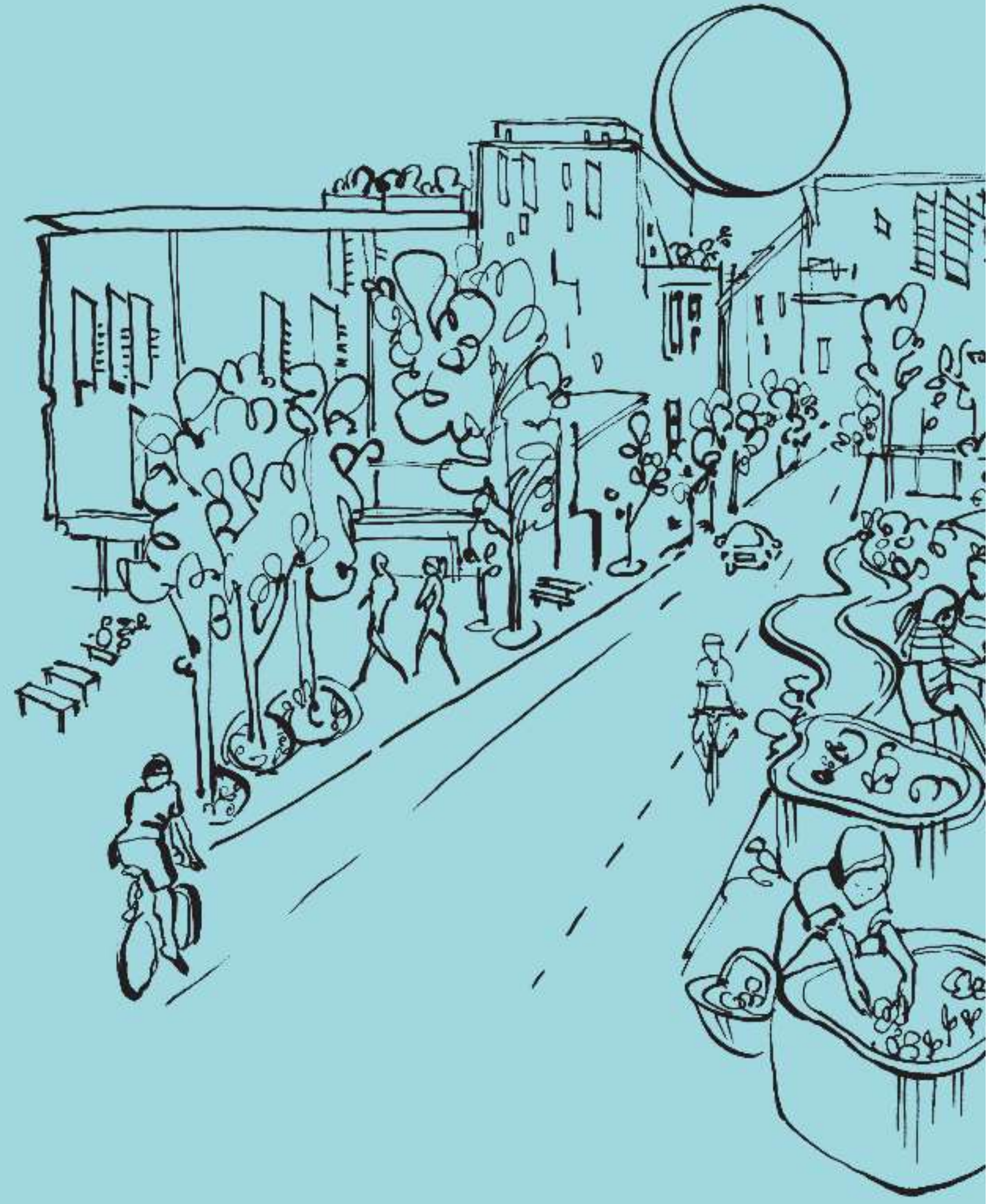
LOW CARBON LIVING CRC

# Mainstreaming Low Carbon Retrofits in Social Housing.

## Targeted review of evidence of direct and co-benefits of energy efficiency upgrades in low income dwellings in Australia.



| | |
|---|---|
| Authors | Daly D, Halldorsson J, Kempton L, Cooper P |
| Title | Targeted review of evidence of direct and co-benefits of energy efficiency upgrades in low income dwellings in Australia. |
| ISBN | |
| Date | 14/05/2018 |
| Keywords | Co-benefits, low income, retrofit, non-energy benefits, Social Housing, Community Housing, Energy |
| Publisher | CRC for Low Carbon Living |
| Preferred citation | Daly D, Halldorsson J, Kempton L, Cooper P, 2018, *Targeted review of evidence of direct and co-benefits of energy efficiency upgrades in low income dwellings in Australia.* CRC for Low Carbon Living |

Australian Government
Department of Industry, Innovation and Science
Business
Cooperative Research Centres Programme

## Acknowledgements

This research is funded by the CRC for Low Carbon Living Ltd supported by the Cooperative Research Centres program, an Australian Government initiative.

## Disclaimer

## Peer Review Statement

The CRCLCL recognises the value of knowledge exchange and the importance of objective peer review. It is committed to encouraging and supporting its research teams in this regard.

The authors confirm that this document has been reviewed by the project's steering committee. These reviewers provided constructive feedback, which was considered and addressed by the authors.

# Contents

## List of Tables

## List of Figures

# Acronyms

| | |
|---|---|
| ASBEC: | Australian Sustainable Built Environment Council |
| CHP: | Community Housing Provider |
| CIBSE: | Chartered Institution of Building Services Engineers |
| COPD: | Chronic Obstructive Pulmonary Disease |
| DI: | Discomfort Index |
| FACS: | NSW Department of Family and Community Services |
| GHG: | Greenhouse gas |
| HILDA: | Household Income and Labour Dynamics in Australia study |
| LAHC: | Land and Housing Corporation |
| MHRV: | Mechanical Heat Recovery Ventilation systems |
| NatHERS: | Nationwide House Energy Rating Scheme |
| NPV: | Net Present Value |
| RH: | Relative humidity |
| RIS: | Regulatory Impact Statement |
| WBGT: | Wet Bulb Globe Temperature |

## Executive Summary

The current CRC Low Carbon Living Research Project (RP3044) has the aim to encourage mainstream uptake of low carbon retrofits in social housing. The social housing sector, including public, community and Aboriginal housing, own or manage a significant proportion of residential property in Australia; the management is relatively centralised as compared with owner-occupiers and is governed by design and performance standards. The sector therefore presents an opportunity for a large scale, aggregated approach which could result in low carbon retrofits being applied to an extensive portfolio of residential building stock.

Low income occupants, and social housing tenants in particular, are highly vulnerable to energy price rises and extreme weather conditions, and face specific barriers to accessing energy efficient dwellings and improvements. Further, low income occupants often use little energy and rely on compensatory measures to cope with energy bills, such as minimising the use of heating and cooling. This means that traditional benefit-cost assessments, considering the benefit of utility bill reduction only, are often unfavourable for low income dwellings. However, low income tenants are also the most likely to receive non-energy benefits, or co-benefits, from energy efficiency upgrades.

There has been much research in recent years attempting to quantify the co-benefits of energy efficiency intervention, particularly health co-benefits, and particularly for low income occupants. The links between housing and health are complex, although a number of previous reviews have identified a correlation between poor housing and poor health. In the context of health and housing, vulnerability is a function of exposure to unhealthy housing environment, sensitivity to housing environment, and adaptive capacity, as summarised in Figure 1. More vulnerable groups, such as the sick, the elderly, and the unemployed (all demographics which are more highly represented in social housing than the general population), are more likely to live in poor quality housing. These groups are also likely to spend a greater amount of time at home, exposed to the environment in the home (Thomson *et al.* 2009). Low income groups are also more likely to have a lower adaptive capacity to deal with unhealthy environments.

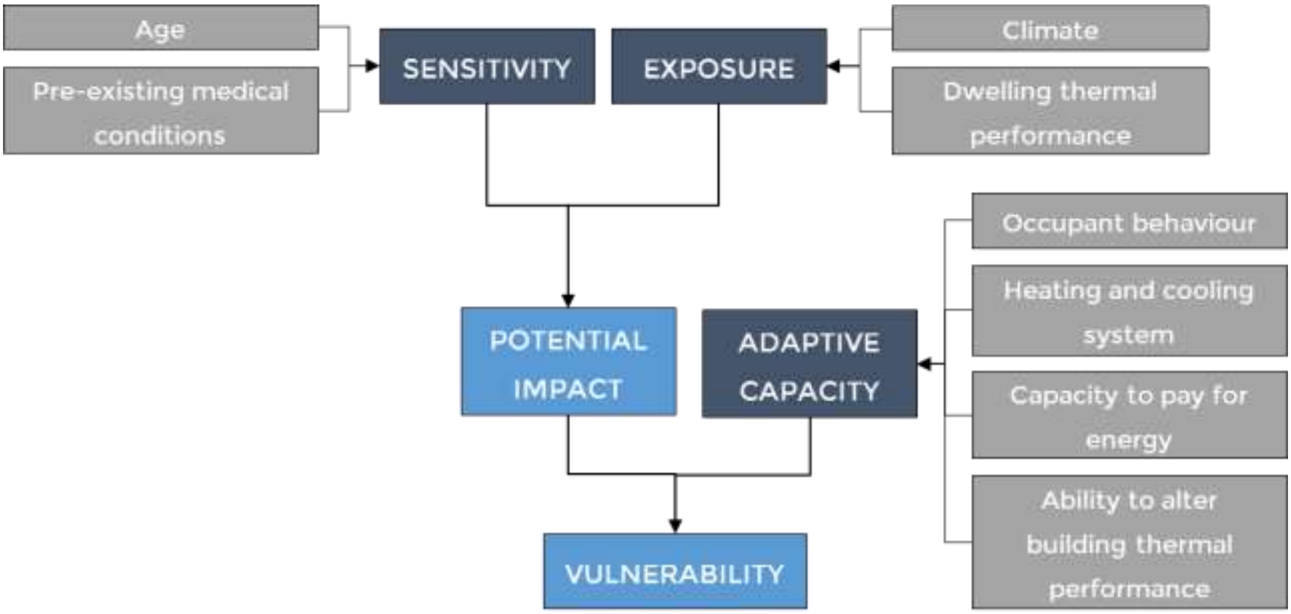


Figure 1. Key factors influencing vulnerability to health risks in housing, adapted from Allen Consulting Group (2005).

There have been a number of high-quality studies and reviews of evidence published in recent years. However the studies reviewed have typically been undertaken in other countries, and it is not clear how applicable the results are to the Australian climate. The current targeted review considered the evidence of direct benefits from different energy efficiency measures in Australia, and the evidence for health impacts from improved winter heating, improved resilience to summer heat wave events, and measures to minimise mould and dust mite risk.

Low internal ambient temperatures are likely to be an important issue in Australia. Whilst much of Australia experiences mild winter conditions, Australia experiences a relatively high occurrence of excess winter deaths. This is consistent with previous studies which have linked high excess winter deaths to climates with mild winters; explanatory factors for this in other locations include energy inefficient and difficult or expensive to heat homes, and adaptive behavioural actions (such as winter clothing levels). High-quality reviews have found consistent and increasingly strong evidence that energy efficiency interventions which increase winter warmth may improve the health of occupants, particularly in children, the elderly, and those with pre-existing health issues. In studies where the cost-benefit has been calculated, the health co-benefits vastly outweigh the direct energy benefits. However, there remains significant uncertainty regarding the direct causal pathways linking energy efficiency interventions aimed to reduce winter cold, and health outcomes.

There is less developed evidence regarding the impact of energy efficiency interventions on heat-related health risk, as compared with low internal temperatures. Heat waves are a major natural hazard in Australia, responsible for the death of more people than all other natural combined, and low income populations are at greater risk of morbidity and mortality from heat wave events. Major simulation studies have shown that energy efficiency interventions to dwellings would be expected to reduce the health risk of heat wave events in Australia, although, in climates with hot and humid summers, air-conditioning will be increasingly required to maintain a safe indoor thermal environment. However, there is a lack of evidence regarding the direct causal relationship between exposure to heat stress (e.g. as measured by discomfort index) in homes and health outcomes in Australia and the likely impact of energy interventions.

The risk of mould growth in homes, and therefore negative health outcomes from exposure to mould and dust mites, is closely related to the hygrothermal conditions in a home, particularly the presence of low internal ambient temperatures, and associated condensation. A recently published review of evidence found 'moderate to very low-quality evidence that repairing mould-damaged houses and offices decreases asthma-related symptoms and respiratory infections compared to no intervention in adults.' (Sauni *et al.* 2015). Interventions to reduce mould risk, as opposed to those focused on cleaning and chemical treatment of mould, generally focus on increasing internal ambient temperatures. There is some evidence that heating system improvements, improvements to insulation, and improved air-tightness and controlled ventilation can reduce mould risk and occurrence, which may result in decreased respiratory illness.

The current targeted review found there is some evidence that low income tenants in social housing in Australia may realise health benefits as a result of energy efficiency interventions, and there is some evidence from international studies that the financial benefits may be substantial. The strongest evidence relates to benefits from increasing winter warmth above identified risk threshold temperatures; there is also evidence of benefits from reducing internal temperatures during summer heat events and reducing the occurrence of mould in homes. However, the link between health outcomes and energy efficiency interventions is exceedingly complex, and there are numerous confounding factors affecting any study in this space. Therefore, the understanding of the exact causal pathways linking energy efficiency interventions and health outcomes, and the relative importance of those pathways, is still limited. Further, there is currently insufficient evidence to make an estimate of the actual financial impact from co-benefits resulting from a specific energy efficiency intervention or package of interventions. There is a need for high quality, randomised controlled trials of interventions in multiple climate zones, such as the recently commenced Victorian Healthy Homes Program (Sustainability Victoria 2018).

# 1. Introduction

There are numerous reasons to improve the poor performance of the existing residential building stock in Australia. Energy consumption in the residential sector contributes a significant proportion of Australia's greenhouse gas (GHG) emissions (EES 2008), with associated environmental impact. The current housing stock will still make up over 50% of the future housing stock present in Australia in 2050 (the demolition rate of residential buildings has been estimated at ≈0.18% p.a., and the rate of new stock addition at ≈2% pa (EES 2008)). This means that to make meaningful reductions in GHG emissions it is necessary to make improvements to the environmental performance of the existing stock. Many studies have identified significant emissions reductions opportunities in the Australian residential sector, often with attractive financial savings. For example, the Australian Sustainable Built Environment Council (ASBEC) (2016) highlighted the potential for a reduction of 100Mt in Australian greenhouse gas emissions through existing building retrofits, to be achieved by 2050 with a resultant $9 billion in cost savings, with residential buildings accounting for about half of this amount. However, the report also noted that 'Despite the achievements of market leaders, broader progress in energy efficiency - particularly retrofitting of existing buildings - has been slow, with overall energy intensity improving by only …. 5 percent in residential' over the past decade. In particular, addressing the needs of low income households who 'tend to live in more inefficient dwellings than other households, spend more of their household income on energy, and face stronger barriers to upgrading' (ASBEC, 2016), was identified as a key area for action.

There are a number of additional factors that make improving the energy efficiency of residential dwellings with lower income occupants particularly pressing, and that make the improvement of social housing properties relatively easier to realise. Low income occupants are particularly impacted by barriers to improving the energy efficiency or quality of their dwellings. ACOSS (2013) identified three main barriers to investment in energy efficiency measures facing low income occupants, namely: i) lack of access to capital required to pay for the cost of new energy efficient appliances; ii) split incentives, whereby those investing in energy efficiency measures are not directly receiving the benefit of a lower energy bill; and iii) information barriers which prevent people experiencing disadvantage from accessing energy efficiency, including literacy and language barriers, particularly for those with recent migrant or refugee status, illness and disability, as well as information on products and programs often being conflicting and complex, and understanding the most effective ways to save energy.

Baker et al. (2016) identified that there is a sizeable under-acknowledged cohort of people in Australia whose health is affected by the poor condition of their dwelling. This cohort of people is thus faced with a double disadvantage of living in poor quality housing within a nation that does not adequately acknowledge the existence and impact of poor quality housing. Using data from the 6 year longitudinal study on Housing Income and Labour Dynamics in Australia (HILDA), they found that 4.9% of dwellings were rated as poor-derelict. It was also found that 19% of public renters lived in housing that was classified as poor-derelict, which was 6 times more prevalent than the 3% of homeowners who lived in poor-derelict buildings. More than 60% of individuals residing in poor-derelict housing had low household incomes, compared to 36% of people in good-excellent homes with low income. They also showed that those living in poor-derelict dwellings had a statistically significant lower self-assessed general health. Liu *et al.* (2016) reported that low income households were relying on compensatory measures to cope with energy bills, including: selective heating and cooling, rationing their use of appliances, finding alternative methods of staying comfortable (e.g. going to a shopping centre on hotter days), and skipping, or seeking assistance, on other essentials (e.g. food and medication) to allow them to pay bills. An analysis of the home retrofitting program undertaken by Cooper *et al.* (2016), identified that older low income people (the target of the program) generally use little energy and 'often consider energy use through the lens of thrift and not being frivolous or wasteful.' This frugal energy usage can be problematic, and create 'tyrannies of thrift' whereby being thrifty with energy use can lead to significant risks to comfort, health and wellbeing (Waitt *et al.* 2016).

Social housing tenants are particularly vulnerable to energy price rises and extreme weather conditions and face specific barriers to self-driven energy upgrades (Walker and Day, 2012). Their energy bills are typically a relatively higher proportion of household income, as they spend long hours in their homes (Urmee *et al.* 2012). Tenants of social housing properties are also more likely to be in fuel poverty (defined as having an expenditure on gas and electricity more than 10% of household income): 11.8% of social housing renters were found to be in fuel poverty, compared with 4.8% for the whole population (Burke *et al.* 2015). The issue of split incentives is also particularly pertinent to social housing tenants in Australia. It is difficult for community housing providers (CHP) to recoup their investment costs through higher rent due to regulations around rent protection. Further, there often exists an additional incentive split, where the property is owned by a government authority but managed by a community housing provider.

Despite the barriers identified above, the social and community housing sector represents a significant opportunity for the development of a major, aggregated approach to low carbon retrofits in large portfolios of residential building stock. The management of these properties involves significant investment in maintenance and regular upgrades to maintain dwelling quality in accordance with relevant regulation and maintenance standards. It is therefore possible to realise substantial residential energy efficiency improvements on an extensive stock of buildings which are managed, maintained and upgraded through relatively centralised processes (as compared to the owner-occupied building stock). This opportunity, and an assessment of how best to mainstream low carbon upgrade in the social housing sector, has been explored in detail in an earlier report from the current project (Daly *et al.* 2018).

The social housing sector in NSW is currently in a period of transition. *Future Directions for Social Housing* (NSW Government 2016) sets out a 10-year transition plan for social housing in NSW, including substantial construction of new housing, and transfer of management from state housing to Community Housing Providers. This represents a considerable change to the social housing sector and presents an opportunity for CHPs to establish best practice systems as they adapt to the changing situation. *Future Directions* has a specific action item committing to provide 'better maintenance and community amenity', as well as a commitment to provide 'improved physical environment in social housing areas'.

