwellings is to modify their roofs by increasing their total solar reflectance, adding reflective foils and increasing thermal insulation.
- Implement appropriate quality assurance measures of insulation installation in roofs consistent with other regulations in OECD countries.
- In addition to considering reducing annual energy and power demand for existing housing, special attention must be paid to minimise peak cooling demand in new buildings. The inclusion and use of cool retreats has been demonstrated to provide thermal comfort at dramatically reduced power consumption.
- Incorporate air conditioners within NATHERS considering the peak electrical demand.
- Regulate the sizing of air conditioners installed in dwellings.
- Incorporate the whole of air conditioning system in regulations, ensuring all regulations apply to all new systems rather than those installed in new buildings.
- Adopt quality assurance measures for installed air conditioners
- Adopt adaptive thermal comfort settings in air conditioning design guides and standards, and have these standards regularly updated.
- Educate public on the links between climate change and heat waves, likely impact on health and actions for reducing its impact
- Develop adaptation information which is currently lacking but welcomed within the community.
- Develop targeted interventions for specific vulnerable groups

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APPENDIX: ONLINE SURVEY QUESTIONS

SECTION A – ASK ALL RESPONDENTS

A2. Are you male or female?

Male 1
Female . 2

A3. How old are you?

17 years or under..01
18-24 years...........02
25-29 years...........03
30-34 years...........04
35-39 years...........05
40-44 years...........06
45-49 years......07
50-54 years......08
55-59 years......09
60 years or over 10
Rather not say . 11

SECTION B: ASK IF AGED 18 YEARS OR OVER IE CODE 02-10 IN A3. CODE 01, 11 TERMINATE WITH THANKS

B1. Are you the main/equal main decision-maker in your household for financial matters, or are you not one of the main decision-makers?

Main/equal main decision maker................................ 1 .... * B2
Not decision maker .... 2 .... # ....Term

ASK IF HOUSEHOLD DECISIONMAKER, IE CODE 1 IN B1. CODE 2 TERMINATE WITH THANKS

SR

B2. Which of the following best describes the area where you live?

Please select one option only

A regional/rural town………………1
Regional city (not a state capital) 2
Suburbs of a capital city…….. 3
In the CBD of a capital city 4
A farm/rural property……… 5

SR

B3 Do you own or rent your home?

Own outright/no mortgage..........1

Please select one option only

Own with a mortgage 2
Rent (or pay board).................... 3
Involved in a rent-buy scheme ... 4

Live there rent free/life tenure/ ive with parents/live with adult children.. 5
Don't know 6

SR

B4 Which of the following best describes your home?

Please select one option only

Single-family home...........................1
Duplex, triplex, fourplex or townhouse (semi-detached or attached home)…...2
Apartment/unit in a residential building 3
Seniors apartment or residence without assisted living care services ……….4

Nursing home or other type of assisted living...5
Apartment/flat in commercial building/ over shops 6
None/Don't know 7

MR

B5. Which of the following types of air conditioning does your home have, if any

Please select all that apply

Central ducted system (The unit distributes air conditioning through vents in the ceiling) .... 1 * B6
Window or wall unit .... 2 * *
Evaporative cooler portable floor unit ..... 3 # #
Electric/ceiling fans .... 4 # B8

None/Don't know 5

ASK IF HAVE AN AIR CONDITIONER UNIT, IE CODE 1-2 IN B5. CODE 3-5 GO TO B8

		SR
B6	If you own an air conditioner, how old is it? **Please select one option only**	Less than 1 year ...... 1 1–4 years................. 2 5–9 years................. 3 10–19 years............ 4 ------------------------------------ 20 years and older ... 5 You do not own an air conditioner ..... 6 Don't know.............. 7
		MR
B7.	In which of the following rooms do you have air conditioning (excluding ceiling fans or mobile portable floor units)? **ROTATE 1-4** **Please select all that apply**	All through the house 1 Bedroom(s) .... ……….2 Lounge / dining room…..3 Another room .... ……….4 None/Don't know……….5

ASK ALL ELIGIBLE

		SR
B8	Do you think that climate change...? **ROTATE 1-3** **Please select one option only**	Is increasing the frequency and severity of heat waves .... 1 Is decreasing the frequency and severity of heat waves .... 2 Does not have an impact on heat waves .... 3 None – there is no climate change .... 4 Don't know............................ 5