One of the key strategic priorities in the *Future Directions* plan is 'a better experience in social housing', including the provision of suitable, safe and quality housing. This priority has been further expanded by LAHC to include 'a better social housing experience – (ensure thermal comfort does not cause energy poverty)' (LAHC 2016). Under the competitive tender process for CHPs wishing to participate in the management transfer of LAHC properties, CHPs will be required to "work toward achieving, measuring and reporting on how tenant outcomes have improved through the Social Housing Outcomes Framework" (currently under development, based on the Human Services Outcomes Framework (FACS 2017)). The Human Services Outcome Framework includes two impact pathways related to the provision of good quality housing, one leading to improved health outcomes and the other leading to feelings of safety via housing in safe environments.

## Direct and co-benefits from energy efficiency upgrades

There are a wide range of options for improving the energy performance of an existing residential building. The selection of the optimal strategy to improve the energy efficiency of a dwelling is complex and may involve improvement to the thermal performance of the building envelope, reducing the energy consumption of appliances and services, and/or encouraging changes to occupant behaviours. The generic building retrofit problem has been described by Ma *et al.* (2012) as 'to determine, implement and apply the most cost effective retrofit technologies to achieve enhanced energy performance while maintaining satisfactory service levels and acceptable indoor thermal comfort, under a given set of operating constraints.' The optimal strategy will be influenced numerous factors, including the existing building structure and materiality, local climate, and occupant behaviour and preferences. Further, the primary goal of an intervention may vary. Most commonly interventions are aimed at either reducing energy usage (and therefore greenhouse gas emissions), reducing utility bills or improving occupant comfort; however other targets exist, such as reducing peak loads, reducing mould and condensation and improving health outcomes. The decreasing cost of renewable energy generation through rooftop solar photovoltaic panels and increasing efficiency of reverse cycle air conditioning means that understanding the target of an upgrade is increasingly important, as bill reductions and comfort improvements can be achieved through a combination of these measures.

Typically, the performance of household energy efficiency upgrades are assessed on the basis of energy or utility bill savings expected from an upgrade with a defined cost. The performance is either predicted based on building performance simulation or evaluated based on pre- and post-retrofit energy monitoring or billing data. When the upgrade is assessed using building performance simulation, it is typically assumed that the majority of the building space is conditioned. The economic performance may then be expressed by a number of measures, including net present value (NPV), internal rate of return, overall rate of return, cost-benefit ratio, discounted payback period, and simple payback period (Remer *et al.* 1995a, Remer *et al.* 1995b). Any improvement to thermal comfort in the dwelling has typical been classified as 'rebound effect' and largely excluded from cost-benefit consideration, or included in a qualitative manner. However, this approach to economic evaluation is problematic in the low income sector, as it overlooks many of the compensatory measures that low income residents may have been forced to adopt by the poor quality of their existing housing, such as selective heating and cooling. Further, it overlooks the many additional benefits that energy efficient upgrades to a dwelling may realise for different stakeholders.

These additional benefits are variously termed co-benefits, multiple benefits, ancillary benefits, or non-energy benefits. The current report will utilise co-benefits to refer to these additional benefits, whilst noting that in the low income space, the co-benefits may be the driving reason to undertake a property upgrade. There is an extensive emerging body of literature focussed on identifying these co-benefits, and attempting to quantify the reliability and magnitude of the effect of different upgrades. The International Energy Agency (IEA 2014) provided a review of the diverse range of co-benefits that may be realised by different stakeholders as a result of an energy efficiency initiatives. The most prominent benefits identified in that review are shown in Figure 2. As noted above, traditional economic assessment of energy efficiency upgrades has not included any systematic assessment of these co-benefits, due largely to a lack of evidence from previous studies, critical data, and mature methodologies to measure their scope and scale (IEA 2014).

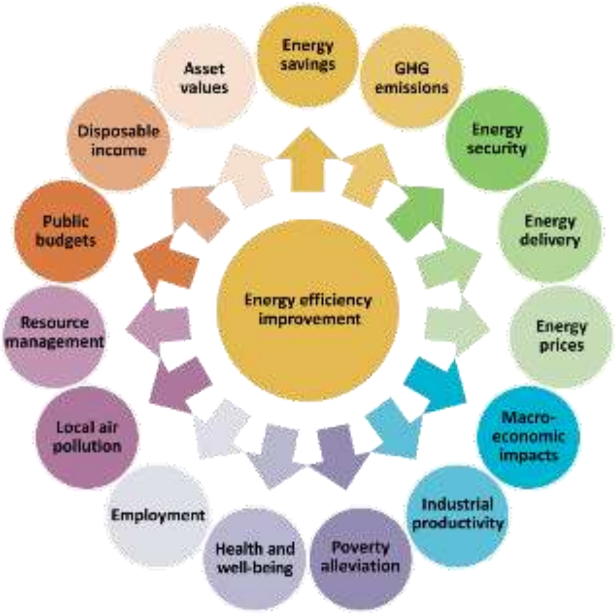


Figure 2. Key co-benefits from energy efficiency initiatives.

The challenge of evaluating the impact of co-benefits of low income energy efficiency programs was explored by an IEA workshop (Heffner & Campbell, 2011) which considered a range of strategies and approaches to quantifying the co-benefits achieved. They concluded that the financial, economic and social welfare co-benefits obtained through various energy efficiency programs are substantial, however they are mostly excluded from the program evaluation. Different approaches are required for different co-benefits, and caution is required when new methods are developed to ensure that the evaluation method is sound. They also highlighted that there are some co-benefit areas which stand out as opportunities for further research, including children's health.

The NSW Office of Environment and Heritage started early efforts to develop a 'Non-Energy Benefits Indicator Framework for Residential and Community Energy Efficiency Programs' (Kenington *et al.* 2016). The paper identified nine key benefit areas to be measured in this framework, namely; thermal comfort, new business opportunities, physical health, employment opportunities, subjective mental well-being, self-efficacy, level and quality of partnerships, support for vulnerable people and community engagement. The paper provides a methodological basis for future evaluation of these indicators, however it is not clear how much further development was undertaken for this framework. ACIL ALLEN (2017) have since developed a more comprehensive policy framework for the assessment of co-benefits in Australia. The framework sets out the economic logic for policy interventions in household energy efficiency, mapping the expected outcomes for the householder, energy utility companies, and society in general. This assessment framework is shown in Figure 3. One of the most promising co-benefits identified in previous studies is improved health outcomes for tenants as a result of changes to the internal hygrothermal conditions in dwelling following an energy intervention.

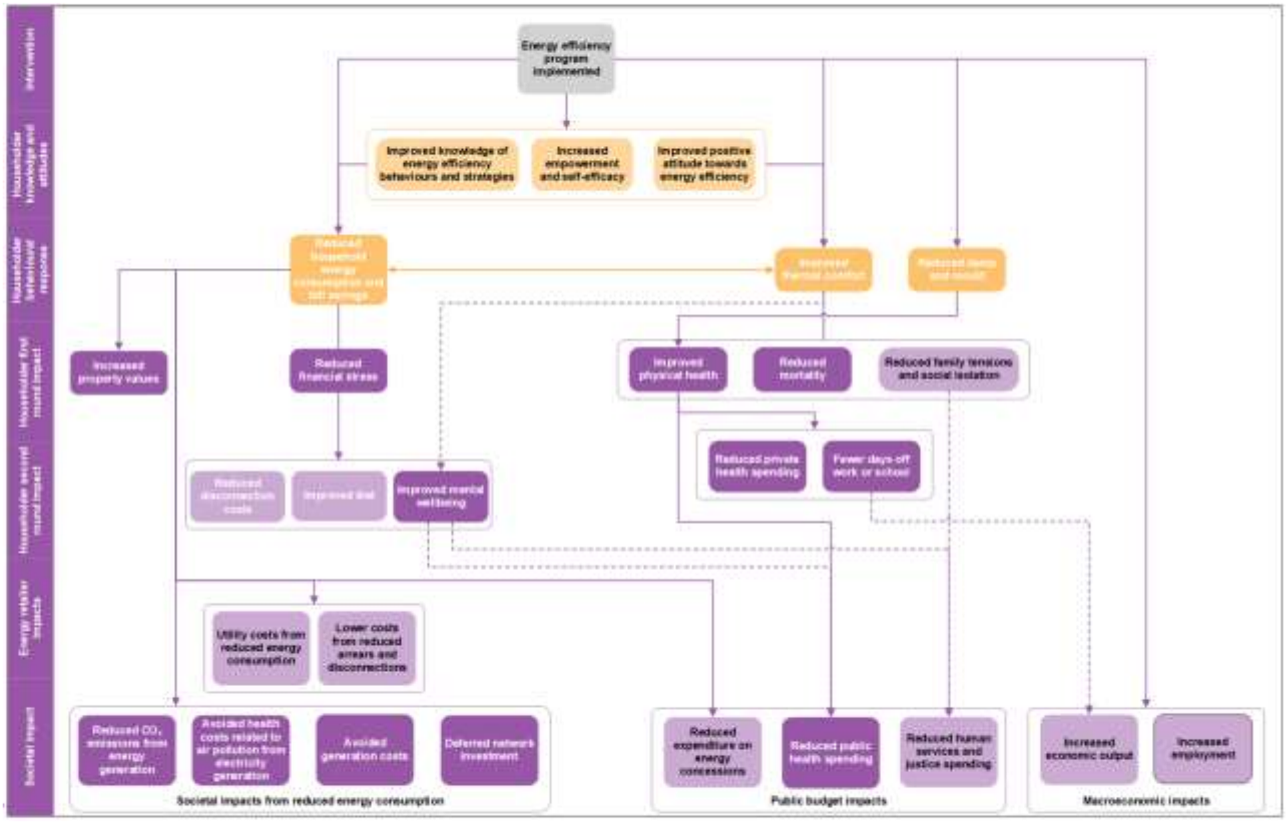


Figure 3. Energy efficiency impacts logic map which underpins the co-benefits assessment framework from ACIL ALLEN (2017). Reprinted from ACIL ALLEN (2017).

## Health co-benefits from energy efficiency interventions

The current report is focussed on the impacts (both positive and negative) to the health of occupants. There is a substantial body of literature linking housing, and the quality of the housing, with the health of the building occupants. The links between housing and health are multiple and complex, and include factors such as overcrowding, the presence of damp/mould, the presence of indoor pollutants, pest and/or vermin infestations, and cold/hot indoor ambient temperatures. Housing quality is a complex issue, and unpicking the complexities in the relationship between poor housing and poor health is difficult. As noted in Thomson *et al.* (2009), it is often vulnerable groups, such as the sick, the elderly, and the unemployed, that are more likely to live in poor quality housing, and these groups are also likely to spend a greater amount of time at home, exposed to the environment in the home. In the context of health and housing, vulnerability is a function of exposure to unhealthy housing environment, sensitivity to housing environmental, and adaptive capacity, as summarised in Figure 4.

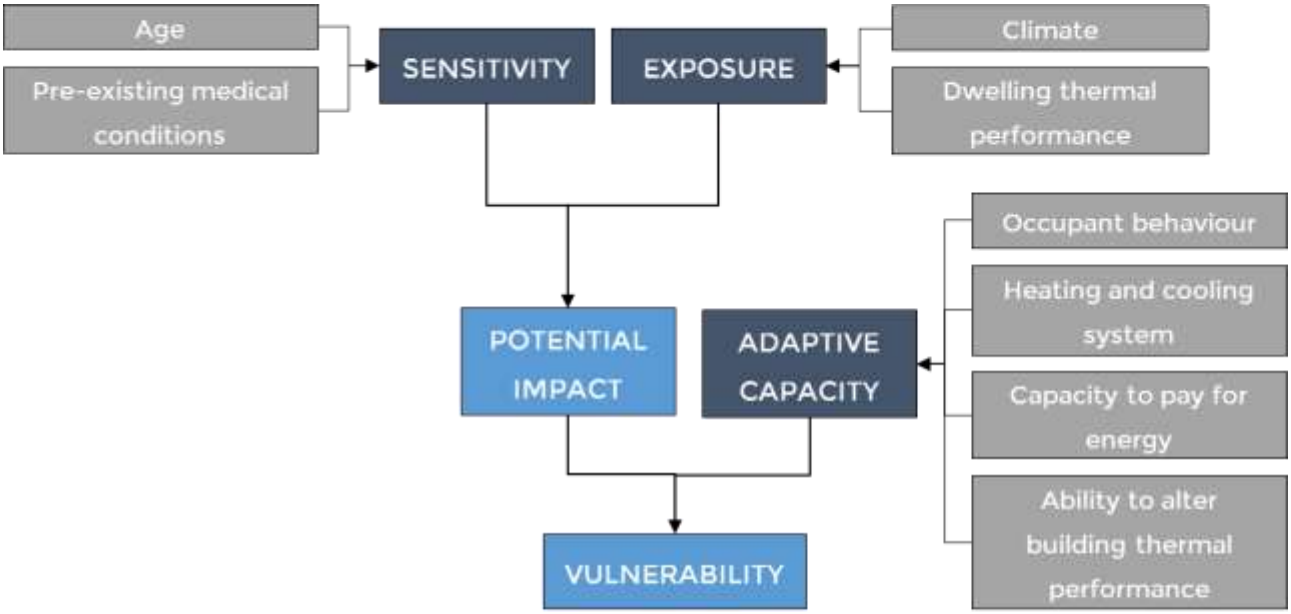


Figure 4. Key factors influencing vulnerability to health risks in housing, adapted from Allen Consulting Group (2005).

Whilst there is a substantial body of evidence associating housing quality and health outcomes, there remains significant uncertainty regarding the strength of the causal links (Thomson *et al.* 2013), which therefore makes it difficult to isolate the impact of a single intervention. The main factors linking health and housing quality, as outlined by Thomson *et al.* (2013), are:

- Hygrothermal conditions (warmth and humidity)
- Air quality (particles and fibres causing death among the very ill)
- Noise
- Radon
- Slips, trips, and falls
- House dust mites
- Environmental tobacco smoke
- Fires

From the above list, hygrothermal conditions and air quality are the two factors most likely to be impacted by an energy efficiency intervention to an existing property. The primary hygrothermal risk factors for health in housing can be defined as exposure to high temperatures, long term exposure to low ambient temperatures and exposure to mould, which requires hygrothermal conditions which are conducive to mould growth.

The implementation of an energy efficiency upgrade to a dwelling, including interventions in the building fabric, appliances and heating/cooling systems, can allow an occupant to create a warmer, drier, and more comfortable indoor environment. This improved thermal comfort has commonly been considered under "the rebound effect". The rebound effect has been used to explain lower energy savings from upgrades than predicted from engineering estimates. Simply put, the rebound effect states that an improvement in the energy efficiency of a service makes that service cheaper, and thereby encourages increased consumption of that service (Sorrell *et al.* 2009). The rebound effect is a useful method for explaining lower than anticipated energy savings when only the direct energy benefits are considered. When consideration is given to the co-benefits of energy efficiency upgrades, it is often more useful to view rebound as occupants displaying a preference to "take-back" the gains from an energy efficient upgrade in the form of increased comfort (Howden-Chapman *et al.* 2009). This is particularly so for occupants in poor quality housing who may have been engaging in compensatory measures prior to the energy upgrade. Importantly, both energy cost reductions and improved thermal comfort have been linked with both direct and indirect physical health benefits (Thomson et al., 2013).

Milne *et al.* (2000) investigated the relationship between energy savings and temperature improvements which can be expected from energy efficiency interventions. They found that the results of an upgrade program were highly influenced by the average internal temperature of a dwelling prior to the intervention. At 14 °C, 50% of the benefits of an energy upgrade were found to be taken as temperature increases, at 16.5 °C approximately 30% of the benefits were taken as a temperature increase, and at 20 °C all the benefits were taken as energy savings. This relationship between indoor temperature and predicted energy savings is highly relevant for the current focus on energy efficiency intervention in poor quality dwellings with vulnerable occupants.

The association between housing quality and health is related to external climatic conditions. A dwellings' fabric serves to moderate the external climatic conditions, and the internal conditions experienced by an occupant will depend upon housing quality, occupant behaviour and external climatic conditions. Exposure to high or low internal temperatures, as well as the likelihood of mould growth, in a poorly constructed dwelling will therefore likely be more pronounced in more extreme climates. The relationship between external temperatures and mortality generally shows an increase at higher and lower external temperatures, with the lowest rate at moderate temperatures (Braga *et al.* 2001, McMichael *et al.* 2008, Anderson *et al.* 2009, Gasparrini *et al.* 2015). Populations in colder climates are generally more affected by hot weather, and vice versa (Keatinge *et al.* 2000, Basu 2002).

Whilst it is generally accepted that exposure to non-optimal temperatures is linked to increased morbidity and mortality, the exact physio-pathological pathways have not been fully explained (Gasparrini *et al.* 2015). Exposure to both high and low temperatures have been associated with an increased risk for a wide range of cardiovascular, respiratory, and other mortality causes, suggesting the existence of multiple biological pathways. Heat stroke and hypothermia only account for a small proportion of the increased mortality (Keatinge 1986, Gasparrini *et al.* 2015). Living in cold homes, and the associated long-term exposure to low ambient temperatures, has been linked to excess winter deaths, Chronic Obstructive Pulmonary Disease (COPD), and respiratory tract infections, as well as increased risk of heart attacks and strokes due to raised blood pressure. Inability to maintain reasonable temperatures during high temperature heat wave events has been linked to cardiovascular and respiratory illnesses. Occupants of dwellings with damp or mould issues, which are often related to the building fabric, have been shown to be at increased risk of respiratory symptoms, respiratory infections and exacerbation of asthma.

As noted above, there remains significant uncertainty regarding the precise causal pathways leading to health improvements from energy efficiency upgrades. A clear understanding of the causal pathway under investigation is essential to the design of effective experimental studies to quantify the health co-benefits that are likely to result from an energy efficiency intervention. There are a large number of potential causal and confounding factors, which make it difficult to attribute benefits on the basis of observational studies. An example of a causal map link energy efficiency, housing quality and health outcomes is shown in Figure 5, which highlights the numerous potential causal pathways which may explain a change in health, as well as the causal factors which must be considered in a well-designed study. The example given below is not comprehensive, much more exhaustive mapping exercises have been completed by others; for instance Macmillan *et al.* (2014), Shrubsole *et al.* (2014), Hamilton *et al.* (2015), which consider a wider range of housing related issues, e.g. household crowding, community connection and physical quality of neighbourhoods. The complexity of the interactions shown in Figure 5 make well-designed experimental studies, for example randomised controlled trials, particularly valuable in this area.

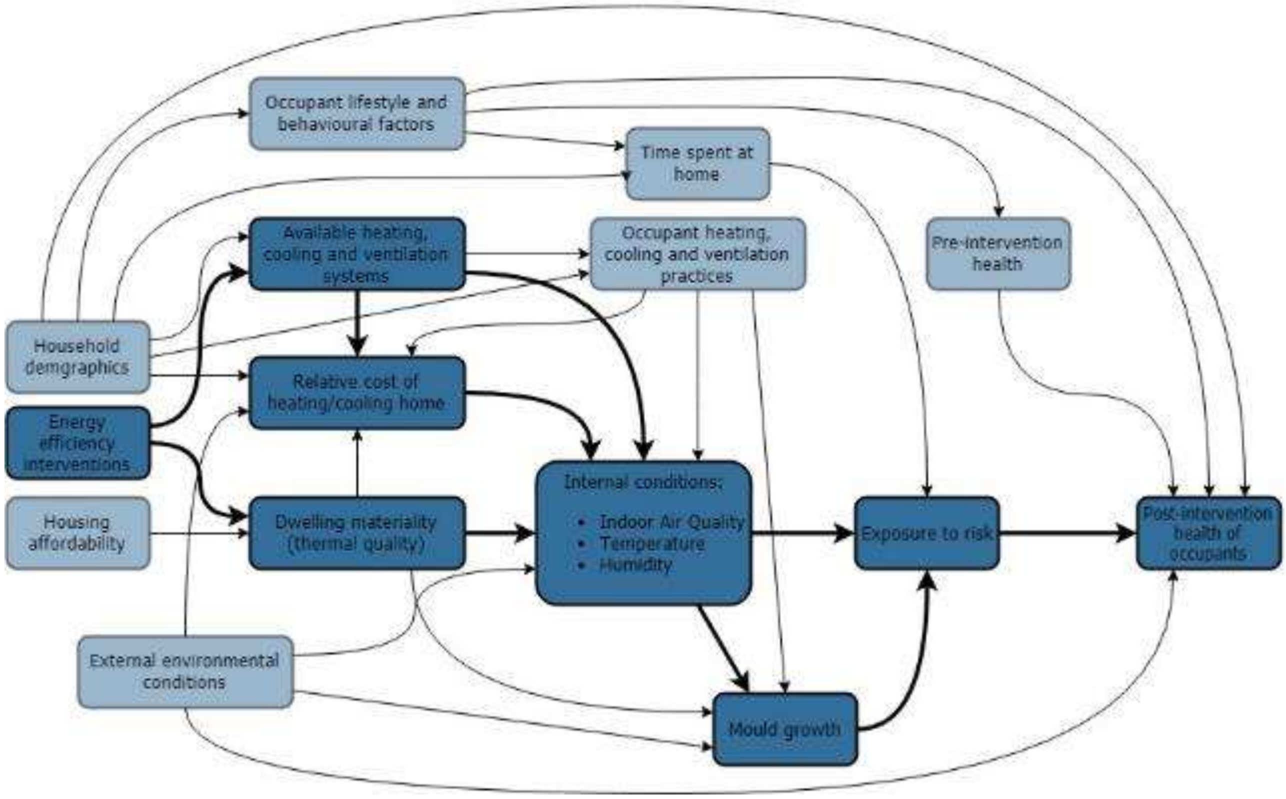


Figure 5. A non-comprehensive example of the causal and confounding factors when assessing the likely health implication of energy efficiency interventions in low income housing.

## Health, energy efficiency and housing: major studies in Australia

At the time of writing there has not been a large scale, high quality randomised control trial exploring the link between health and housing energy efficiency interventions in Australia (the Victorian Healthy Homes Program, a major intervention study that would meet these criteria is currently underway, with results expected in 2019/20). Indeed, there have been relatively few studies examining the link between housing quality or energy efficiency and health outcomes (Phibbs *et al.* 2011). There are, however, a small number of previous Australian studies with some relevance.

Willand (2017) published findings from a recent intervention study from Victoria. The study included temperature observation of 100 homes in Melbourne, and an assessment of the impact of insulation and draught proofing on 16 homes with low income older or frail householders over 12 months, against a control group of 13 homes. Analysis of the temperature data for the 100 homes found that energy efficiency of dwellings was a poor predictor for internal conditions in both winter and summer and that the heating and cooling practices of the household were highly influential on the indoor temperatures. However, Willand *et al.* (2016) reported that buildings with higher star rating were warmer during heat wave events. Six-star NatHERS buildings were 0.89 °C warmer than 4-5 star buildings during heat wave events. The energy efficiency interventions were found to have a significant impact on electricity cost and perceived comfort, and resulted in an increased daily mean living room temperatures in the intervention homes. However, only a small effect was noted regarding reduced underheating. No significant effect was found for heating energy consumption and only a weak effect on heating cost and greenhouse gas emissions. The author concluded that contextual factors, such as energy tariff, payment method, and personal preferences and relationships (e.g. 'heating as part of caring') were highly important in understanding energy consumption in low income homes.

Baker *et al.* (2016) undertook an analysis of the Household Income and Labour Dynamics in Australia (HILDA) dataset to explore the association between dwelling condition and self-assessed mental, physical and general health. The authors found that, after controlling for age, marital status, labour force status, indigenous and migrant status, residential location, and gender, an occupant in a poor-derelict condition building had a small to moderate (statistically significant) lower self-assessed general health as compared with a similar occupant in good-excellent dwellings. Similar results were found for physical health and mental health. This study offers evidence that the link between health and housing identified in international literature is present in the Australian population.

Williamson *et al.* (2009) undertook a modelling study to explore the potential health benefits that may be predicted from increased stringency in the Australian National Construction Code Energy Efficiency provisions. The predicted changes in internal temperatures for free running buildings from an increase in stringency were simulated. Wintertime minimum temperatures were predicted to increase by an average of 0.38 °C (range 0 °C in Darwin to 0.54 °C in Canberra). A tenuous quantitative estimate of the value of the health benefit was attempted using the intervention data from Chapman *et al.* (2009) New Zealand study, yielding an estimated benefit of AUD$9.50 per household per annum for an increase from 5-star NatHERS to 6-star NatHERS. The inherent inaccuracies of this approach are noted, specifically that the NZ study occurred in a more extreme climate, targeted poorly or uninsulated buildings, and targeted the most vulnerable population. This study did not consider the impact of interventions to existing homes.

NSW Department for Health (2010) reports on a health and safety focussed an intervention study in Aboriginal community housing across NSW. The interventions were very broad, aimed at ensuring there were sufficient facilities in the properties to allow for washing people, washing clothes and bedding, removing waste safely, improving nutrition, reducing overcrowding, reducing the impact of animals, vermin or insects, reducing dust, controlling temperature, and reducing trauma. The study reports highly positive impacts; those who received the intervention had a 38 % reduced rate of hospital separations for all of the studied disease conditions. However, it does not appear that interventions aimed at improving control of temperature were a significant component of the program; indeed, there are no results presented for works associated with this aim.

## Summary

The interaction between housing quality, energy efficiency and occupant health is a highly complex area, with many studies focussing on different aspects from different parts of the world. There have been a number of high-quality review studies published in recent years, however the studies reviewed have typically been undertaken in other countries, and it is not clear how applicable the results are to the Australian climate. The current report provides a targeted review of studies that have examined the effects of energy efficiency interventions for low income properties. Section 2 presents a highly targeted review of the direct benefits to be expected to result from a range of the most commonly applied interventions; the review was limited to studies that had measured real-world impact, or were highly relevant simulation studies in appropriate building types and climates. Section 3 outlines the link between low internal temperatures and health risk, and presents a review of major studies and comprehensive reviews of evidence in this space. Section 4 presents the links between exposure to high internal temperatures, housing energy interventions, and health risk. Section 5 reviews the link between internal hygrothermal conditions, mould risk and health implications. There are differing levels of evidence for each of the different health risks. The current review paper attempts to distil a large amount of complex information aimed at providing the community housing sector with a concise, usable summary of the current state of research. This interim report will provide the evidence for future data analysis, fact sheets, and other resources to be prepared as part of the current project.

# 2. Direct benefits of energy efficiency upgrades in low income dwellings

## Introduction

In comparison with the evaluation of the indirect co-benefits from an energy efficiency intervention, the prediction of the direct energy impacts of an energy efficiency intervention is more straightforward. However, it remains a complex problem. Energy savings (or temperature improvements) are dependent upon the building structure and materials, local climatic conditions, installed appliances and heating and cooling systems, and occupant behaviours. For a single dwelling, it is possible to understand or estimate each of these parameters and thereby predict or evaluate the energy benefits of an upgrade. This is a more difficult task when an attempt is made to predict or evaluate savings for a heterogeneous building stock.

Calculating the cost-benefit analysis of an energy intervention requires an estimation, or record, of the cost associated with the upgrade. As for the prediction of energy benefits, the cost an upgrade is highly contextual and is influenced by the construction details of the existing property, the location, method of procurement, and specification of the works. Consequently, when assessing the cost for the upgrading of a heterogeneous building stock estimates and assumptions for cost inputs are also required. There are a number of resources which provide construction cost estimates, e.g. Cordell Building Publications (2017), Rawlinsons Group (2018), however the focus of these publications is not energy efficiency upgrades, and therefore there is limited relevant information.

This section presents the results of a tightly targeted review, including results of the actual performance of monitored intervention studies in Australia, or results of highly relevant simulation studies with results for NSW and Australia. The existence of a substantial performance gap between model predicted savings and real-world achieved savings must be noted, as well as the issue of comfort take-back (or rebound effect) as discussed above. Where available, cost estimates for various upgrades have been included in the review presented below.

## Major retrofit studies in Australia

Sustainability Victoria have published a number of reports on retrofit trials undertaken in a small number of properties in Victoria in 2015. An initial assessment of the upgrade potential of 60 dwellings in Victoria constructed pre-2005 was undertaken to identify possible and practical energy efficiency interventions (Sustainability Victoria 2016d). Energy modelling, based on a relatively detailed assessment of the buildings including air tightness testing, was completed and the baseline consumption and potential energy, energy bill and greenhouse savings for a variety of common building upgrades were estimated. Adjusted capital cost estimates for each upgrade were made by the authors to allow for the calculation of the predicted payback period. A summary of the estimated cost, benefits and payback periods for the modelled upgrades is provided in Appendix A. The upgrades which were found to have a payback of less than ten years were: low flow shower rose installation, ceiling insulation, lighting, draught sealing, clothes washer replacement, water heater upgrade to high-efficiency gas, and installation of an efficient heating system.

A number of the modelled opportunities from Sustainability Victoria (2016d) were then practically implemented in a small number of case study properties as part of the Residential Energy Efficiency Retrofit Trials, presented below. These retrofit trials presented a substantial resource regarding the cost, benefits and practical implementation issues for a range of energy retrofits in Victoria. Trials were undertaken for a number of different upgrades, in a small sample of properties. Cost-benefit assessments were undertaken using calibrated model prediction and actual monitored impacts. However the monitoring period was relatively short, and there were consequently a number of outliers (generally affected by changes in occupant behaviour pre- or post-retrofit) that complicated the impact assessment. A summary of the retrofit trials is provided below for each relevant technology.

Cooper *et al.* (2016) presented results from a recently completed Low Income Energy Efficiency Project, which targeted retrofits at low income older people living in the greater Illawarra region in NSW. A detailed energy audit and retrofit allocation process was undertaken to match households with appropriate upgrades, considering the house fabric, occupant behaviour and existing systems. Implemented upgrades included ceiling insulation, subfloor insulation, fridge and freezer replacement, hot water system upgrades, ceiling and pedestal fan installation, draught stripping, reverse cycle air conditioner for heating, lighting upgrades, and the installation of an in-home energy display. At the time of writing, only interim results were available, based on limited post-retrofit data. Relevant information, including estimated performance assessments, have been reported below as available.

Thomas (2011) completed a simulation study exploring energy efficiency retrofit options for social housing dwellings. Six dwellings, which were considered representative of the social housing stock in NSW and good prospects for future retrofitting programs, were selected for assessment in consultation with the state housing provider. The dwellings included one detached cottage, three units, and two townhouses. These were simulated using AccuRate (an energy modelling software accredited to produce home energy ratings under the NatHERS scheme) in six different NSW climate zones (NatHERS climate zones 11 (Grafton), 24 (Goulburn), 28 (Liverpool), 46 (Cobar), 56 (Bellambi) and 69 (Thredbo)). Numerous upgrade scenarios were considered, including increased air-tightness, improved ceiling insulation, improved wall insulation (both insulated external cladding and pump-in cavity insulation), underfloor insulation, external shading, internal shading, glazing improvement, roof ventilation and ceiling fans. Indicative cost information was collated from industry material and online searches. Draught sealing, ceiling insulation and ceiling fans were found to have a payback period of less than ten years. Further details of each measure are included in the appropriate section below.

Beyond Zero Emissions (2013) completed a substantial modelling exercise in order to develop a plan of how best to retrofit Australia's existing building stock to achieve zero emissions. A single detached residential floorplan was simulated with three wall variants and two floor variants (6 variants total) for ten climate zones. A base case and five progressive upgrade scenarios were simulated, namely i) the addition of R2.5 ceiling insulation, ii) addition of R1.5 wall insulation (R1.0 for brick cavity walls), iii) upgrade ceiling insulation to R6.0 and walls to R2.5 (R1.5 for cavity brick walls), and iv) double glazing, draught sealing and curtains and pelmets for cool climates, and low-e glazing, draught sealing, curtains and pelmets, and ceiling fans for warm climates. The first upgrade scenario (addition of ceiling insulation) was assumed as the base case average of current stock, and all improvements were reported against this baseline. Where possible, the effect of an individual upgrade has been extracted and reported in the relevant section below, however as the upgrades were simulated as progressive upgrades this was not always possible.

Energy Efficient Strategies (2011) presents results from an earlier simulation study undertaken for Allen Consulting Group (2011) as part of a regulatory impact statement (RIS) for the introduction of mandatory disclosure of residential building performance. The RIS explored stock level implications based on extensive simulation of typical houses. Figure 6 shows the average benefit to cost ratio for a range of common building envelope interventions calculated as presented in Energy Efficient Strategies (2011). The calculations were based on AccuRate simulations of the thermal performance of a representative sample of the residential building stock in each state and territory in Australia.

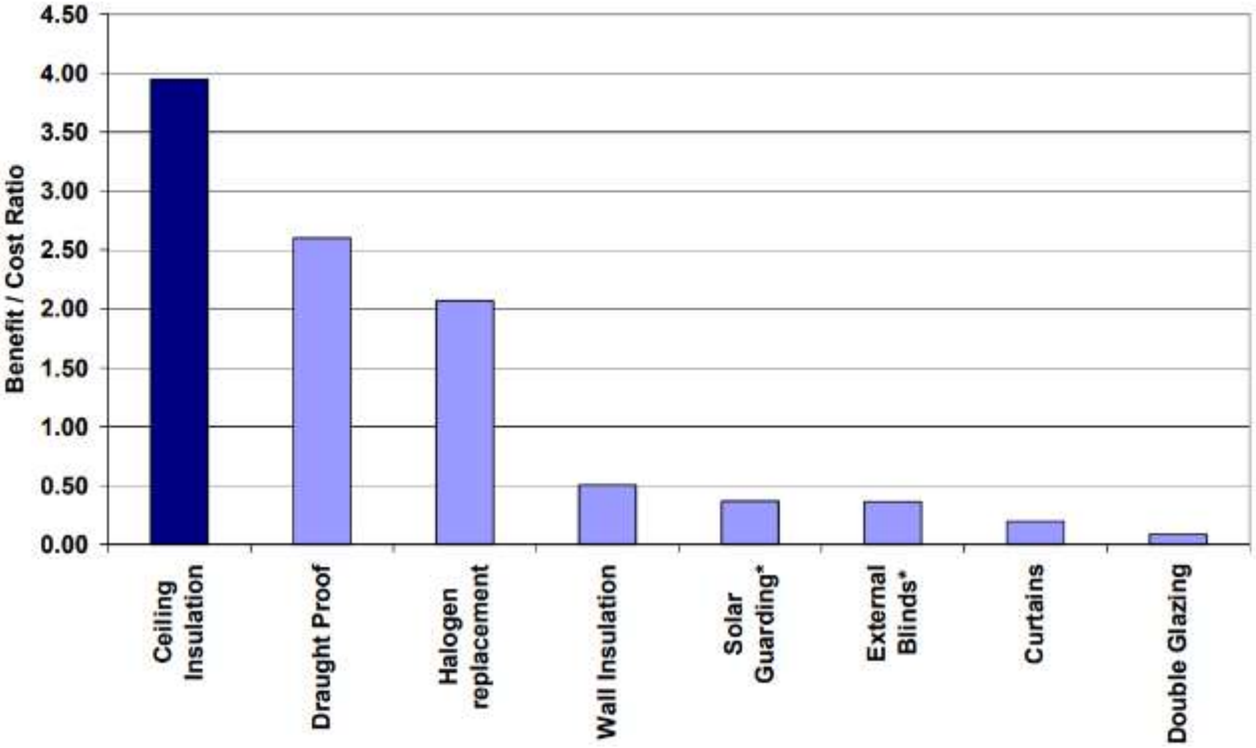


Figure 6. Average cost ratios for various residential energy efficiency interventions, calculated from simulations of typical homes in a range of Australian climate zones (Allen Consulting Group 2011, Energy Efficient Strategies 2011). Note: i) benefit to cost ratio shown is for a ten year payback period with 0% discount rate, and ii) comparisons for solar guarding and external blinds are based on results for Queensland and Northern Territory only where such energy saving measures are most beneficial.

## Intervention-specific information

### Ceiling insulation

It is generally accepted that ceiling insulation is a cost-effective intervention to improve the energy performance of uninsulated dwellings. The Home Insulation Program, a major insulation rebate program which ran from 2009 – 2010 and resulted in 1.2 million ceiling insulation installations, was a recognition of the cost-effectiveness of this measure. Whilst the program was discontinued due to delivery issues (Australian National Audit Office 2010), the effectiveness of the measure remains. Modelling undertaken by Energy Efficient Strategies (2011) found that retrofitting R3 – R4 insulation to previously uninsulated ceiling had a lifetime benefit-cost ratio greater than 1 for all studied locations, and simple payback of 5 years or less for NSW, Victoria, ACT, Tasmania and SA (average for all Australia was 7 years). Previous research by the authors of Energy Efficient Strategies (2011) had found that ceiling insulation had the highest average benefit to cost ratio of a range of common energy interventions, followed by draught proofing.

In a recent ceiling insulation intervention study focussed at low income older people in the Illawarra, Cooper *et al.* (2016) reported an increase in average indoor temperature for any given outdoor temperature of between 1 °C and 2 °C. Post-intervention utility data for this study is yet to be reported.

Thomas (2011) simulated the effects of the installation (in warmer climates) or improvement (in cooler climates) of ceiling insulation in social housing properties. As a base case, no insulation was assumed for warm climates, and R1.5 insulation was assumed for colder climates. The intervention improved the ceiling insulation to R4.1 and R6.1 for the alpine zone (Thredbo). An average payback period of 2.5 years was calculated for warmer climates, 6.9 years for colder climates, and 6.4 years for the alpine climate. The poorer payback for colder climates was assumed to be due to diminishing returns of improving existing insulation, as opposed to adding insulation to a previously uninsulated ceiling. A small increase in cooling energy requirement was also noted in cooler climates.

Simulations undertaken for Beyond Zero Emissions (2013) indicated that the installation of R2.5 ceiling insulation would reduce heating and cooling energy demand by an average of 44% (30% in hot climates, up to 55% in colder climates). The locations which showed the largest reduction in consumption had the largest base case heating load; energy savings were relatively small for cooling energy demand in all locations other than Darwin, Townsville, and to a lesser degree, Brisbane. Further improvement to the ceiling insulation (lumped with a wall insulation upgrade for the study) resulted in a further 22% reduction in total energy consumption, again largely driven by reduced heating demand in all but the warmest climates.