		SR
B9	How would you rate your household's current ability to cope with periods of extreme heat? **Please select one option only**	Very good... 1 Good .... 2 Neutral .... 3 Poor .... 4 Very poor.... 5

		SR
B10.	Do you know ahead of time if it's going to be very hot for one or more days? **Please select one option only**	Almost always .1 Frequently ....2 Occasionally....3 Rarely/never....4

		MR
B11.	Do you or another person living in your household currently have ongoing effects of any of the following? **ROTATE 01-17** **Please select all that apply**	Disability or reduced mobility .... 01 Diabetes .... 02 High blood pressure, also known as hypertension....................................... 03 High levels of LDL cholesterol (the so-called "bad" cholesterol) .... 04 -- Coronary disease .... 05 Angina (also known as angina pectoris) .... 06 Myocardial infarction/heart attack .. 07 Stroke .... 08 -- Any other cardiovascular disease .. 09 Emphysema.................................. 10 Chronic bronchitis.......................... 11 Asthma 12-- Other respiratory problems .... 13 A malignant tumour (cancer) of any type .... 14 Multiple sclerosis 15

Parkinson's disease 16

Severe obesity 17

None/Don't know 18

SR

B12. To what extent do you agree or disagree with the following statement: "Only people in poor health are at risk of illness or even death during heat waves"?

Please select one option only

Strongly agree……1

Agree .... ……..2

Neutral .... ……..3

Disagree...... ……..4

Strongly disagree 5

SR

B13. During the last 5 years, how many days on average per year have you felt uncomfortably hot at home?

Please select one option only

Never ....………1

1–4 days ....…….…2

5–10 days .... ……….3

More than 10 days …4

MR

B14. Below is list of heat mitigation strategies for coping during heat waves. From the list, please select the strategies that your household **CURRENTLY** adopts when faced with a period of extreme heat.

ROTATE 01-24

Please select all that apply

Plan the day in a way that allows you to stay out of the heat 01
.... *
.... *

Buy extra items ahead of the hotter weatherl to make sure there is enough food to last...... 02
.... *

Pay bills online or over the phone to avoid going out 03
.... *

Stay indoors or in the shade during the hottest part of the day.................................... 04
.... *

Spend more time in the workplace where it is cooler 05
.... *

Move to a cooler room in the house.......... 06
.... *

Avoid strenuous activity 07
.... *

Wear a hat, loose clothing, sunglasses and sunscreen if going out is unavoidable............. 08
....*

Drink plenty of water................................. 09
.... *

Spend more time working from home 10
.... *

Use awnings, shadecloths or external blinds on the sides of the house facing the sun 11
.... *

Use external shades or draw curtains to reduce the heat from the sunlight 12
.... *
....B15

Use your air conditioner............................ 13
.... *

Use an evaporative cooling portable unit .. 14
.... *

Use ceiling or pedestal fan 15
.... *

Avoid time in the car/reduce the number of trips in the car..16
....*

Adjust the setting of air conditioner to cope with heat wave..17
....*

Ensure sufficient air circulation by leaving a secured window or door open........................18
....*

Take cool showers or splash yourself with cold water several times a day 19
....*

Go to an air-conditioned building in the local area (shopping mall, community centre, etc.) 20
....*

Avoid alcohol, tea, coffee and sugary or fizzy drinks 21
....*

Eat little and often, and try to eat more cold food..22
....*

Go to a swimming pool 23
....*

Sit in your car with the air conditioning on.24
....*
....*

None/Don’t know 25
....#
....B16

PIPE IN RESPONSES FROM B14. CODE 24 GO TO B16

MR

B15. And what are the THREE main strategies that your household **CURRENTLY** adopts when faced with a period of extreme heat (select THREE options only)

ROTATE OPTIONS

Please select three options only

Plan the day in a way that allows you to stay out of the heat 01

Buy extra items ahead of the hotter weather to make sure there is enough food to last.......... 02

Pay bills online or over the phone to avoid going out 03

Stay indoors or in the shade during the hottest part of the day 04

Spend more time in the workplace where it is cooler 05

Move to a cooler room in the house.......... 06

Avoid strenuous activity 07

Wear a hat, loose clothing, sunglasses and sunscreen if going out is unavoidable............ 08