### Draught proofing

Sustainability Victoria (2016c) undertook comprehensive draught sealing for 16 houses in Victoria. Measures implemented to reduce air leakage included caulking obvious leakage points, sealing doors, windows, chimneys, downlights, manhole covers, plumbing penetrations, vents and exhaust fans, taping leaking ductwork, caulking around heating/cooling outlets, and sealing evaporative cooling outlets. Blower door testing was undertaken before and after; an average measured reduction in infiltration of 54%, from 1.80 ACH (min = 1.21, max = 3.1, sd = 0.45) to 0.97 ACH (min = 0.53, max = 1.66, sd = 0.28), was achieved. Average cost of the works was $1,001 (min = $437, max = $1371, sd = $248). The most cost-effective measures (in terms of cost per reduction in air leakage) were sealing louvre windows and taping leaking ductwork, however these were only applied to a single house. The most effective measures to reduce infiltration across all houses (i.e. number of times implemented multiplied by average reduction) were general caulking, sealing evaporative cooler outlets, and sealing exhaust fans/vents. Full details of the effectiveness of individual measures are included in Appendix A. Bill savings were estimated using two methods; i) from the previously completed modelling (Sustainability Victoria 2016d) an annual saving of $150 and payback period of 6.2 years was estimated, ii) by measuring heating energy consumption during periods of steady state heating operation[1] an annual saving of $115 ($132 with outlier removed) and payback of 8.7 years (7.5 with outlier removed) was calculated. An average internal temperature increase of 0.06 °C was also recorded.

Cooper *et al.* (2016) provide estimated quantitative values for the effectiveness of draught sealing based on case studies of 5 homes which had air-tightness testing undertaken. However the disclaimer attached to the values, which notes the significant assumptions used in their calculation, warns against using these values for generalisation. The authors concluded that 'for [do-it-yourself] DIY installations the payback period [for draught proofing] could be very favourable (i.e. significantly less than one year). But a number of major assumptions were made in these calculations, and very significant variations in payback period were found (by factors of >20 for DIY costs).'

Thomas (2011) assessed the impact of adding weather stripping to all door and windows in the modelled properties, and reducing the general infiltration rate; however, no quantitative values were given for the pre- or post-intervention air-tightness. Draught sealing was found to result in reduced energy consumption loads in all dwelling types in all locations, with greater effectiveness in colder climates. A small increase in cooling energy due to this upgrade was noted in cold climates. An average payback of 5.2 years was estimated (min = 1.1 years, max = 10.9 years). Climate zone had a substantial influence on the predicted energy savings from increased air-tightness and was almost twice (1.7 times) as influential as building type in determining cost-effectiveness. Comprehensive draught sealing was identified by Beyond Zero Emissions (2013) as a cost-effective retrofit. However it was not possible to extract information of the isolated performance of the upgrade from the simulation results. An earlier simulation study by Energy Partners (2006) found that implementing comprehensive draught stripping to an insulated house resulted in a mean reduction in NatHERS heating and cooling requirements of 28.5% in Sydney (based on simulation of 10 common house plans). The strategies simulated included weather stripping all doors and windows (2.2% reduction), sealing all external vents (6.1% reduction), and sealing downlights (7.1% reduction).

### Wall insulation

Sustainability Victoria (2016a) installed pump-in cavity wall insulation in 15 homes, which were either brick veneer or weatherboard, and used gas ducted heating. Hydrophobic granulated rockwool was selected to minimise the risk of issues with damp and rain penetration. A number of houses were excluded from the study for practical issues; a minimum cavity width of 40 mm was required, and the cavity needed to be relatively clear of obstacles. Access issues, such as wasps nest, solar panels, water tanks, and pipes or cabling in the wall, were noted as preventing insulation of sections of walls in the included houses. The average cost of installation was $4,286 ($3,032 to $6,527). Average heating energy usage was estimated to be reduced by 19.3%, saving $174.0/yr, and resulting in an average simple payback of 27.2 years, when the baseline calibrated model was used for estimation. Using the steady state

---

[1] The steady state heating technical analysis methodology sought to estimate the average power consumption of the heater during times of steady state operation, when the heater was cycling on and off. Periods when the heater was cycling in a relatively uniform manner, with relatively stable internal temperature and internal-external temperature differences were manually isolated. The average power consumption and internal-external temperature difference during these periods was then plotted, and the line-of-best-fit for the data was calculated for pre- and post-retrofit periods. A comparison of the pre- and post-gradient provided an estimate of the technical energy saving achieved.

heating technical method described above resulted in a heating energy saving of 9.4% (15.5% with outliers removed), or $88.2/yr ($150.9/yr) and a simple payback of 48.1 years (29.4 years). A number of the participating houses noted a reduction or elimination in supplementary electric heating, but this was not captured by the monitoring undertaken. An average increase in internal temperature during periods with low expected heater usage of 0.53 °C was found.

Thomas (2011) simulated the impacts of pump-in cavity wall insulation or external insulative cladding in typical social housing properties. In both cases it was assumed there was no pre-existing wall insulation; the external insulation added R1.5 to the wall construction, and the pump in insulation added R1. An average payback period of 23.6 years was calculated for external insulation and 14.7 years for pump-in insulation. As expected, greater energy savings were predicted for the higher R-value external insulation; the shorter payback calculated for pump-in insulation was due to the lower assumed cost, which was between 11% and 24% of the actual costs from Sustainability Victoria (2016c) (although insulated wall area will vary between house types). A small increase in cooling energy requirement was noted for colder climates.

As noted above, wall insulation was considered concurrently with an improvement to ceiling insulation by Beyond Zero Emissions (2013). An average reduction in heating and cooling energy demand of 22% was recorded for these two measures, compared to a base case with R2.5 ceiling insulation. Adding R1.0 wall insulation to a range of common houses (which had ceiling insulation in the base case) was found to reduce NatHERS heating and cooling demand by an average of 13.3% in Sydney, based on a simulation study from Energy Partners (2006).

### Floor insulation

Thomas (2011) modelled the impact of retrofitting R1 underfloor insulation to properties with a suspended timber floor (ventilated enclosed subfloor). A small increase was noted in cooling energy for all climate zones, and this balanced or outweighed the reduction in heating energy in all but two of the two coldest climate zones (Goulburn and Thredbo). For these two climate zones the payback period was relatively short at 8.2 and 3.4 years, respectively, however for other climate zones this upgrade was not recommended. Likewise, Energy Partners (2006) predicted a small increase in NatHERS heating and cooling demand of 0.7% for the installation of R2.0 insulation houses modelled in Sydney. The addition of R2 underfloor insulation to suspended timber floors was one of the upgrades in the upgraded package identified in Beyond Zero Emissions (2013) as cost-effective, however it was not possible to extract information of the isolated performance of the upgrade from the simulation results.

### Glazing upgrades

Sustainability Victoria (2017b) trialled the installation of secondary glazing in 8 homes, using a low-cost heat shrink polyolefin plastic film installed using double-sided tape around the window frame. An average of 10.2 $m^2$ of window area was fitted with secondary glazing in the trail. Two cost figures were provided, the cost of using contractors to install ($504) and a cost for DIY install ($84) based on material cost. An engineering estimate of energy savings, based on the reduction of window U-value, produced a maximum heating energy saving of 6.3%, cost saving of $62.6, and payback of 8.0 years, or 1.3 years when the DIY installation cost was used. Using the steady state heating method[1] resulted in predicted energy savings of 2.6% (3.7 with outliers removed), cost savings of $27.4 ($40.7) and a simple payback of 20.9 years (14.6 years) for commercial install and 3.5 years (2.4 years) for DIY install. An average increase in internal temperature during periods with low expected heater usage of 0.31 °C was found.

Thomas (2011) modelled the impacts of retrofitting low-e window and double glazing. As expected, low-e glazing was found to be more effective at reducing cooling demand, and double glazing at lowering heating demand. This upgrade was only simulated for a single climate zone (Liverpool), with two orientations. The most effective option for reducing total energy consumption varied according to orientation, however low-e glazing consistently had the lower payback period. The high cost of both retrofit option meant that neither options were cost-effective, with a lowest calculated payback period of 50.9 years for low-e glazing, and 111.8 years for double glazing.

### Shading

Thomas (2011) simulated the impact of the installation of canvas and shade cloth awnings to provide external shading of windows. It was found that the effectiveness of external shading strongly affected by the building orientation, with predicted payback periods ranging from 7.3 to 289.5 in the single climate zone simulated (Liverpool). It is likely that the presence of eaves had a moderating influence in some orientations for this study. Similarly, simulations of the influence of internal shading measures (roller blinds or heavy curtains and pelmets) showed a strong orientation influence. Internal shading was found to be approximately 25% less effective at reducing cooling loads as compared with external shading, and heavy curtains and pelmet were more effective at reducing heating load than roller blinds. Curtains and pelmets were estimated to cost approximately 50% more than roller blinds but return a 500% greater estimated annual energy reduction.

### Ceiling Fans

The effectiveness of ceiling fans installed in main living areas and bedrooms was also assessed by Thomas (2011). Ceiling fans were found to reduce cooling demand in all climate zones, with a relatively short payback period. Average payback for all modelled building types and climates was 13 years. Ceiling fans were not found to be economically attractive in Cobar, the only location simulated which was in a climate zone with a hot dry summer, where an average payback period of 33 years was calculated. Average payback for all other climate zones was six years. Ceiling fans were also part of the cost-effective upgrade package recommended by Beyond Zero Emissions (2013), however it was not possible to extract information of the isolated performance of the upgrade from the simulation results.

### Appliances

A number of appliance replacement retrofit trials were undertaken by Sustainability Victoria, including upgrades to heat pump clothes dryers, pool pump replacements,  gas water heater, and refrigerator upgrades. Several other relevant studies were identified which trialled appliance replacements.

- Sustainability Victoria (2016f) trialled lighting system upgrades in 16 houses, with halogen downlights replaced by either CFL or LED globes. Energy savings were estimated based on measured hours of light usage, and rated power of the lamps. On average, cost per globe was $61.41 ($43.79 material, $17.62 labour), yearly cost saving was estimated at $9.15, resulting in a payback of 6.7 years (compared to the estimated payback of 5.7 years). CFL replacement had the shortest payback of 3.4 years, however this simple economic measure ignores the substantial longer life of LED lamps. The authors note the rapidly changing price of light globes and suggest the economics of this retrofit are likely to improve significantly in the short term. It was found that lighting usage time increased for the properties upgraded with CFL lighting; possible explanations include warm-up time of CFL bulbs and reduced light levels as compared to halogen downlights. Practical installation issues were common, and included incompatibility with the existing transformer/converter, existing light fitting or existing wiring, electrical interference with the TV or radio, slow start-up and warm-up time, and humming. Cooper *et al.* (2016) reported estimated direct cost-benefits for DIY retrofits of LED bulbs to replace incandescent, halogen and CFL bulbs of 0.9, 1.3 and 8.7 years, respectively.

- Sullivan (2017) reported on a major Hot Water System (HWS) replacement study undertaken with low income homes in Victoria, with 793 replacements. Solar, heat pump, gas storage and gas instantaneous upgrades were all trialled. On average, electricity consumption was reduced by 25%, and gas usage by 7%. The installation of solar HWS was found to be the least effective intervention, resulting in electricity savings of only 4%. Sustainability Victoria (2016e) reported the results of the replacement of low efficiency storage gas hot water systems with high efficiency gas instantaneous hot water systems. A payback of 26.3 years, or 10.3 years for end-of-life replacements, was reported based on appliance cost of $2,061 and average energy savings of $78.4/yr.
- The refrigerator trial (Sustainability Victoria 2017a) found savings of $169.3 and a payback of 12.3 years (or 3.8 years at end-of-life) for the installation of high efficiency models. This represented an energy saving of 67.4%. A concurrent fridge trial looking at business-as-usual replacements (i.e. not prioritising high efficiency models) found energy savings of 53.4% due to technology improvements in more modern fridges.
- The clothes drier trial (Sustainability Victoria 2016b) found a reduction in energy use per drying cycle of 69% and found an average annual saving of $171.2, and a simple payback of 9.0 years (based on appliance cost of $1,536). The payback period was very sensitive to the estimated number of dryer loads per day, however for driers in regular use the payback period was relatively short.
- Pool pump replacements were also found to be highly attractive (Sustainability Victoria 2016g), with a simple payback of 6.9 years (appliance cost was $1,628, and annual savings were $235.00). It was noted that pool pumps are likely to be replaced at end-of-life, which makes this upgrade more economically viable.

# 3. Health impact of improved internal low temperatures

## Winter cold, housing quality and excess mortality in Australia

There have been a relatively large number of studies that have explored the link between long term exposure to low internal ambient temperatures and the health of occupants, however at present no major studies have been completed in Australia. Whilst much of Australia has a relatively mild winter compared to other countries, there is some evidence that for occupants in poor quality housing there may exist a significant health risk due to cold homes.

In their comprehensive exploration of the link between excess mortality and external ambient conditions, Gasparrini *et al.* (2015) found that from the minimum mortality point, generally mortality risk increased slowly and linearly with decreasing temperatures, and increased quickly and non-linearly for increasing temperatures. The point of minimum mortality was generally found to be at the 80th to 90th temperature percentile. Further, the study found that the fraction of all-cause mortality attributable to temperature conditions was highest for moderately cold conditions (as opposed to extreme cold, moderate heat or extreme heat) for all countries. In Australia, temperature was found to be an attributable factor in 6.96% of mortalities, with cold weather associated with 6.50%, and hot weather with 0.45%. This breakdown of the attributable fraction for each temperature band is shown in Figure 7. It is important to note that this is referring to external conditions and therefore does not consider the internal conditions experienced by dwelling occupants. However, it is anticipated that occupants of poorer quality housing will be exposed to more extreme internal conditions in a given climate.

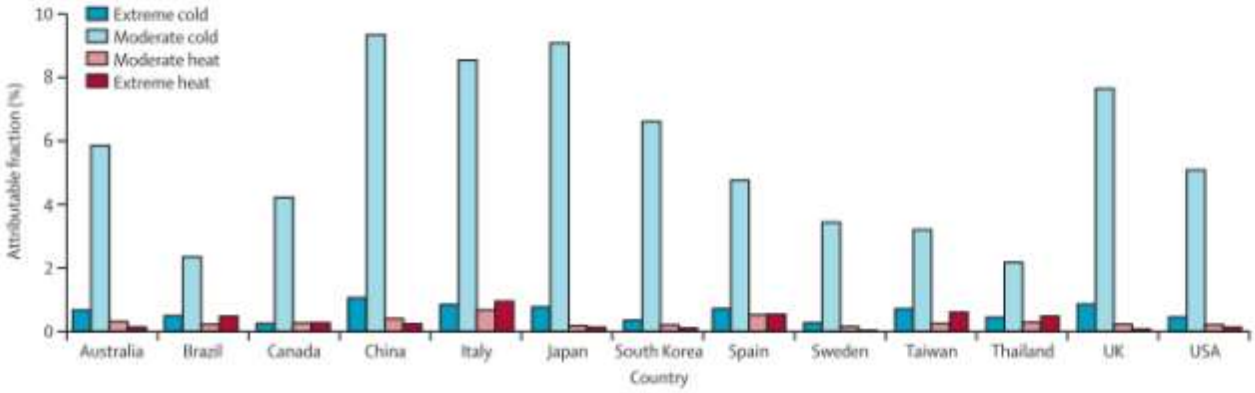


Figure 7: Fraction of all-cause mortality attributable to moderate and extreme hot and cold temperature by country. Extreme and moderate high and low temperatures were defined with the minimum mortality temperature and the 2.5th and 97.5th percentiles of temperature distribution as cut-offs from Gasparrini *et al.* (2015). This means that the temperature bounds vary according to local climatic conditions. For example, moderate cold in Australia is defined as 11 – 23 degrees C, whilst in Sweden it is approximately -6 to 19 degrees C.

Whilst the findings of Gasparrini *et al.* (2015) may be unexpected, given the relatively mild winters in Australia, they are supported by numerous related studies. The increase in mortality during winter months is referred to as Excess Winter Mortality, and can consistently be observed in mortality statistics across the globe. In Australia, there are more deaths in the winter months of June, July and August, and less deaths in the summer months of December, January and February, compared to the yearly average. This relationship is clearly shown in Figure 8. In Australia there was an average of 5,150 excess winter deaths between 2004 and 2014, or a 15.2% increase over other seasons (ABS 2014). Although there are some excess winter deaths in all age groups, it becomes significant for those in the

45+ age group, and then becomes increasingly significant with increasing age (Looper 2002, The Office of the Deputy Prime Minister 2006).

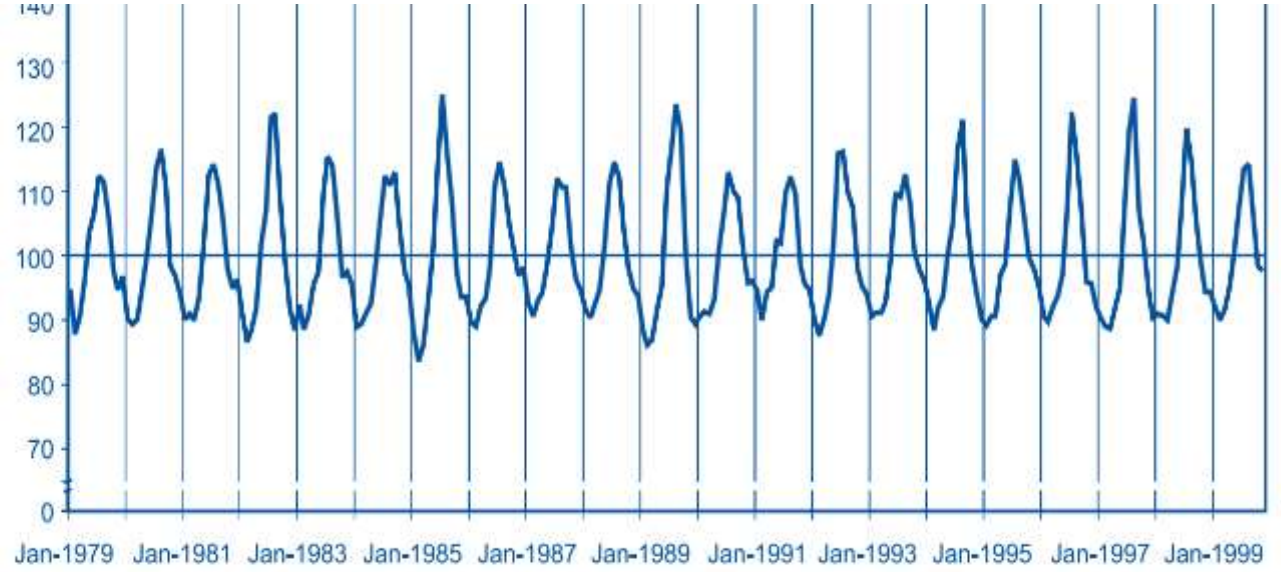


Figure 8. Seasonality of deaths, January 1979 to December 1999 from Looper (2002).

Whilst studies into the relationship between cold homes and health have historically been largely undertaken in countries with cold winters, the increase in mortality during winter has been found to be greater in climates with more moderate winters, supporting the findings from Gasparrini *et al.* (2015). In their study looking across European countries, Keatinge *et al.* (2000) found that cold-related mortality was associated with high mean winter outdoor temperatures, low living-room temperatures, limited bedroom heating, and low proportions of people wearing hats, gloves, and anoraks. Similarly, Healy (2003) found that excess winter mortality was substantially correlated with both high winter external temperatures and poor thermal efficiency of housing, suggesting that poor housing quality may be an explanatory factor for the increased winter mortality in warmer climatic regions. Clinch *et al.* (2000) restated this link between housing quality, indoor temperatures and excess mortality by comparing conditions between Norway and Ireland.

There have been numerous investigations linking poor quality housing with an increases health risk from cold indoor conditions. Wilkinson *et al.* (2001) examined the relationship between excess winter mortality and housing quality, as assessed by the English Housing Condition Survey. The authors concluded that there was ‘strong, although not conclusive, evidence that winter mortality and cold-related mortality are linked to sub-optimal home heating.’ They further found that ‘older, less thermally efficient and intrinsically colder houses were specifically associated with vulnerability to cold related mortality.’ Further evidence of the link between energy inefficient housing and excess winter mortality was provided by Rudge *et al.* (2005), who found that the Fuel Poverty Risk Index (an index including energy inefficient housing, low income, householder age and under occupation) was significantly related to, which provides

Wilkinson *et al.* (2001) found that the main determinants of low internal temperature in dwellings were the age of the property, the absence of central heating, dissatisfaction with the heating system, cost of heating the dwelling to a minimum standard, small household size and low net income. They also found that living in a difficult-to-heat home was a greater disadvantage to low income households, likely due to the additional energy cost to heat the property to an adequate indoor temperature. The health risk was found to be greater for occupants of colder homes, with excess winter deaths for occupants in the coldest homes in the study being almost three times as high as that of the warmest homes (Geddes *et al.* 2011).

In the UK, the regularly conducted English Housing Condition Survey has included the Housing Health and Safety Rating System since 2006. This risk-based evaluation system is used to assess the Health and Safety risks in dwellings, including excessive cold temperatures and damp and mould growth, and provides a substantial data resource for researchers. In the official guidance notes to the Health and Safety Rating System prepared by the UK Office of the Deputy Prime Minister (2006), several of the relationships identified by Wilkinson *et al.* (2001) are restated, namely: i) that the percentage rise in deaths in winter is greater in dwellings with low energy efficiency ratings; ii) that there is a gradient of risk with age of the property, the risk being greatest in dwellings built before 1850, and lowest in the more energy efficient dwellings built after 1980, and; iii) that absence of central heating and dissatisfaction with the heating system also show some association with increased risk of excess winter death.

There are numerous pathways by which cold internal temperatures are linked to excess winter deaths and illness in occupants. The major health concerns associated with cold internal temperatures are respiratory problems and cardiovascular or circulatory diseases, although other issues such as exacerbation of arthritis and rheumatisms, and mental health impacts have been linked to exposure to cold conditions (Geddes *et al.* 2011). In the UK, it has been estimated that cardiovascular conditions account for between 40% and 50% of the excess winter deaths (The Office of the Deputy Prime Minister 2006, Department of Health 2007, Geddes *et al.* 2011), and respiratory diseases account for additional third (The Office of the Deputy Prime Minister 2006, Department of Health 2007), and deaths directly attributed to influenza or hypothermia represent a small proportion of excess winter mortality (Bowie *et al.* 2002).

Whole body exposure to cold conditions can cause a rise in blood pressure, which in turn places additional stress on the cardiovascular system, and increases the risk of winter morbidity and mortality due to heart attacks and strokes (Collins 1986). Collins *et al.* (1985) found significant blood pressure rises occurred in elderly participants at 6 °C, 9 °C, 12 °C but not at 15 °C. Exposure to cold air streams may affect the respiratory tract and immune system and can reduce resistance to infection (The Office of the Deputy Prime Minister 2006). A recent cross-sectional study involving 148 patients suffering from Chronic Obstructive Pulmonary Disease found that their symptomatic health status was significantly worse when there were fewer days where the indoor temperature failed to reach and be maintained at 21.1 $^{o}$C for at least 9 hours (Osman *et al.* 2008). In Australia, Enquselassie *et al.* (1993) found that coronary events, both fatal and non-fatal, were 20-40% more likely to occur in winter and spring than at other times of the year, and suggested that avoiding temperature extremes (through improved temperature control in housing) could contribute to reduction in the annual peaks in coronary events.

Cold-related excess mortality has a longer time lag, in the order of 3 – 4 weeks (Anderson *et al.* 2009). In the UK, the increase in deaths from heart attacks was found to occur about 2 days following the onset of a cold spell, the delay was about 5 days for deaths from stroke, and about 12 days for respiratory deaths (The Office of the Deputy Prime Minister 2006).

## Recommended temperature ranges for healthy homes

There have been numerous studies attempting to establish what is a healthy indoor temperature; that is a temperature band where health risks are minimised, as opposed to the thermal comfort temperature bands which focus on occupant comfort. The World Health Organisation has recommended temperatures be maintained between 18 and 24 °C, with a 2-3 °C warmer minimal temperature for rooms occupied by sedentary elderly, young children and the disabled (Ormandy *et al.* 2012). Ormandy *et al.* (2012) recently reviewed the WHO guidance and found it was based on evidence and has been supported by subsequent research.

In the UK, the Housing Health and Safety Rating System Guidance notes state that a small risk of adverse health effects begins once the temperature falls below 19 °C, serious health risks occur below 16 °C with a substantially increased risk of respiratory and cardiovascular conditions, and the risk of hypothermia becomes appreciable below 10 °C, especially for the elderly (The Office of the Deputy Prime Minister 2006). The Chartered Institution of Building Services Engineers (CIBSE) Technical Memorandum related to health issues in building services (CIBSE 2006) reaffirmed the WHO safe band of 18-24 °C. The report cites research showing that i) internal temperatures below 16 °C and above 65% relative humidity may create additional risk, particularly from respiratory diseases and allergic responses to moulds, fungi and yeasts, ii) temperatures below 12 °C may pose additional risk for preschool children and the elderly, sick and handicapped, and this risk may be exacerbated when bedroom temperatures fall at night, and iii) susceptibility to infection from airborne pathogens is believed to increase below 16 °C. The guide recommends minimum temperatures of 18 °C for the general population and 20 °C for the old and very young. Table 1 provides a summary of recommended minimum temperatures and the health risks associated with sub-optimal temperatures.

Table 1. Summary of indoor temperature links with health.

| Indoor Temperature | Effect |
|---|---|
| 21 °C | Recommended living room temperature |
| 20 °C | Recommended minimum temperature for the old (65+) and very young |
| 18 °C | Minimum temperature with no health risk though may feel cold |
| Under 16 °C | Resistance to respiratory diseases may be diminished |
| 9-12 °C | Increases blood pressure and risk of cardiovascular disease |
| 5 °C | High risk of hypothermia |

## Energy Efficiency intervention for increased winter warmth

As the research linking low internal temperatures and poor health outcomes has become stronger, much research has been focussed on quantifying the health benefits that can be realised through housing upgrades to improve warmth. There have been several comprehensive reviews in recent years of intervention studies in this space; the section below presents the findings of the reviews, as well as the results from several key interventions studies.

The Cochrane Database of Systematic Reviews (CDSR) is the leading resource for systematic reviews in health care, and there has been a relatively recent systematic review focussed on housing improvements for health and associated socio-economic outcomes (Thomson *et al.* 2013). The review concluded:

> *'There is now stronger support for the hypothesis that housing improvement can improve health in the short term than there was at the time of our 2001 review. Improvements in warmth, in particular, can lead to tangible improvements in health, but the potential for health benefits may depend on baseline housing conditions and careful targeting of the intervention. The health impacts of area-based programs of housing improvement remain unclear, but there is little to suggest that housing improvement is detrimental to health.' (Thomson et al. 2009, p.691)*

Fifteen intervention studies which had focussed on warmth and energy efficiency improvements to dwellings and met the relatively stringent inclusion criteria for quality and accessibility of quantitative data were included in the Cochrane review. The majority (10 of 15) of studies were completed since 2000. Interventions varied, but the most common interventions were installation, upgrade, or repair of central heating, installation of insulation (roof or cavity wall, or both), installation of double glazing, or any combination of these. The studies were primarily undertaken in the UK (11), with the remainder coming from Europe (2) and New Zealand (2).

The health impacts reported in the Cochrane review were separated into three categories, namely general health impacts, respiratory health impacts and mental health impacts, and a quality grade was given to each study. It should be noted that in some cases, the intervention studies were specifically targeted at occupants with pre-existing health conditions, e.g. Howden-Chapman *et al.* (2008) targeted children with asthma, and Osman *et al.* (2010) targeted people with chronic obstructive pulmonary disease. Further, studies generally had a focus on low income occupants. The summarised outcomes from the high quality intervention studies are summarised below (with specific odd ratios for different measures from different studies shown in Appendix A):

- General Health: Five high quality studies presented results for general health impacts. Two high quality experimental studies in New Zealand reported statistically significant lower levels of fair or poor general health among occupant in the dwellings which received the intervention compared with the control group (Howden-Chapman *et al.* 2007, Howden-Chapman *et al.* 2008). A third experimental study in the UK reported a small and non-statistically significantly improvement in general health among the intervention group (Osman *et al.* 2010). Two non-experimental studies reported small improvements in general health outcomes (Platt *et al.* 2007, Braubach *et al.* 2008).
- Respiratory Health. Ten studies which reported respiratory health impacts were assessed as high quality. All studies reported improvements in some of the wide range of respiratory outcomes assessed, with six finding in improvements in both children and adults (Barton *et al.* 2007, Howden-Chapman *et al.* 2007, Platt *et al.* 2007, Shortt *et al.* 2007, Howden-Chapman *et al.* 2008, Osman *et al.* 2010). Three studies reported statistically non-significant increases in some respiratory complaints amongst the intervention group (Hopton *et al.* 1996, Platt *et al.* 2007, Shortt *et al.* 2007), and one study reported no change in some measures following the intervention (Platt *et al.* 2007).

- Mental Health. Seven high quality studies reported mental health impacts. One study (Howden-Chapman *et al.* 2007) found statistically significant better mental health in adults in the intervention group. The remaining studies reported a mix of positive, negative and no change for the intervention group, however the effects were not found to be statistically significant.

There have been several comprehensive reviews published since the Cochrane review, which have incorporated additional relevant high quality studies. In 2014, Maidment *et al.* (2014) undertook a meta-analysis of results from thirty-six studies, involving more than 33,000 participants, which had examined the health impact of energy efficiency interventions. The interventions included in the various studies included heating, insulation, glazing, and draught sealing. It was found that energy efficiency interventions had a small, positive effect on health, with a sample-weighted average effect of 0.08[2] (95% confidence interval from -0.01 to 0.18, range in individual studies from d=-0.43 to +1.41). The individual study results from the meta-analysis are shown in Table 5 in Appendix A. It was further found that low income participants received a greater benefit and that more recent studies, and studies where medical tests for health impacts were used, recorded larger positive impacts.

Most recently, Milner *et al.* (2017) identified twenty one intervention studies that reported quantitative associations between interventions and health outcomes (including thirteen which were included in the Cochrane review). The review was broadly consistent with previous related reviews and concluded that:

> *'there is now a suggestive body of evidence that energy efficiency and heating interventions in housing may improve the health of some population groups, notably those with respiratory and other chronic diseases. Positive effects on health may include improvements in respiratory symptoms and the symptoms of other chronic illnesses, improved mental well-being, reduced contacts with the health service, and fewer days of absence from school or work. For some key target groups, such as children with asthma, housing intervention may be sufficiently justified in its own right as a means of helping to manage the clinical condition.'*

Several high quality studies have been completed since the last published comprehensive review in 2017, and have generally supported the finding of the previous reviews. Poortinga *et al.* (2017b) report on the health impacts of a large scale project to upgrade social housing in a region of Wales. Upgrades were categorised as involving: windows and doors; boilers; kitchens; bathrooms; electrics; ceiling insulation; cavity wall insulation; external wall insulation; and safety improvements to external paths. Five repeated cross-sectional health surveys were conducted on occupants of the properties to be upgraded over a seven-year period from 2009 to 2016. In general, interventions were associated with improved mental health, fewer respiratory symptoms, and better general health, although many of the associations were not statistically significant. Further, both the count of the number of measures installed and total amount spent on a property were associated with better health outcomes. Unexpectedly, cavity wall insulation was associated with poorer mental and general health, and an increase in reported respiratory issues. A related study, Poortinga *et al.* (2017a) presented changes in internal conditions associated with the intervention

---

[2] The sample-weighted average effect size is the standardised mean difference in outcomes between an experimental and a control group. Maidment, Jones et al. (2014) cite a previous study stating that values of d = 0.20, 0.50 and 0.80 indicate small, medium and large effects respectively.

program. An average increase of 0.84 ºC [3] was found in the dwellings (largest change 1.17 ºC during the evening), as well as a reduction in cumulative hours below 16 ºC and 18 ºC, and relative humidity (RH) above 60%. External wall insulation was found to be the most effective measure to increase indoor air temperature; the results for cavity wall insulation were not explicitly stated, however properties with cavity walls were found to be an average of 0.17 ºC colder post-intervention, which may provide an explanation for the poor health outcomes seen in Poortinga *et al.* (2017a). No cost-benefit data was presented in either study for the intervention programme.

Several relevant studies have been completed in New Zealand which may be particularly relevant to the Australian context, including two of the studies graded as high quality in the Cochrane review. Importantly, the cost-benefit of different interventions has been calculated in several of the studies completed in New Zealand. Chapman *et al.* (2009) presented the cost-benefit analysis calculated from the insulation intervention study presented in Howden-Chapman *et al.* (2007). The net present value (5% discount rate, 30 year horizon) of the installation of 'basic' insulation (i.e. insulation in the ceiling, draught-stopping around the windows and doors, insulated foil strapped under the floor joists and a polyethylene covering over the ground in the sub-floor space) in uninsulated homes was calculated at NZ$1574 per household, with reduced hospital admission contributing 66.1% of the benefits, and energy and $CO_2$ savings accounting for 26% of the benefits. Similarly, Preval *et al.* (2010) calculated the cost and benefits (including health co-benefits) of the installation of energy efficient and healthy heaters (heat pump, wood pellet burner or flued gas heater) in homes with asthmatic children, as reported in Howden-Chapman *et al.* (2008). The net present value (5% discount rate, 12-year horizon) was found to be NZ $219 for a household with high rates of asthma, and NZ -$1666 for properties with typical rates of asthma. As for the insulation intervention, health (and associated caregiver) benefits outweighed energy benefits, in this case contributing 90.9% and 68.6% of the benefits depending on assumed rates of asthma (note that the assumed cost of adult care required for a child sick with asthma was a highly sensitive input, the study used the conservative assumption of minimum wage).

Following the positive results reported above for New Zealand interventions, the New Zealand government introduced subsidies to support retrofitting insulation and/or installing clean heating for pre-2000 houses. Grimes *et al.* (2011) calculated the energy, health and employment benefits of the subsidies, using two years of actual and two years of planned installs. A number of scenarios were considered, with a central assumption of 4% discount rate, 85% additionality (i.e. 85% of the installs would not have occurred without the subsidy), 30-year life for insulation, and ten year life for heaters. Net benefits from energy savings and health improvements were found to be NZ$1,214 Million, with a benefit-to-cost ratio of 4.3. Health benefits (including numbers of hospitalisation, hospitalisation costs, pharmaceutical costs, reductions in mortality, GP visits, and sick days or days off school) were found to account for 98.8% of the benefits, with the insulation responsible for 99.8% of the benefits. The report recommended the benefits may be increased by prioritising insulation installation and targeting colder climates, low income and other at-risk groups in terms of illness, and properties which use gas for heating.

Preval *et al.* (2017) analysed cohort data of individuals aged over 65, with cardiovascular- or respiratory-related hospitalisation who had lived in a home that received subsidised upgrades under the Warm Up New Zealand: Heat

---

[3] Recorded conditions (pre – post ºC): overall average 18.09 – 18.95, daytime average 18.19 – 18.97, night time average 17.93 – 18.81, daily average (living room) 18.53 – 19.33, daily average (bedroom) 18.16 – 18.86, daily average (kitchen) 18.09 – 18.68.

Smart programme previously analysed in Grimes *et al.* (2011). They found evidence of a protective effect (reduced risk of mortality for vulnerable older adults) from the installation of insulation in the cardiovascular sub-cohort, and suggestive evidence of a protective effect for the respiratory sub-cohort. There was no evidence of an additional benefit from receiving heating. A similar scheme to those above was undertaken in Canterbury, New Zealand in the wake of the 2010 earthquake, and found similar, highly positive results (Shone *et al.* 2016). 1500 insulation installations and 450 heating installations were undertaken in the homes of high health system users. Internal conditions were found to be warmer and drier in the properties which received the upgrades; hospital discharges were reduced by 15.9% and hospital bed days by 29.2% (control group showed no change). The reduced health cost equated to an annual saving of $945,000, giving the program an approximately one year simple payback period.

It should be noted that the studies summarised above occurred in New Zealand, which has a colder, damper climate, and an acknowledged history of poorly constructed properties with insufficient weatherproofing (Howden-Chapman *et al.* 2010) which may increase the benefits in these studies relative to what could be expected in Australia.

# 4. Health impacts of heat waves and high internal temperatures

## Summer heat, housing quality and health risks in Australia

Heat waves are Australia's deadliest natural hazard and since 1900 have been responsible for the death of more people than all other natural hazards (such as hurricanes, lightning, tornadoes, floods and earthquakes) combined (PwC 2011, Coates *et al.* 2014). There has been an estimated total of at least 5332 deaths attributable to heat waves in Australia from 1844 to 2010 (Coates *et al.* 2014). Most of these fatalities were in the southern region of Australia (primarily Victoria, NSW and South Australia) during the summer months, particularly January. Definitions of heat wave tend to vary as it is often difficult to determine exactly when they begin and end due to the more gradual nature in which they occur, compared to other natural disasters. In addition, the term is relative to the usual weather of an area with no universal threshold to delineate between 'normal' climate variability and extreme temperature events. As Lee (2014) notes, 'This means what is considered a heat wave in one location may be considered as normal climatic fluctuation for another location.' According to the Bureau of Meteorology, heat waves are defined in Australia as a period of at least three days where the combined effect of high temperatures and excess heat is unusual within the local climate (BoM 2012, Nairn *et al.* 2013).

Heat waves in Australia are becoming more intense, lasting longer and occurring more often (PwC 2011, Steffen *et al.* 2014). Modelling carried out by PwC (2011) suggests that that deaths associated with 'top heat events' (extreme heat events which have significant health, social and/or economic impacts on a particular community) are likely to more than double by 2050 if the national strategy for preventing, preparing for and responding to these events is not changed (Figure 9), and that climate change has the potential to increase the subsequent death toll greatly.

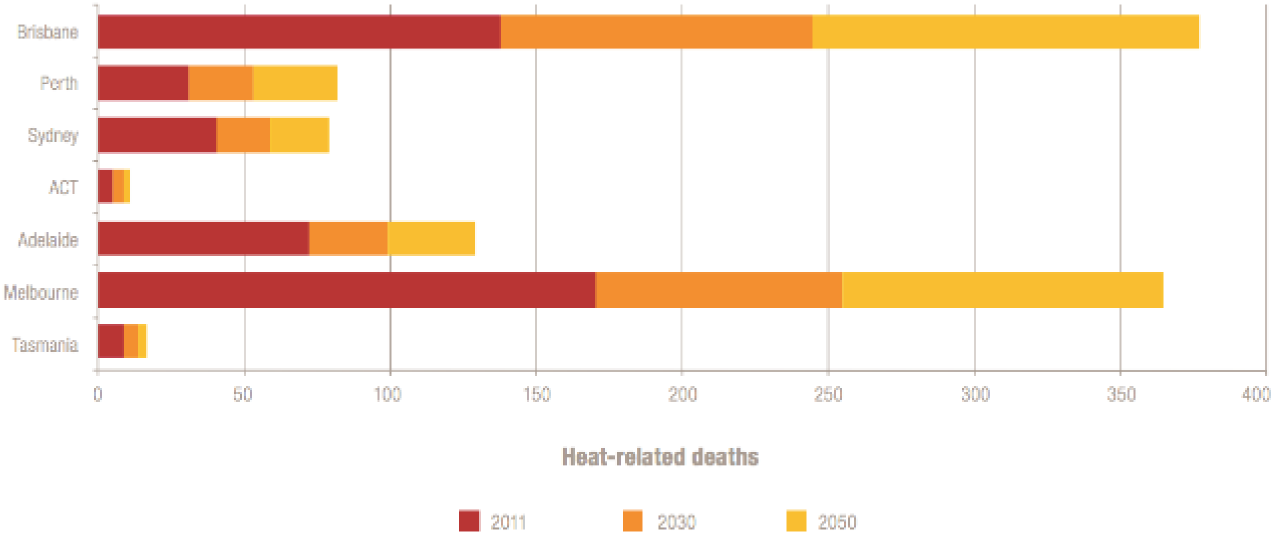


Figure 9. Estimates of heat-related deaths associated with top heat events (PwC 2011).