Drink plenty of water................................ 09

Spend more time working from home 10

Use awnings, shadecloths or external blinds on the sides of the house facing the sun 11

Use external shades or draw curtains to reduce the heat from the sunlight............................. 12

Use your air conditioner............................ 13

Use an evaporative cooling portable unit .. 14

Use ceiling or pedestal fan 15

Avoid time in the car/reduce the number of trips in the car 16

Adjust the setting of air conditioner to cope with heat wave... 17

Ensure sufficient air circulation by leaving a secured window or door open 18

Take cool showers or splash yourself with cold water several times a day............................. 19

Go to an air-conditioned building in the local area (shopping mall, community centre, etc.) 20

ASK ALL ELIGIBLE

MR

B16. The list of heat mitigation strategies for coping during heat waves is repeated below. This time, please select the MAIN strategies that your household is most likely to adopt in **FUTURE** periods of extreme heat

ROTATE 01-24

Please select all that apply

Plan the day in a way that allows you to stay out of the heat 01

Buy extra items ahead of the hotter weather to make sure there is enough food to last........ 02

Pay bills online or over the phone to avoid going out 03

Stay indoors or in the shade during the hottest part of the day 04

Spend more time in the workplace where it is cooler 05

Move to a cooler room in the house........ 06

Avoid strenuous activity 07

Wear a hat, loose clothing, sunglasses and sunscreen if going out is unavoidable........ 08

Drink plenty of water........ 09

Spend more time working from home 10

Use awnings, shadecloths or external blinds on the sides of the house facing the sun 11

Use external shades or draw curtains to reduce the heat from the sunlight........ 12

Use your air conditioner........ 13

Use an evaporative cooling portable unit.. 14

Use ceiling or pedestal fan 15

Avoid time in the car/reduce the number of trips in the car 16

Adjust the setting of air conditioner to cope with heat wave........ 17

Ensure sufficient air circulation by leaving a secured window or door open 18

Take cool showers or splash yourself with cold water several times a day........ 19

Go to an air-conditioned building in the local area (shopping mall, community centre, etc.) 20

Avoid alcohol, tea, coffee and sugary or fizzy drinks 21

Eat little and often, and try to eat more cold food 22

Go to a swimming pool 23

Sit in your car with the air conditioning on . 24

None/Don’t know 25

MR

B17. Below is a list of changes you can make to your home to better cope during heat waves. From the list, please select the changes, if any, that your household is most likely to consider adopting in **FUTURE** periods of extreme heat. **ROTATE 01-10**

Please select all that apply

Install or upgrade insulation in the roof ... 01

Install new air conditioning 02

Upgrade your existing air conditioning 03

Move to a smaller/more energy-efficient home 04

Have air conditioner serviced before summer 05

Buy more pedestal fans 06

Install ceiling fans 07

Install awnings, shadecloths or external blinds on the sides of the house facing the sun 08

Use external shades or draw curtains to reduce the heat from the sunlight 09

Install awning or shade cover over a veranda, balcony or outdoor area 10

None/Don’t know 11

MR

B18. What are/would be the most important reasons for using an air conditioner in your household during a heat wave (select THREE options only) **ROTATE 1-8**

Please select up to <u>three</u> options

To continue daily activities as usual 1

To feel comfortable 2

To keep your health stable 3

To reduce stress and irritability 4

To reduce the impact of heat on the Illness/existing conditions of yourself or others 5

To sleep better 6

To stop feeling tired and debilitated 7

To reduce the humidity level 8

Don't know...9

MR

B19. Which of the following could prevent or limit you from using air conditioning in your household during a heat wave? (select THREE options only) **ROTATE 01-08**

Please select up to <u>three</u> options

It is too expensive to buy 01

It is too expensive to run........... 02

It is difficult to adjust the temperature 03

It is not good for your health 04

It prevents fresh air from getting in 05

It makes your home too cold..... 06

It is not comfortable 07

It makes too much noise........... 08

Landlord won't install air conditioning 09

Don't know................................ 10

SR

B20 How much would you be willing to spend to make your house and air conditioner cope better during a heat wave which will also reduce your energy bill?