The changes in Australian heat waves are part of a long-term global trend, with record-breaking heat waves recorded in many parts of the world over the last decade (Coumou *et al.* 2012, Steffen *et al.* 2014). Europe (2003), Russia (2010) and several regions in the US in 2011 and 2012 have experienced extreme heat waves. These trends are very likely to be influenced by human driven climate change (IPCC 2013). As Lee (2014) notes: 'The IPCC has predicted with virtual certainty (99–100 % probability) that "increase in the frequency and magnitude of warm daily temperature extremes will occur in the twenty-first century at the global scale" and that it is very likely (90–100 % probability) that "the length, frequency, and/or intensity of warm spells or heat waves will increase over most land areas" (IPCC 2012).' The Climate Council's report 'Heatwaves: Hotter, Longer, More Often' provides an in-depth look at the observed changes to heat waves in Australia in the context of increasing extreme heat events around the world.

As environmental temperatures rise, thermal stress on the body increases and the body, in turn, responds by thermoregulation: blood flows towards the skin transferring heat from the body's core and sweating transfers heat from the skin by evaporation (Havenith 2005). This can strain the cardiovascular system as it strives to maintain a normal temperature. Excessive sweating may result in potentially serious health impacts due to dehydration and loss of salt. Contrary to the statistics reported in Section 3, heat and subsequent dehydration have been reported to be a greater contributor to temperature-related deaths than cold (IEA 2014). Heat events exist along a spectrum of increasing severity. At the lower end of this continuum exists a risk of increased illness from heat rash to heat stroke along with an exacerbation of existing co-morbidities (in addition to a range of social and economic impacts). As heat events become more intense the risk for unexpected deaths becomes greater, as does the potential for heat-related illness and the exacerbation of existing co-morbidities (PwC 2011). A range of conditions may be experienced during heat events, from less serious issues such as heat rash, oedema (swelling of the lower limbs), heat cramps and heat syncope (dizziness or brief loss of consciousness), through to the more serious conditions of heat exhaustion (including intense thirst, weakness, discomfort, anxiety, fainting, where the core body temperature is below 40 °C) and heat stroke (including confusion, coma, nausea, tachycardia, where the body temperature is greater than 40 °C) (PwC 2011). Barnett *et al.* (2013) note that an increase of the core body temperature to 38 °C results in a diminished capacity for physical work, mental impairment and risk of an accident. Heat exhaustion and heat stroke may occur at core body temperatures of 39 °C, and the situation becomes life threatening at above 40.6 °C.

The increased mortality associated with heat waves is primarily due to cardiovascular and respiratory illnesses (Ballester *et al.* 2003). Exposure to high temperatures causes increases in blood viscosity and blood cholesterol levels (Huynen *et al.* 2001). A Dutch study (Huynen *et al.* 2001) into the impact of heat waves and cold spells on mortality from 1979 to 1997 found the excess total mortality during the six heat waves investigated ranged from 8.7 to 24.4% (average of 12.1%, or 39.8 deaths/day), presenting a significant increase in mortality for all heat waves in the study. Mortality was the highest during the longest heat wave in the study and was generally found to be largest for respiratory diseases (although mortality caused by malignant tumours and cardiovascular disease were also affected by extreme heat), and those over 65 were found to be most affected by extreme heat. Those most susceptible to heat have been found to be those with certain chronic medical conditions such as cardiovascular and cerebrovascular diseases, diabetes, respiratory and renal diseases, Parkinson's disease, Alzheimer's disease and epilepsy (Semenza *et al.* , McGeehin *et al.* 2001). For children less than three years old, child health and development have been found to be adversely affected by the inability to heat or cool houses adequately (Cook *et al.* 2008). In Australia, Wang *et al.* (2012), found significant increases in mortality and hospital admission in Brisbane during heat waves; the most vulnerable were the elderly and people with pre-existing cardiovascular, renal or diabetic disease.

Global epidemiological studies have shown extreme heat events impact sub-sections of society disproportionally (Coates *et al.* 2014). Major risk factors for heat-related morbidity and mortality are reported to include urban living (such as residing on the top floor of apartment buildings, access to air conditioning, the urban heat island effect and retention of heat overnight), age (the elderly and young people are particularly vulnerable), and socioeconomic factors (particularly poverty and social isolation) (McGeehin *et al.* 2001). The most important physiological and socio-economic risk factors identified in relation to extreme heat events are listed in Table 2.

Table 2. Identified risk factors that can affect an individual's vulnerability to extreme heat events (McGeehin *et al.* 2001, PwC 2011, Coates *et al.* 2014).

| **Physiological** | **Contextual** |
|---|---|
| Age | Geographical location, particularly urban living |
| Gender | Access to air conditioning |
| Acclimatisation | Outdoor exposure + strenuous outdoor physical activities |
| Chronic mental disorders | Education surrounding heat events |
| Alcohol/narcotics | Social interaction/isolation |
| Existing co-morbidities and associated medication<br>• High risk: cardiovascular diseases (including oedema and heart failure, ischemic heart diseases, hypertensive diseases, circulatory conditions), genitourinary diseases, respiratory diseases<br>• Medium risk: Low blood pressure, angina, diabetes mellitus, mental health conditions<br>• None: All other conditions | Socio-economic factors, ethnicity and race |
| Disability | Transport accessibility/mobility |
|  | Homelessness |

The effects of heat have been noted to be stronger at the start of summer when vulnerable people have not yet acclimatised to the higher temperatures (Diaz *et al.* 2002). Huynen *et al.* (2001) note that a temporary fall in deaths exists in the weeks after an extreme heat event which is suggestive of a mortality displacement or 'harvesting' effect whereby 'heat principally affects those whose health is already compromised and who would have died in the short term anyway'. However, modelling carried out by PwC (2011) did not reveal an obvious corresponding decrease in excess deaths during the subsequent weeks after a heat wave that would be expected if the deaths were solely due to harvesting.

A time series analysis on the delayed effects of weather on mortality in twelve US cities found that the risk of death on hot days increases with increasing variation in the summertime temperatures (Braga *et al.* 2001). This is of particular significance given predictions that temperature variability will increase throughout the 21st century as a result of global climate change. The authors note that although they observed acclimatisation to higher *mean* temperatures, they did not see any acclimatisation to increases in temperature *variability*, indicating potential public health implications in a changing climate.

Guo *et al.* (2017) recently conducted a thorough study comparing the effects of heat waves on mortality globally; previous studies have typically focussed on a single city or region with considerable variation in the temperature thresholds and lengths of time. They analysed the community-specific heat wave–mortality relation for 400 communities in 18 countries/regions, taking different regional norms into account by defining heat waves based on different percentiles of daily mean temperatures (90th, 92.5th, 95th, and 97.5th) and looking at periods of abnormally high temperature lasting at least 2, 3 and 4 days. The authors found that:

> *'in all countries/regions, heat waves were associated with increased risk of death for all types of heat wave definitions. The estimated effects of heat wave on mortality were higher when using higher temperature thresholds (e.g., 97.5th vs. 95th percentile of temperature). In general, the effects of heat waves varied by country; for example, Italy had highest heat wave effects. The effects of heat waves [on mortality] appeared acutely and lasted for 3 and 4 [days] for most countries. Heat waves effect estimates were higher in moderate cold and moderate hot areas than in cold and hot areas. However, heat waves did not have added effects on mortality when controlling for the effects of daily mean temperature in all countries/regions, except for Brazil, Moldova,* and Taiwan, using the *≥ 97.5th percentile of temperature as the heat wave definition. Heat waves defined by daily mean and maximum temperatures produced similar effect estimates, which are higher than those defined by daily minimum temperature.'*

An important point to note is that in contrast with previous research, e.g. (Anderson *et al.* 2011) the number of days that a heat wave persisted did not modify the heat wave-related mortality risk. The authors suggest that instead of developing heat wave warning systems to reduce health risks that efforts may be better spent on developing high temperature warning systems.

## Recommended temperature ranges for healthy homes

As noted in Section 3, the healthy indoor temperature range recommended by the World Health Organisation is 18 to 24 °C, with a 2-3 °C warmer minimal temperature for rooms occupied by sedentary elderly, young children and the disabled (Ormandy *et al.* 2012). Ormandy *et al.* (2012) note that the majority of work on maintaining indoor temperatures within the thermal comfort range has thus far been focused on the health impact of low temperatures. However, high temperatures caused by heat waves can have serious health impacts in situations of fuel poverty and energy efficiency particularly in the most vulnerable populations such as the young, elderly or infirm.

A Dutch study on the self-perceived health of elderly individuals in high indoor temperatures found that the relationship with heat-related health problems in the elderly is stronger with indoor (living room and bedroom) temperature than with outdoor temperature, with thirst, sleep disturbance and excessive sweating the most reported symptoms (van Loenhout *et al.* 2016). The UK's Housing Health and Safety Rating System guidelines note that high internal temperatures can increase cardiovascular strain and trauma, an increase in mortality and strokes occur where temperatures exceed 25 °C, and that dehydration is a problem primarily for the elderly and the very young. (The Office of the Deputy Prime Minister 2006).

The health risk associated with heat stress is not represented accurately by dry bulb temperature alone (Shapiro *et al.* 1984). Other environmental factors, namely mean radiant temperature, air velocity, and wet bulb temperature, influence the thermal condition experienced by an occupant (Fanger 1970). Numerous indices have been developed for assessing thermal comfort and heat stress, taking into account various physiological, behavioural and environmental factors. In their review of the indices Epstein *et al.* (2006) recommend the use of 'direct indices', that is those calculated from measurements of the environmental factors only (i.e. excluding behavioural and physiological). The Wet Bulb Globe Temperature (WGBT) and the Discomfort Index (DI) are well-known, relatively simple indices which been most commonly used in epidemiological studies in recent decades (Epstein *et al.* 2006). Both indices are closely correlated. The WGBT is a weighted combination of dry bulb temperature, wet bulb temperature and black-globe temperature. The DI value is the average of the dry bulb and wet-bulb temperature (thereby taking into account the effect of humidity) and is the index recommended by Epstein *et al.* (2006) and employed by Barnett *et al.* (2013). The DI value represents the environmental heat load and associated heat-related health risk as shown in Table 3.

Table 3. Discomfort Index and heat-related risk (Epstein *et al*. 2006, Barnett *et al*. 2013)

| DI Value | Thermal sensation | Approximate equivalent dry bulb temperature (ºC) at: | | |
|---|---|---|---|---|
| | | 10% RH | 50% RH | 90% RH |
| <22 | No heat stress is encountered | <30.8 | <25.6 | <22.7 |
| 22-24 | Most people feel a mild sensation of heat | 30.8 – 33.4 | 25.6 – 27.7 | 22.7 – 24.7 |
| 24-28 | Heat load is moderately heavy, people feel very hot | 33.4 – 38.5 | 27.7 – 32.0 | 24.7 - 28.7 |
| >28 | Heat load is severe, people at increased risk of heat illness | >38.5 | >32.0 | >28.7 |

## Energy efficiency intervention for improved heat wave resilience

The importance of energy efficiency retrofitting to mitigate the effect of heat events and subsequently protect inhabitants from the worst impacts has been acknowledged in the literature. The following section describes the findings from several key intervention studies. Many of the energy efficiency interventions that help to keep houses warm in cold temperatures such as insulation and energy efficient windows, in addition to building positioning and the depth of eaves, will similarly keep heat out when outdoor temperatures are high (IEA 2014). However, many studies point to the importance of home air conditioning in alleviating the effects of high indoor temperatures and the resultant increased risk of heat-related morbidity and mortality (Centers for Disease Control and Prevention 1995, McGeehin *et al.* 2001, Curriero *et al.* 2002), particularly in extreme climates with severe heat related risk. As noted above, and by previous studies (e.g. Saman *et al.* (2013)) lower income occupants are the least able to afford to use air conditioning during high heat events and are therefore particularly at risk.

In their study on thermal performance and indoor environment of low income housing types in the Australian context, Barnett *et al.* (2013) investigated how different climate adaptation options implemented at the building scale can impact heat-related health risk. This study addressed a major research gap, identified by Williamson *et al.* (2009), and is therefore one of few highly relevant studies for the Australian climate. A range of different retrofit options were tested on ten building typologies, developed from a database with information of 142,210 social housing dwellings. Simulations were conducted using the AccuRate software tool for seven climate zones (using reference cities) and included predicted climatic conditions up to 2070. The retrofit options investigated included altering roof materials and colour, increasing ceiling insulation, reducing air leaks and infiltration, building orientation and solar aspect, windows shading, glazing and further insulation options (such as floor and wall). The authors used a DI threshold value of 28 to define health-related heat risk (Table 3). The report concluded that:

> *'House types in climate zones with hot and humid summers were found to be most vulnerable. In these locations, house retrofits cannot mitigate the level of severe heat-related health risk (DI > 28), and air*

> *conditioning will be increasingly required to maintain a safe indoor thermal environment. Retrofits are more effective in temperate locations, largely ameliorating climate impacts in the short term.'*

Simulations were undertaken to identify the reductions that could be achieved in thermal discomfort for four retrofit scenarios, namely worst case, base case, cheap retrofit and expensive retrofit, for the ten housing types. The authors found that:

> *'While there are differences between the house types, across climate zones, what appears to be more important is the quality of the house type, rather than the type itself. In other words, there is often greater variation in the performance between 'worst case' and 'expensive retrofit' within a house type, than there is between the different house types. This is not always true, but does suggest the significant role for climate adaptation engineering. It highlights the need to address the 'worst case' scenarios in each house type first, as the best way to improve performance.'*

The authors also simulated how each representative housing type in the social housing portfolio would perform during an extreme heat event, with the one year period covering the January 2009 heat wave in Melbourne used for this study. Across the five-day duration of the heat wave, the DI threshold of 28 (beyond which severe heat-related health risk occurs) was breached for every housing type, with the 'worst case' scenario resulting in severe heat-related risk for an average of 30% of the five-day heat wave across the housing types. The cheap and expensive retrofits were found to reduce this number to 17% and 13%, respectively. Poor performing house types were also found to amplify the heat-related health risk with indoor DI values often higher than that which would be experienced outside. A temporal lag was similarly found to exist particularly in house types characterised by high thermal mass, with important implications for behavioural adaptations, as such house types will retain heat during prolonged weather events and occupants will need to either air condition the space, or to seek alternative locations for respite. The authors note that:

> *'adaptation of buildings can help to reduce the level of severe heat-related health risk (DI > 28) during heatwaves. The current standard slab-on-ground brick veneer house clearly performs the best, but significant improvements can be made to the older slab- on-ground homes and to high rise apartments to reduce heat exposure. For example, on average across all ten house types, a 'cheap retrofit' could reduce severe heat-related health risk (DI > 28) as measured in the 'base case', by 25%.'*

Importantly, the authors advise a variety of building upgrades and adaptations be employed across varying scales in order to ensure maximum effectiveness. Findings for specific retrofit interventions may be summarised as follows:

- Roof materials and colour: Changing the roof colour from dark to light significantly reduced the total annual hours of severe heat-related risk to inhabitants (i.e. D > 28) across all reference cities. Roof colour was found to be more important than roof material in reducing the thermal risk to occupants, highlighting the importance of cool roofs.
- Increasing ceiling insulation: Ceiling insulation was found to be an important strategy in reducing heat-related health risk to occupants, and a significant reduction in heat-related health risks could be achieved by installing R1.5 ceiling insulation.

- Reducing air leaks and infiltration: Weatherproofing was found to have little influence on reducing the level of severe thermal risk to occupants across all reference cities, suggesting that other engineering adaption strategies will be far more effective.
- Building orientation and solar aspect: The building orientation was found to be important, with north-south orientations performing better than east-west orientation.
- Windows, shading and other options: Following ceiling insulation, window shading, double glazing, wall insulation and lastly floor insulation were found to have the greatest impact on improving thermal comfort.

Alam *et al.* (2016) predicted that by increasing the energy star rating of houses by changing insulation and air leakage, the effects on the health of particularly vulnerable people from a heat wave could be mitigated. They simulated the temperatures in a standard four bedroom house during the 2009 Melbourne heat wave and compared the predicted heat stress indicators (Discomfort Index – DI and wet bulb globe temperature – WBGT) with the number of excess deaths, ambulance calls, ED presentations and after hours calls over the duration of the heatwave. By changing the simulation to achieve different energy star ratings in the simulated house, they looked at how the heat stress indicators changed with the energy star rating. It was estimated that the number of excess deaths from a heat wave similar to the Melbourne 2009 heat wave could be reduced by 90% if all Victorian houses were upgraded to a minimum of 5.4-star energy rating. Similarly, Ren *et al.* (2014) undertook simulation to explore the internal conditions that would have been experienced during two recent heat waves events (Melbourne 2009 and Brisbane 2004) in conventional and energy efficient dwellings without air conditioning. Whilst it was found that generally increasing energy efficiency in buildings (measured by NatHERS star rating) resulted in decreased heat-related health risk, there were some individual interventions that were found to be problematic. In the Melbourne climate, it was found that buildings with improved air-tightness and insulation, but unimproved windows were likely to worsen the heat stress experienced by occupants.

PwC (2011) developed a national framework entitled 'Protecting human health and safety during severe and extreme heat events' to contribute to efforts in reducing risk and increasing the resilience of Australian cities, buildings and infrastructure to heat events. The authors carried out modelling to understand the impact of past and potential future heat events. Several key mitigation areas for decreasing exposure of at-risk individuals and communities to extreme heat events are identified, with potential approaches summarised as follows:

- Buildings: Consideration of design aspects such as green roofs, use of materials with lower thermal mass or increased albedo, use of building compliance standards such as Six Star building ratings and LEED compliance standards, and insulation.
- Urban ecology and planning: Reduction of the urban heat island effect through building materials in new developments, as well as landscaping and the use of green spaces. Policies and programs to support those within urban areas who are at increased risk during extreme heat events.
- Transport: Consideration of the resilience of transport networks, particularly public transport, during periods of prolonged exposure to high temperatures to minimise systemic malfunction.
- Improving access to cooling: Develop programs to improve access to air conditioning targeted at those at most risk (rather than the general population), with a particular focus on educating 'at-risk groups about

how best to use air conditioners, and to provide financial assistance to certain at-risk groups so they can use their air conditioners without worrying about, or suffering from, financial stress.'

- Electricity supply: Enhance the resilience of electricity supply by greater consideration of extreme heat event risks by infrastructure managers when designing network additions and upgrades, particularly interstate connections, and greater uptake of smart meters and smart appliances in order to help level peak demand when the grid is threatened with an overload.

Numerous other studies have contributed to the understanding of the use of interventions to mitigate the impact of extreme heat events on the population. The role of urban vegetation in reducing heat-related mortality in Melbourne has been investigated using modelling to understand the effect of urban vegetation schemes on local climates, and subsequent indoor thermal performance of residential buildings using these vegetation-modified local climates (Chen *et al.* 2014). Simulations showed a potential reduction in the average seasonal summer temperatures of around 0.5 and 2 °C if Melbourne CBD was replaced by vegetated suburbs and parklands, respectively. An increase in vegetation coverage from 15% to 33% was found to have the potential to reduce the average heat related mortality rate by approximately 5% - 28%. A reduction in the excess mortality rate from 37% - 99% was estimated to be possible by replacing the entire CBD area with forest parkland. The authors acknowledge there is room for improvement in this study given it is a first attempt at quantifying urban vegetation in mitigating heat related mortality rate at the scale of buildings, however the findings show the potential benefits of using urban vegetation to reduce heat related deaths by mitigating the impacts of heat waves in a changing climate. Barnett *et al.* (2013) found an association between land surface temperatures and the concentration of low income housing; meaning that those vulnerable to heat-related health impacts were found to be concerted in areas of the studied cities with the highest heat exposure.

# 5. Health Impacts of Mould Growth and House Dust Mites in Housing

Mould is a broad definition for a range of fungal organisms found in the indoor and outdoor environment. The presence of moulds in the natural environment is not always detrimental. However, their concentrated presence in the indoor environment is a cause of concern both for the visual appearance of the surfaces, but more importantly for the health impact on the occupants of the building. It has been estimated that one in three houses in Australia are affected by mould and moisture (Cheong 2013). This is in line with statistics from around the world, showing the prevalence of mould to be in the range of 10-50% of all houses in the most affluent countries (Heseltine *et al.* 2009). Studies from around the world show varying prevalence rates such as 35% in New Zealand (Howden - Chapman *et al.* 2005), 16.5% for a combination of any one or more indicators of dampness issues in European countries (Haverinen-Shaughnessy 2012), or as high as 47% in the US (Mudarri *et al.* 2007). A survey of 597 households in Edinburgh, Glasgow and London found that 23.3% had evidence of damp and 45.9% had actual mould growth visible (Platt *et al.* 1989).

Many studies have been conducted to investigate the impact of mould issues in homes on adverse health conditions (Curtis *et al.* 2004, IOM 2004, Heseltine *et al.* 2009, Braubach *et al.* 2011, Cheong 2013). There is difficulty in providing definitive links between the two, however, it is generally accepted that there is sufficient evidence to show that the occupants of damp or mouldy buildings are at increased risk of respiratory symptoms, respiratory infections and exacerbation of asthma. Airborne mould exposure has also been linked to other adverse health effects on the immune system, nervous system, haematological system or skin (Curtis *et al.* 2004). Results from a small number of intervention studies show that remediation of dampness can reduce adverse health outcomes (Heseltine *et al.* 2009). Specific studies, such as Platt *et al.* (1989), have focused on the prevalence of symptoms among those living in houses affected by damp and mouldy conditions. This study found a significant relationship between damp and mouldy housing and symptomatic health, particularly among children. Likewise, direct estimation of the health impact of dust mite exposure is difficult, however, it has been identified as a significant factor underlying allergic rhinitis and allergic asthma. The greatest risk of exposure is for occupants with an underlying allergen sensitisation; however, the prevalence of this sensitisation is difficult to establish (Calderon *et al.* 2017). The concentration of dust mite allergen has been shown to be associated with the prevalence of asthma symptoms across multiple countries in the Asia-Pacific region (Wickens *et al.* 2004).

## Causes of Mould in Residential Homes

Mould requires five basic factors for growth including mould spores to germinate, food, oxygen, favourable temperatures and moisture (Yost *et al.* 2002). The first four of these are readily found in any building environment. The prevalence of mould spores in the natural outdoor environment means that most effective way to manage mould in a building is to eliminate or limit the conditions that foster its establishment and growth (Holme 2006). Mould decomposes dead organic material so can grow on wood, paper-covered gypsum board (drywall) or other wood-based materials, but it can also grow on microscopic dust collecting on surfaces not cleaned regularly. Therefore, the governing factor affecting mould growth in buildings is generally considered to be excess moisture. This undesirable moisture can come from a number of sources including ingress from outside (i.e. rain), flooding, internal leaks from plumbing, condensation on walls or interstitial (i.e. between structure) condensation. While most of these are governed by building maintenance, condensation on walls and interstitial condensation are heavily influenced by the building design. Condensation occurs when the temperature of a surface drops below the dew point temperature (or saturation temperature) of the air, thus allowing for moisture in the air to condense out on the surface. The dew point temperature of the air is a function of the temperature and the moisture content of the air.

Many attempts have been made to understand the temperature and humidity conditions under which mould will germinate and grow. Experimental studies have been conducted on various building materials under specified conditions (e.g. Johansson *et al.* (2010)), however the results are often specific to the material type or mould species. Generally, it is accepted that a minimum sustained level of relative humidity of 80% is required for mould growth. The British code of practice for control of condensation in buildings (British Standards Institution 2016) recommends that the average relative humidity in a room be kept below 70%, as if it is above this level then the humidity at the wall surface is likely to exceed 80% and cause favourable conditions for mould growth. The CIBSE guide also recommends 40–70% RH for normal conditions in buildings, with a target value for design of 60% RH (CIBSE 2006).

Factors affecting the formation of condensation and hence the extent and severity of mould can either be building fabric characteristics (such as the location, orientation, wall and flooring materials etc.) or occupational behaviour (density of occupants, cooking or bathing habits). Several studies have attempted to investigate and highlight the impact of each of these characteristics on the formation of mould. Altamirano-Medina *et al.* (2009) provide a good summary of the different studies relating the severity of mould to various factors, however they conclude that the variation and interrelationships of and between each of these factors are complex and difficult to assess. Becker (1984) conducted a visual assessment of mould and analysis of the occupant habits and building characteristic for 200 houses in the coastal, mild winter environment of Israel. Their study found that the major factors affecting the extent and severity of mould growth were location and orientation of the dwelling, occupancy density, cooking habits and type of wall covering. A survey conducted on 613 houses in New Zealand found that house design and construction factors that were independently associated with reported mould included: poorer house condition, older house age (>22 years), relative lack of sun exposure, and having no insulation (Howden - Chapman *et al.* 2005).

Another aspect affecting the indoor hygrothermal environment is the ventilation of the building, as it affects the transport of air - and therefore moisture - throughout the building. Ventilation is affected by a number of factors – natural ventilation, that is the opening of windows or doors, cross flow of air etc., forced ventilation through the use of exhaust fans or air conditioning and the air-tightness of the building fabric. The use of exhaust fans is a highly utilised and effective method of mitigating moisture, especially if they are located as close as possible to the water vapour source, such as the bathroom or laundry. Reduced air change rate, indicating inadequate ventilation, has also been linked to the formation of condensation on bedroom windows (Bekö *et al.* 2011) and therefore increased mould risk.

There is evidence to show that those in low income housing who find it difficult to keep their house warm experience greater damp and mould issues (Sharpe *et al.* 2015, Boomsma *et al.* 2017). Fuel poverty behaviours have been linked to a higher risk factor for damp and mould conditions, regardless of heating and ventilation practices (Sharpe *et al.* 2015). This study raised the concern that the symptoms of mould conditions may persist regardless of energy efficiency and ventilation measures implemented, therefore it was advised that such measures need to be implemented with awareness messages and improved ventilation strategies to reduce the risk of mould growth. High prevalence of mould in social housing properties has also been linked to poor maintenance of such properties (Doutney 2016).

Dust mites prefer a warm, humid environment and tend to inhabit carpets, mattresses or furniture within the house. Control of dust mite populations based on temperature and humidity levels has been proposed, however the limits that seem to be required to prevent dust mite growth are often not achievable given the surrounding environment conditions (Lowe 2000).

## Energy efficiency interventions and Mould Risk

A number of studies have been undertaken globally to explore the impact of energy efficiency interventions of mould and mould risk. The section below presents a summary of the observed impacts of various interventions. A Cochrane review has recently been completed to assess the evidence for remediating buildings damaged by dampness and mould for preventing or reducing respiratory tract symptoms, infections and asthma (Sauni *et al.* 2015). The review identified six studies of sufficient quality focussed on houses. Of these, one was related to post-flooding remediation, and the remaining five included some energy intervention, generally in conjunction with mould cleaning and education. Where possible specific results are reported below, however many studies refer to generic 'mould rehabilitation', including non-specific terms such as 'reducing moisture in crawlspaces and basements' or 'heating/ventilation/air conditioning alterations' (Kercsmar *et al.* 2006); the results from these individual studies are not reported below. The review concluded that there is 'moderate to very low-quality evidence that repairing mould-damaged houses and offices decreases asthma-related symptoms and respiratory infections compared to no intervention in adults.'

### Heating Improvements

Somerville *et al.* (2000) analysed data available from interventions in 59 houses with children diagnosed with asthma focused around the installation of various types of heating. Gas central heating was considered as a preference, however where gas supply was not available, electric storage heaters, solid-fuel or oil-fired central heating was considered. The results showed that the proportion of children sleeping in a damp bedroom decreased from 61% to 21%, and a damp and mouldy bedroom decreased from 43% to 6%. Respiratory symptoms and lost school time from asthma significantly decreased following the interventions. Shortt *et al.* (2007) compared the results of 100 households in Northern Island, 46 of which had new central heating systems installed. Of these houses, 63% reported that their experienced mould, condensation or dampness problems had been resolved following the intervention. In comparison, only 24% of houses in the non-intervention group stated that their condensation, mould and dampness issues were now absent over the same period.

### Improving air-tightness and ventilation

One of the areas targeted in improving the energy efficiency of dwellings is improving the air-tightness of the building, as this reduces the energy required to control the indoor environmental conditions. However, the air-tightness and subsequent ventilation rate of a household is known to have a direct impact on the indoor air quality as well as areas such as mould and dust mite proliferation. Davies *et al.* (2004) reviewed an extensive body of literature examining the relationship between ventilation and indoor air quality. They found a consensus of a link between ventilation rates and respiratory hazards such as house dust mites, as well as a corresponding link to respiratory problems. However, they noted that most of the data is inadequate to draw a direct association between ventilation rates and respiratory problems. Lowering ventilation rates has also been shown through numerically modelling to cause an increase in house dust mite concentrations in a mattress (Ucci *et al.* 2011).

The impact of reduced air change rate on the conditions for dust mite growth has also been used as justification for considering mechanical heat recovery ventilation systems (MHRV). In a study by Howieson *et al.* (2003), MHRV systems were shown to substantially reduce the concentration of house dust mites compared to a placebo, as well as improve the asthma symptoms of occupants. Additionally, Bone *et al.* (2010) have pointed to the need for mechanical ventilation systems following energy efficient upgrades.

Often, the issue with air-tightness comes as a combination of multiple factors affecting the indoor environment. The combined influence of installing insulated windows and central heating systems on dust mite concentration was analysed by Hirsch *et al.* (2000). They found that the air exchange rate decreased from 0.73 to 0.53 per hour, however temperature and absolute humidity both increased. In terms of the effect on dust mite and mould concentrations – concentration of one particular type of mould (which has an affinity for higher temperature and humidity) increased, whereas concentrations of other species of mould were largely unaffected or decreased. Mite allergen concentrations were found to increase after the building modifications.

Hall *et al.* (2013) simulated results of a combination of building upgrades for a solid/thin cavity masonry walled UK domestic building, including reducing the infiltration, draught-proofing, upgrading window design, and options including new mechanical ventilation with heat recovery installation or passive buffering of indoor air psychrometric conditions using conventional (clay, timber) and advanced (mesoporous silica) wall surface treatments. They used simulation techniques to analyse the mould growth potential of the various scenarios, and whilst they found that most of the scenarios resulted in a substantially decreased mould growth potential, there were some situations were a high mould growth potential was reached, specifically cases where infiltration was reduced, but there was no upgrade to the mechanical ventilation system.

Burr *et al.* (2007) found a significant improvement in wheeze affecting activities, perceived improvement of breathing and perceived reduction in medication from an intervention involving mould removal, fungicide application, and the installation of an extraction fan in the ceiling cavity. Eick *et al.* (2011) found a significant reduction in house dust mite allergen as well as significant reductions in breathlessness during exercise, wheezing, and coughing during the day and night from the installation of mechanical ventilation heat recovery; however, this was only for a relatively small sample of 16 homes.

### Insulation

The impact of insulation on hygrothermal performance of building envelopes has become a recent concern. Insulating external walls of a building will typically increase their surface temperature, which reduces the risk of mould growth. However, this also results in changing the hygrothermal performance within the wall and can lead to a greater risk of mould in the internal wall assembly. Performance analysis of certain types of insulation assemblies has shown that the relative humidity monitored inside the wall cavity can exceed the 90% criterion for mould growth (Li *et al.* 2016). Another study by Odgaard *et al.* (2018) in Copenhagen compared the effect of adding interior insulation to a section of a multi-storey building with an uninsulated section over two years, eight months. Their results found that the addition of insulation increased the surface temperature of the wall, while the relative humidity throughout the wall assembly increased and the temperature throughout the wall decreased. Visual assessments and mathematical predictions of mould risk were evaluated and found there to be no risk of mould damage from the addition of insulation.

The major New Zealand insulation intervention study reported on by Howden-Chapman *et al.* (2007), and discussed in detail in Section 3, also identified a significant reduction in the odds of insulated households reporting dampness or mould. No attempt was made by the authors to isolate the health effects of a reduction in mould and dampness from the improvement in indoor temperature, as they are inextricably linked.

As it is often difficult to monitor and assess the long term hygrothermal performance of buildings, simulation tools are becoming increasingly important in identifying potential risks. Abdul Hamid *et al.* (2017) demonstrated how the use of hygrothermal simulation tools such as WUFI Pro could be used to analyse the mould risk of installing internal insulation. For the situations they considered, there was an appreciable risk of mould growth found from installing insulation. Marincioni *et al.* (2014) tested experimentally and using a hygrothermal simulation, the effect of internal wall insulation on the interstitial temperature and relative humidity. They found that the relative humidity varied considerably, and in many cases the insulation systems increased the relative humidity at the wall, which could lead to mould issues. It is therefore vital that any internal insulation systems proposed in existing homes need to consider the impact on relative humidity and ensure that ventilation is adequate to prevent mould growth.

## 6. Conclusions

The current interim report has reviewed evidence regarding the direct energy benefits and health co-benefits which are likely to result from energy efficiency upgrades to low income housing in Australia. For all benefits there is a lack of evidence from large scale, high quality randomised control trials in Australian climates and for Australian dwellings. There have been a number of high quality international studies completed, and a number of relevant previous studies in Australia, however this is an area that would benefit from a major, national study.

Whilst there is not conclusive evidence regarding the direct costs and benefits of energy efficiency interventions, a number of relevant real world trials and simulation studies have been undertaken in recent years. These studies highlight the difficulties involved in determining cost-benefits for intervention at any level of aggregation, as both the cost and direct benefits are highly contextual. However, there is evidence that many commonly implemented interventions to improve the energy performance of poor quality buildings are economically viable, and will likely result in substantial utility bill savings.

It is not currently possible to provide concrete conclusions reading the health benefits of interventions to improve winter warmth in Australian climates. The uncertainty regarding the direct causal pathways from an energy intervention to a health outcome means large scale experimental studies are necessary to explore this area. There is evidence that Australia experiences a relatively high occurrence of excess winter deaths, which has been linked to climates with milder winter, and to energy inefficient housing. Reviews of previous studies in other countries have found increasingly strong evidence that energy efficiency interventions which increase winter warmth may improve the health of occupants, particularly those with health issues. Studies which have assessed the cost-benefit of these interventions have identified that health benefits may vastly outweigh the energy benefits. This is a promising area for future research in Australia, however large-scale randomised controlled trials are needed to provide reliable quantitative conclusions.

There is a relative lack of high quality review papers exploring the impact of energy interventions on heat-related risk, as compared with low internal temperatures. As such, it is not currently possible to provide concrete conclusions reading the health benefits of interventions to improve housing performance. However, heat waves have been identified as a major natural hazard in Australia, responsible for the death of more people than all other natural hazards combined. As for low temperatures, low income populations have been shown to be at greater risk of morbidity and mortality from heat wave events. As the effects of heat waves are observed more quickly than for cold weather, i.e. in the days following a heat wave event, it is somewhat easier to link exposure to high heat stress environments with negative health outcomes. However, to date the only studies identified for Australia utilised simulation to identify heat stress exposure within typical homes, reported using an index accounting for temperature and humidity. This approach has identified that energy efficiency interventions to dwellings would be expected to reduce the health risk of heat wave events in Australia, although in climates with hot and humid summers, air conditioning will be increasingly required to maintain a safe indoor thermal environment. Understanding the direct causal relationship between exposure to heat stress (e.g. as measured by discomfort index) in homes and health outcomes in Australia, and the likely impact of energy interventions, will require further research.

A recent Cochrane review of evidence found 'moderate to very low-quality evidence that repairing mould-damaged houses and offices decreases asthma-related symptoms and respiratory infections compared to no intervention in adults (Sauni *et al.* 2015)'. Mould risk is closely related to low internal ambient conditions, which can lead to condensation and thereby provide the required moisture for mould growth. Therefore, interventions to reduce mould occurrence often focus on increasing internal ambient temperatures. There is some evidence that heating system improvements, improvements to insulation, and improved air-tightness and controlled ventilation can reduce mould risk and occurrence, which may result in decreased respiratory illness. However, the direct causal pathways linking energy efficiency intervention to health outcomes from reduced exposure to mould are not clearly defined. This is a promising area for future research in Australia, and large-scale randomised controlled trials are needed to provide meaningful conclusions.

There is emerging evidence that the health co-benefits experienced by low income occupants, particularly young children, the elderly, and those with pre-existing health conditions, could represent a substantial benefit to both occupants and general society that is not currently captured by standard cost-benefit assessments. However, further research is required to improve the understanding of the direct causal pathways between housing quality, internal environmental conditions and health outcomes, and the impact to these outcomes that can be achieved through energy efficiency interventions.

## 7. References

Abdul Hamid, A. and P. Wallentén (2017). "Hygrothermal assessment of internally added thermal insulation on external brick walls in Swedish multifamily buildings." Building and Environment **123**: 351-362.

ABS (2014). Deaths, Australia, 2014, Australian Bureau of Statistics.

ACIL ALLEN (2017). Multiple Impacts of Household Energy Efficiency: An Assessment Framework, ACIL ALLEN CONSULTING PTY LTD.

ACOSS (2013). Energy Efficiency & People on Low Incomes, Australian Council of Social Service,.

Alam, M., J. Sanjayan, P. X. W. Zou, M. G. Stewart and J. Wilson (2016). "Modelling the correlation between building energy ratings and heat-related mortality and morbidity." Sustainable Cities and Society **22**: 29-39.

Allen Consulting Group (2005). Climate Change Risk and Vulnerability: Promoting an efficient adaptation response in Australia. Canberra, Australian Greenhouse Office, Department of the Environment and Heritage.

Allen Consulting Group (2011). Mandatory disclosure of residential building energy, greenhouse and water performance: Consultation Regulation Impact Statement, Allen Consulting Group.

Altamirano-Medina, H., M. Davies, I. Ridley, D. Mumovic and T. Oreszczyn (2009). "Guidelines to avoid mould growth in buildings." Advances in Building Energy Research **3**(1): 221-235.

Anderson, B. G. and M. L. Bell (2009). "Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States." Epidemiology **20**(2): 205-213.