Please select one option only

You are not willing to spend anything 1

Up to $2000........................... 2

$2000–$4,999 3

$5,000–$9,999 4

$10,000 or more.................... 5

Not applicable/Don't know 6

B21.	If heat waves became more common, would you be willing to stay confined to one part of your house during heat waves to stay cool and save on air conditioning costs?	Yes .... 1 No......... 2
		SR
B22.	If your electricity price were to go up, what percentage increase above your last bill would you consider to be large? **Please select one option only**	5%............. …….1 10%........... …….2 20%............……3 30%............……4 40%........... …….5 50% and above….6
		SR
B23	In your opinion, what is the largest contributor to your energy bills? **ROTATE 1-7** **Please select one option only**	Heating and cooling............... 1 Hot water.............................. 2 Lighting................................. 3 Fridge................................... 4 --- Cooker/oven/kitchen appliances 5 TV and other entertainment units 6 Computer and other home office appliances...........………..7 Don’t know..................... ……….8

B24 To what extent do you support the following energy pricing mechanisms?

ROTATE A-G

	A LOT	SOME	A LITTLE	NONE
A. Higher prices during peak periods and lower prices at other times	1	2	3	4
B. Reduced prices if your energy retailer could temporarily and marginally control and reduce your air conditioner use	1	2	3	4
C. A more variable time-of-use (monthly) price, where prices can vary between off-peak and on-peak on a **monthly** basis	1	2	3	4
D. A more variable time-of-use price (hourly), where prices can vary between off-peak and on-peak on an **intraday** basis	1	2	3	4
--				
E. A single flat price all year round	1	2	3	4
F. A set schedule of prices for: peak summer, peak winter, and all other times	1	2	3	4
G. A peak penalty mechanism where you pay a penalty if you exceed a limit during peak periods in exchange for an overall lower rate for the rest of the year	1	2	3	4

DEMOGRAPHICS

C1. What is your highest level of educational attainment?

Please select one option only

	SR
Primary school	1
Year 9 or below	2
Year 10	3
Year 11 or 12	4
--	
TAFE Certificate/ Diploma/apprenticeship	5
Undergraduate university	

		diploma/university degree…..6
		Postgraduate university……...7

C2.	Which of the following best describes your employment status?	Not working or looking for work ….1 ....# C4
		Unemployed and looking for work ..2 ....#
		Employed.......................... …3 * *
		Self-employed......................4 * C3

ASK IF EMPLOYED OR SELF-EMPLOYED, IE CODE 3-4. CODE 1-2 GO TO C4

C3.	If you are employed or self-employed, how many hours per week do you usually spend in paid work, including any paid or unpaid overtime?	Less than 10…01
		10-19......... …02
		20-29......... …03
		30-34......... …04
		35-39......... …05
		40-44......... …06
		45-49......... …07
		50-54......... …08
		55-59......... 09
		60-69......... …10
		70-79......... …11
		80 or more…..12
		Not applicable.13

ASK ALL ELIGIBLE

C4.	What is your household's combined annual income from all sources before tax?	Under $30,000 per year ($577 per week).. 01
		$30,000–$39,999 per year ($577–$769 per week).................. 02
		$40,000–49,999 per year ($770–$962 per week).................. 03
		$50,000–59,999 per year ($963–1,154 per week)................. 04

$60,000–69,999 per year
($1,155–$1,346 per week)............ 05
$70,000–79,999 per year
($1,347–$1,538 per week)............ 06
$80,000–89,999 per year
($1,539–$1,731 per week)............ 07
$90,000–99,999 per year
($1,732–$1,923 per week)............ 08

$100,000–129,999 per
year ($1,924–$2499 per week)...... 09
$130,000 or more per
year ($2500+ per week) 10
Prefer not to say............................ 11

C5. How many people live in your household, including yourself?

One ....1 # C7
Two ....2 * *
Three.........3 *
Four...........4 * C6
Five ....5 *
Six or more.6 * *

ASK IF TWO OR MORE LIVE IN HOUSEHOLD IE CODE 2-6 IN C5, ONE PERSON HOUSEHOLDS GO TO C7

C6. How many children aged 17 years or younger live in your household?

None ....…1
One ....…2
Two ....…3
Three....... ….4
Four .... ….5
Five or more..6

ASK ALL ELIGIBLE

C7. How many adults (including yourself) in your household are aged over 65?

None 1
One 2
Two 3
Three..........4
Four............5
Five or more..6

SR

C8. Which of the following best describes your household?

Please select one option only

Couple family with dependent children only 1
Couple family with dependent children and other persons 2
One parent family with dependent children only 3
One parent family with dependent children and other persons 4

Couple only................................. 5
Multiple family household with dependent children 6
Multiple family household without dependent children 7
Single person household 8

C9. On a typical weekday (i.e. Monday to Friday), who is at home in your household during the day

Please select all that apply

One or more adults aged 18-64..............
One or more adults aged 65 or over........
One or more children aged 5 years or younger...
One or more children aged 6-12 years ....
One or more children aged 13-17...........
No-one (all at work or at school).............
Don’t know ....

Those are all of the questions. Thank you for your time and participation.

Table A1: Groups most likely to agree that climate change increases the frequency/severity of heat waves, per cent

	% perceive increase frequency/severity of heat waves due to climate change
18-34 years	47.3
35-49 years	45.0
50+ years	33.3
University education	47.1
TAFE/VET education	35.6
Year 11/12	40.8
Year 10 or below	40.9
Employed	43.6
Unemployed	39.7
Not in labour force	38.5
Rent	47.1
Other arrangement	46.8
Own home with mortgage	42.1
Own home outright	33.7
Adelaide	43.8
Brisbane	46.8
Sydney	39.9

Table A2: Groups most likely to agree that there is no climate change, per cent

	% agree there is no climate change
Men	20.0
Women	13.0
Partnered without children	19.4
Sole adult household	18.1
Partnered with children	15.4
Sole parent	12.2
Multiple family member	11.5
Sydney	18.4
Brisbane	15.5
Adelaide	12.2

Table A3: Type of air conditioning by social demographics and housing type, online survey respondents, per cent

	Central ducted	Evaporative/ portable unit	Electric/ceilin g fans	None
Partnered with children	34.3	7.7	31.5	10.6
Sole parent	26.3	13.2	37.6	12.2
Partnered without children	31.8	4.9	26.8	19.1
Multiple family members	25.5	5.3	25.5	15.2
Sole adult household	15.6	5.2	23.6	28.6
Employed	28.8	7.5	-	-
Not in labour force	24.9	2.8	-	-
Unemployed	16.9	7.5	-	-
Own home outright	33.2	4.4	25.9	13.9
Own home with mortgage	37.2	8.4	32.1	10.2
Rent	12.0	5.3	25.2	30.3
Other arrangement	31.5	6.3	23.4	15.7
Single family home	32.9	5.5	32.3	11.3
Apartment/unit	24.3	8.0	25.4	18.7
Semi-detached/attached	16.2	8.2	18.9	35.3
< 40k	16.4	-	27.2	25.7
$40k < $69,999k	19.4	-	24.7	18.4
$70k–$89,999k	38.3	-	31.4	18.8
$90k+	35.6	-	30.5	13.0
Adelaide	51.1	42.9	24.7	4.2
Brisbane	9.6	61.6	38.8	15.8
Sydney	28.0	45.3	24.3	23.5

Note. ‘-‘ = no significant difference between groups. Window/wall unit not included in this table as there were very few statistically significant differences between groups.

Table A4: Age of air conditioning by social demographics and housing type, online survey respondents, per cent

	< 5 years	5–9 years	10+ years
Own home outright	33.4	40.2	26.4
Own home with mortgage	44.6	40.5	14.8
Rent	66.7	23.6	9.7
Other arrangement	35.8	43.2	21.0
Single family home	40.8	38.6	20.6
Semi-detached/attached	52.9	33.0	14.0
Apartment/unit	65.4	30.8	3.8
< 40k	49.3	31.6	19.1
$40k < $69,999k	52.8	33.4	13.8
$70k–$89,999k	41.0	44.6	14.4
$90k+	45.5	38.5	16.0
Adelaide	39.8	31.6	28.6
Brisbane	49.7	38.9	11.5
Sydney	47.3	38.0	14.7

Note. ‘-‘ = no significant difference between groups.

Table A5: Reasons for using air conditioning in heat waves by social demographics and housing type, online survey respondents, per cent

	Comfort	Sleep	Stress /irritability	Tired/ debilitated	Daily activities	Reduce impact illness	Keep health stable
Men	-	-	18.5	14.2	13.0	-	-
Women	-	-	24.8	20.0	17.6	-	-
18-34 years	-	52.9	24.6	13.7	-	12.7	9.5
35-49 years	-	54.5	23.8	17.5	-	13.7	6.8
50+ years	-	60.6	15.7	20.7	-	18.9	14.2
Employed	62.8	57.0	-	16.5	-	12.7	7.8
Not in labour force	55.1	50.6	-	20.7	-	22.2	16.9
Unemployed	51.5	61.5	-	11.1	-	14.7	11.0
< 40k	49.5	49.4	16.0	13.4	-	26.1	15.9
$40k < $69,999k	55.6	49.9	20.4	23.0	-	12.3	11.1
$70k–$89,999k	66.4	56.2	28.4	22.0	-	9.0	10.5
$90k+	66.1	61.7	24.5	16.5	-	12.0	7.4
Adelaide	66.1	60.9	26.3	19.6	23.2	-	14.2
Brisbane	59.1	58.6	24.2	20.1	13.7	-	9.2
Sydney	59.6	53.0	19.1	15.0	13.7	-	9.0

Note. ‘-‘ = no significant difference between groups.

Table A6: Reasons for using air conditioning in heat waves by social demographics and housing type, online survey respondents, per cent

	Expense to buy	Expense to run
Men	-	61.5
Women	-	68.0
18-34 years	-	60.2
35-49 years	-	65.0
50+ years	-	69.7
Partnered with children	22.5	-
Sole parent	28.6	-
Partnered without children	22.3	-
Multiple family members	18.1	-
Sole adult household	28.6	-
Employed	24.8	64.0
Not in labour force	20.5	57.0
Unemployed	29.4	69.1
Own home outright	15.0	-
Own home with mortgage	21.6	-
Rent	32.2	-
Other arrangement	25.2	-
< 40k	33.7	-
$40k < $69,999k	24.7	-
$70k–$89,999k	20.9	-
$90k+	19.3	-
Adelaide	16.0	
Brisbane	21.0	
Sydney	27.9	

Note. ‘-‘ = no significant difference between groups.

Table A7: Correctly identified heating and cooling as largest contributor to energy bill by social demographics and housing type, online survey respondents, per cent

	Identified heating/cooling
18-34 years	31.3
35-49 years	33.8
50+ years	38.4
Employed	35.7
Not in labour force	31.1
Unemployed	27.9
Own home outright	41.2
Own home with mortgage	34.3
Rent	31.0
Other arrangement	28.3
< 40k	23.8
$40k < $69,999k	34.1
$70k–$89,999k	34.5
$90k+	39.5
Adelaide	43.9
Brisbane	26.0
Sydney	35.1

Note. ‘-‘ = no significant difference between groups. Data is a proportion of respondents who correctly identified ‘heating and cooling’ as opposed to a range of other appliances in the home that use electricity (e.g. lighting, fridge, computer) or chose ‘none of these appliances’.

Table A8: Amount willing to spend to improve capacity of home and air conditioning to cope during heat waves by social demographics and housing type, online survey respondents, per cent

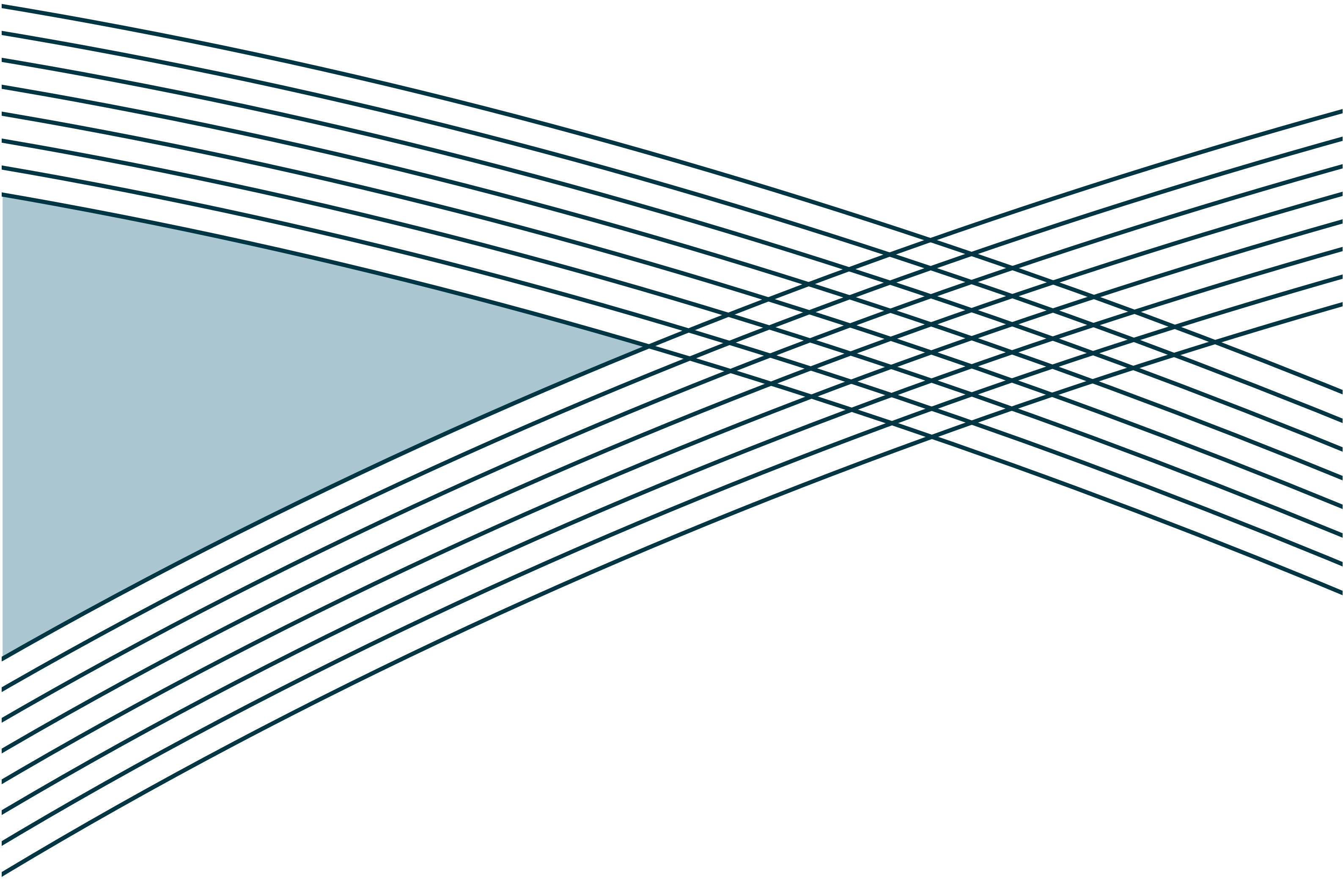
	Not willing to spend anything	Up to $2,000	$2000–$4,999
18-34 years	27.5	51.2	14.6
35-49 years	25.4	53.0	16.2
50+ years	40.7	44.0	12.4
Employed	27.4	51.8	15.5
Not in labour force	38.8	45.4	12.0
Unemployed	44.8	36.8	10.3
Own home outright	36.8	45.8	13.2
Own home with mortgage	21.0	52.1	18.6
Rent	37.8	49.9	10.6
Other arrangement	37.9	49.5	9.5
< 40k	49.9	41.5	7.5
$40k < $69,999k	28.0	54.8	14.0
$70k–$89,999k	30.0	44.0	17.2
$90k+	22.8	52.9	17.0
Adelaide	28.9	49.1	18.0
Brisbane	36.3	49.8	11.0
Sydney	28.2	50.0	15.3

Note. '-' = no significant difference between groups. A very small proportion of respondents (5.1%) reported a willingness to spend $5,000 or more; therefore, this category was not analysed in detail.

Table A9: Not willing to be confined to one part of the house during heat waves to stay cool and save on air conditioning costs, online survey respondents, per cent

	Not willing
18-34 years	24.9
35-49 years	24.7
50+ years	33.5
Employed	26.4
Not in labour force	33.0
Unemployed	15.4
Single family home	29.6
Semi-detached/attached	13.6
Apartment/unit	29.0

Note. '-' = no significant difference between groups.



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