Anderson, G. B. and M. L. Bell (2011). "Heat Waves in the United States: Mortality Risk during Heat Waves and Effect Modification by Heat Wave Characteristics in 43 U.S. Communities." Environmental Health Perspectives **119**(2): 210-218.

Australian National Audit Office (2010). Home Insulation Program Performance Audit Commonwealth of Australia,.

Baker, E., L. H. Lester, R. Bentley and A. Beer (2016). "Poor housing quality: Prevalence and health effects." J Prev Interv Community **44**(4): 219-232.

Ballester, F., P. Michelozzi and C. Iniguez (2003). "Weather climate and public health: Seasonal changes and the impact on public health." Journal of  Epidemiology and Community Health **57**: 759–760.

Barnett, G., M. Beaty, D. Chen, S. McFallan, J. Meyers, M. Nguyen, Z. Ren, A. Spinks and X. Wang (2013). Pathways to climate adapted and healthy low income housing. Gold Coast, National Climate Adaptation Research Facility.

Barton, A., M. Basham, C. Foy, K. Buckingham and M. Somerville (2007). "The Watcombe Housing Study: the short term effect of improving housing conditions on the health of residents." Journal of Epidemiology and Community Health **61**(9): 771-777.

Basu, R. (2002). "Relation between Elevated Ambient Temperature and Mortality: A Review of the Epidemiologic Evidence." Epidemiologic Reviews **24**(2): 190-202.

Becker, R. (1984). "Condensation and mould growth in dwellings—parametric and field study." Building and environment **19**(4): 243-250.

Bekö, G., J. Toftum and G. Clausen (2011). "Modeling ventilation rates in bedrooms based on building characteristics and occupant behavior." Building and Environment **46**(11): 2230-2237.

Beyond Zero Emissions (2013). Zero Carbon Australia Buildings Plan. Melbourne, Melbourne Energy Institute, The University of Melbourne.

BoM. (2012). "Annual Climate Summary 2012." from Accessed at http://www.bom.gov.au/climate/annual_sum/2012/index.shtml.

Bone, A., V. Murray, I. Myers, A. Dengel and D. Crump (2010). "Will drivers for home energy efficiency harm occupant health?" Perspectives in Public Health **130**(5): 233-238.

Boomsma, C., S. Pahl, R. V. Jones and A. Fuertes (2017). "“Damp in bathroom. Damp in back room. It's very depressing!” exploring the relationship between perceived housing problems, energy affordability concerns, and health and well-being in UK social housing." Energy policy **106**: 382-393.

Bowie, N. and G. Jackson (2002). The Raised Incidence of Winter Deaths.

Braga, A. L. F., A. Zanobetti and J. Schwartz (2001). "The time course of weather realted deaths." Epidemiology **12**(6).

Braubach, M., D. Heinen and J. Dame (2008). Preliminary results of the WHO Frankfurt housing intervention project, World Health Organisation.

Braubach, M., D. Jacobs and D. Ormandy (2011). Environmental burden of disease associated with inadequate housing: A method guide to the quantification of health effects of selected housing risks in the WHO European Region, World Health Organization.

British Standards Institution (2016). BS 5250: Code of practice for control of condensation in buildings,. London, British Standards Institution.

Burke, T. and L. Ralston (2015). RP3001: Household Energy Use Consumption and Expenditure Patterns 1993-2012. Sydney, CRC Low Carbon Living.

Burr, M. L., I. P. Matthews, R. A. Arthur, H. L. Watson, C. J. Gregory, F. D. J. Dunstan and S. R. Palmer (2007). "Effects on patients with asthma of eradicating visible indoor mould: a randomised controlled trial." Thorax **62**(9): 767-772.

Calderon, M. A., J. Bousquet, G. W. Canonica, L. O. Cardell, D. H. Fernandez de Rojas, J. Kleine-Tebbe and P. Demoly (2017). "Guideline recommendations on the use of allergen immunotherapy in house dust mite allergy: Time for a change?" J Allergy Clin Immunol **140**(1): 41-52.

Centers for Disease Control and Prevention (1995). Heat-related illnesses and deaths—United States, 1994-1995, Centers for Disease Control and Prevention. **44**.

Chapman, R., P. Howden-Chapman, H. Viggers, D. O'Dea and M. Kennedy (2009). "Retrofitting houses with insulation: a cost-benefit analysis of a randomised community trial." J Epidemiol Community Health **63**(4): 271-277.

Chen, D., X. Wang, M. Thatcher, G. Barnett, A. Kachenko and R. Prince (2014). "Urban vegetation for reducing heat related mortality." Environ Pollut **192**: 275-284.

Cheong, C. D. (2013). "Literature review of current research on health effects and accepted guidelines for the management of indoor mould and water damage in the built environment." Journal of the Australasian College of Nutritional and Environmental Medicine **32**(3): 10.

CIBSE (2006). Health issues in building services: CIBSE TM40. London, Chartered Institution of Building Services Engineers.

Clinch, J. P. and J. D. Healy (2000). "Housing standards and excess winter mortality." Journal of Epidemiology and Community Health **54**: 719-720.

Coates, L., K. Haynes, J. O'Brien, J. McAneney and F. D. de Oliveira (2014). "Exploring 167 years of vulnerability: An examination of extreme heat events in Australia 1844–2010." Environmental Science & Policy **42**: 33-44.

Collins, K., J. Easton, H. Belfield-Smith, A. Exton-Smith and R. Pluck (1985). "Effects of age on body temperature and blood pressure in cold environments." Clinical Science **69**(4): 465-470.

Collins, K. J. (1986). "Low indoor temperatures and morbidity in the elderly." Age and Ageing **15**(4): 212-220.

Cook, J. T., D. A. Frank, P. H. Casey, R. Rose-Jacobs, M. M.Black, M. Chilton, S. E. deCuba, D. Appugliese, S. Coleman, T. Heeren, C. Berkowitz and D. B. Cutts (2008). "A Brief Indicator of Household Energy Security: Associations With Food Security, Child Health, and Child Development in US Infants and Toddlers." Pediatrics **122**(4).

Cooper, P., R. Gordon, G. Waitt, D. Petkovic, N. Burroughs, M. Tibbs, K. Butler, K. Roggeveen, C. McDowell, G. Kokogiannakis, L. L. Gomis and C. Magee (2016). EE3A: Pathways and initiatives for low-income older people to manage energy: Final Report.

Cordell Building Publications (2017). Housing Building Cost Guide. Northbridge, N.S.W., CoreLogic.

Coumou, D. and S. Rahmstorf (2012). "A decade of weather extremes." Nature Climate Change **2**: 491.

Curriero, F. C., K. S. Heiner, J. M. Samet, S. L. Zeger, L. Strug and J. A. Patz (2002). "Temperature and mortality in 11 cities of the eastern United States." Am J Epidemiol **155**(1): 80-87.

Curtis, L., A. Lieberman, M. Stark, W. Rea and M. Vetter (2004). "Adverse health effects of indoor molds." Journal of Nutritional & Environmental Medicine **14**(3): 261-274.

Daly, D., M. Tibbs and P. Cooper (2018). Summary of Existing Processes for Upgrading and Maintenance of Social Housing Properties. Wollongong, CRC for Low Carbon Living.

Davies, M., M. Ucci, M. McCarthy, T. Oreszczyn, I. Ridley, D. Mumovic, J. Singh and S. Pretlove (2004). "A Review of Evidence Linking Ventilation Rates in Dwellings and Respiratory Health – A Focus on House Dust Mites and Mould." International Journal of Ventilation **3**(2): 155-168.

Department of Health (2007). Regional Public Health Group Fact Sheet: Health and winter warmth. . London, Regional Public Health Group in the South East.

Diaz, J., A. Jordan, R. Garcia, C. Lopez, J. C. Alberdi, E. Hernandez and A. Otero (2002). "Heat waves in Madrid 1986-1997: effects on the health of the elderly." Int Arch Occup Environ Health **75**(3): 163-170.

Doutney, I. (2016). Inquiry into the management of NSW public housing maintenance contracts: Submission number 12, City of Sydney.

EES (2008). Energy Use In The Australian Residential Sector 1986 - 2020. Canberra, Energy Efficient Stratgies,.

Eick, S. A. and G. Richardson (2011). "Investigation of different approaches to reduce allergens in asthmatic children's homes — The Breath of Fresh Air Project, Cornwall, United Kingdom." Science of The Total Environment **409**(19): 3628-3633.

Energy Efficient Strategies (2011). The Value of Ceiling Insulation: Impacts Of Retrofitting Ceiling Insulation To Residential Dwellings In Australia, ICANZ.

Energy Partners (2006). Effects of Combined Insulation & Draught Proofing Strategies, Energy Partners,.

Enquselassie, F., A. Dobson, H. Alexander and P. Steele (1993). "Seasons, temperature and coronary disease." International Journal of Epidemiology **22**(4).

Epstein, Y. and D. S. Moran (2006). "Thermal Comfort and the Heat Stress Indices." Industrial Health **44**(3): 388-398.

FACS (2017). Applying the NSW Human Services Outcomes Framework in FACS: an overview, Family and Community Services.

Fanger, P. O. (1970). Thermal Comfort. Copenhagen, Danish Technical Press.

Gasparrini, A., Y. Guo, M. Hashizume, E. Lavigne, A. Zanobetti, J. Schwartz, A. Tobias, S. Tong, J. Rocklöv, B. Forsberg, M. Leone, M. De Sario, M. L. Bell, Y.-L. L. Guo, C.-f. Wu, H. Kan, S.-M. Yi, M. de Sousa Zanotti Stagliorio Coelho, P. H. N. Saldiva, Y. Honda, H. Kim and B. Armstrong (2015). "Mortality risk attributable to high and low ambient temperature: a multicountry observational study." The Lancet **386**(9991): 369-375.

Geddes, I., E. Bloomer, J. Allen and P. Goldblatt (2011). The Health Impacts of Cold Homes and Fuel Poverty, Friends of the Earth & the Marmot Review Team,.

Grimes, A., T. Denne, P. Howden-Chapman, R. Arnold, L. Telfar-Barnard, N. Preval and C. Young (2011). "Cost Benefit Analysis of the Warm Up New Zealand: Heat Smart Programme."

Guo, Y., A. Gasparrini, B. G. Armstrong, B. Tawatsupa, A. Tobias, E. Lavigne, M. Coelho, X. Pan, H. Kim, M. Hashizume, Y. Honda, Y. L. Guo, C. F. Wu, A. Zanobetti, J. D. Schwartz, M. L. Bell, M. Scortichini, P. Michelozzi, K. Punnasiri, S. Li, L. Tian, S. D. O. Garcia, X. Seposo, A. Overcenco, A. Zeka, P. Goodman, T. N. Dang, D. V. Dung, F. Mayvaneh, P. H. N. Saldiva, G. Williams and S. Tong (2017). "Heat Wave and Mortality: A Multicountry, Multicommunity Study." Environ Health Perspect **125**(8): 087006.

Hall, M. R., S. P. Casey, D. L. Loveday and M. Gillott (2013). "Analysis of UK domestic building retrofit scenarios based on the E.ON Retrofit Research House using energetic hygrothermics simulation – Energy efficiency, indoor air quality, occupant comfort, and mould growth potential." Building and Environment **70**: 48-59.

Hamilton, I., J. Milner, Z. Chalabi, P. Das, B. Jones, C. Shrubsole, M. Davies and P. Wilkinson (2015). "Health effects of home energy efficiency interventions in England: a modelling study." BMJ Open **5**(4): e007298.

Havenith, G. (2005). Temperature regulation, heat balance and climatic stress. Extreme Weather Events and Public Health Responses. New York, Springer.

Haverinen-Shaughnessy, U. (2012). "Prevalence of dampness and mold in European housing stock." Journal of Exposure Science and Environmental Epidemiology **22**(5): 461-467.

Healy, J. D. (2003). "Excess winter mortality in Europe: a cross country analysis identifying key risk factors." Journal of Epidemiology and Community Health **57**: 784-789.

Heseltine, E. and J. Rosen (2009). WHO guidelines for indoor air quality: dampness and mould, WHO Regional Office Europe.

Hirsch, T., M. Hering, K. Burkner, D. Hirsch, W. Leupold, M. L. Kerkmann, E. Kuhlisch and L. Jatzwauk (2000). "House-dust-mite allergen concentrations (Der f 1) and mold spores in apartment bedrooms before and after installation of insulated windows and central heating systems." Allergy **55**(1): 79-83.

Holme, J. (2006). Detection, assessment and evaluation of mould in buildings in relation to indoor environment and effects on human health, Nowegian Building Research Institute.

Hopton, J. and S. Hunt (1996). "The health effects of improvements to housing: A longitudinal study." Housing Studies **11**(2): 271-286.

Howden-Chapman, P., J. Bennett and R. Siebers, Eds. (2010). Do Damp and Mould Matter? Health Impacts of Leaky Homes. Wellington, Steele Roberts, .

Howden-Chapman, P., A. Matheson, J. Crane, H. Viggers, M. Cunningham, T. Blakely, C. Cunningham, A. Woodward, K. Saville-Smith, D. O'Dea, M. Kennedy, M. Baker, N. Waipara, R. Chapman and G. Davie (2007). "Effect of insulating existing houses on health inequality: cluster randomised study in the community." BMJ **334**(7591): 460.

Howden-Chapman, P., N. Pierse, S. Nicholls, J. Gillespie-Bennett, H. Viggers, M. Cunningham, R. Phipps, M. Boulic, P. Fjallstrom, S. Free, R. Chapman, B. Lloyd, K. Wickens, D. Shields, M. Baker, C. Cunningham, A. Woodward, C. Bullen and J. Crane (2008). "Effects of improved home heating on asthma in community dwelling children: randomised controlled trial." BMJ **337**: a1411.

Howden-Chapman, P., H. Viggers, R. Chapman, D. O'Dea, S. Free and K. O'Sullivan (2009). "Warm homes: Drivers of the demand for heating in the residential sector in New Zealand." Energy Policy **37**(9): 3387-3399.

Howden‐Chapman, P., K. Saville‐Smith, J. Crane and N. Wilson (2005). "Risk factors for mold in housing: a national survey." Indoor Air **15**(6): 469-476.

Howieson, S. G., A. Lawson, C. McSharry, G. Morris, E. McKenzie and J. Jackson (2003). "Domestic ventilation rates, indoor humidity and dust mite allergens: are our homes causing the asthma pandemic?" Building Services Engineering Research and Technology **24**(3): 137-147.

Huynen, M. M., P. Martens, D. Schram, M. P. Weijenberg and A. E. Kunst (2001). "The impact of heat waves and cold spells on mortality rates in the Dutch population." Environmental Health Perspectives **109**(5): 463-470.

IEA (2014). Capturing the Multiple Benefits of Energy Efficiency, International Energy Agency.

IOM (2004). Damp Indoor Spaces and Health. Washington, D.C., The National Academies Press.

IPCC (2012). Managing the risks of extreme events and disasters to advance climate change adaptation: a special report of working groups I and II of the intergovernmental panel on climate change. Cambridge/New York, Cambridge University Press.

IPCC (2013). Climate Change 2013: The Physical Science Basis. Working Grup I Contribution to the IPCC 5th Assessment Report- Changes to the underlying Scientific/Technical Assessment. , Intergovernmental Panel on Climate Change.

Johansson, S., L. Wadsö and K. Sandin (2010). "Estimation of mould growth levels on rendered façades based on surface relative humidity and surface temperature measurements." Building and Environment **45**(5): 1153-1160.

Keatinge, W. R. (1986). "Seasonal mortality among elderly people with unrestricted home heating." British Medical Journal **293**.

Keatinge, W. R., G. C. Donaldson, E. Cordioli, M. Martinelli, A. E. Kunst, J. P. Mackenbach, S. Nayha and I. Vuori (2000). "Heat related mortality in warm and cold regions of Europe: observational study." British Medical Journal **321**.

Kenington, D., J. Wood, M. Reid and L. Klein (2016). Developing a Non-Energy Benefits Indicator Framework for Residential and Community Energy Efficiency Programs in New South Wales, Australia. International Energy Policies & Programmes Evaluation Conference, Amsterdam.

Kercsmar, C. M., D. G. Dearborn, M. Schluchter, L. Xue, H. L. Kirchner, J. Sobolewski, S. J. Greenberg, S. J. Vesper and T. Allan (2006). "Reduction in Asthma Morbidity in Children as a Result of Home Remediation Aimed at Moisture Sources." Environmental Health Perspectives **114**(10): 1574-1580.

LAHC (2016). LaHCR 2016/162 Review of NSW Land and Housing Corporations (LAHC) heating and cooling policy, practices and requirements and recommend options, F. a. C. S. Land and Housing Corporation.

Lee, W. V. (2014). "Historical global analysis of occurrences and human casualty of extreme temperature events (ETEs)." Natural Hazards **70**(2): 1453-1505.

Li, Y., H. Yu, T. Sharmin, H. Awad and M. Gül (2016). "Towards energy-Efficient homes: Evaluating the hygrothermal performance of different wall assemblies through long-term field monitoring." Energy and Buildings **121**: 43-56.

Liu, E. and B. Judd (2016). Lower income barriers to low carbon living (RP 3038): Summary of focus group and survey findings. Sydney, CRC Low Carbon Living.

Looper, M. d. (2002). Seasonality of death. Canberra, Australian Institute of Health and Welfare. **Bulletin No. 3**.

Lowe, R. J. (2000). "Psychrometric control of dust mites in UK housing " Building Services Engineering Research & Technology **21**(4): 274-276.

Ma, Z., P. Cooper, D. Daly and L. Ledo (2012). "Existing building retrofits: Methodology and state-of-the-art." Energy and Buildings **55**: 889-902.

Macmillan, A., M. Davies and Y. Bobrova (2014). Integrated decision-making about housing, energy and wellbeing: Report on the mapping work for stakeholders. London, The Bartlett, UCL Faculty of the Built Environment

Maidment, C. D., C. R. Jones, T. L. Webb, E. A. Hathway and J. M. Gilbertson (2014). "The impact of household energy efficiency measures on health: A meta-analysis." Energy Policy **65**: 583-593.

Marincioni, V., H. Altamirano and I. Ridley (2014). Performance of internal wall insulation systems - experimental test for the validation of a hygrothermal simulation tool. Lund, Sweden.

McGeehin, M. A. and M. Mirabelli (2001). "The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States." Environmental Health Perspectives **109**(Suppl 2): 185-189.

McMichael, A. J., P. Wilkinson, R. S. Kovats, S. Pattenden, S. Hajat, B. Armstrong, N. Vajanapoom, E. M. Niciu, H. Mahomed, C. Kingkeow, M. Kosnik, M. S. O'Neill, I. Romieu, M. Ramirez-Aguilar, M. L. Barreto, N. Gouveia and B. Nikiforov (2008). "International study of temperature, heat and urban mortality: the 'ISOTHURM' project." Int J Epidemiol **37**(5): 1121-1131.

Milne, G. and B. Boardman (2000). "Making cold homes warmer: the effect of energy efficiency improvements in low-income homes A report to the Energy Action Grants Agency Charitable Trust." Energy Policy **28**(6): 411-424.

Milner, J. and P. Wilkinson (2017). "Commentary: Effects of Home Energy Efficiency and Heating Interventions on Cold-related Health." Epidemiology **28**(1): 86-89.

Mudarri, D. and W. J. Fisk (2007). "Public health and economic impact of dampness and mold." Indoor air **17**(3): 226-235.

Nairn, J. and R. Fawcett (2013). Defining Heatwaves: Heatwave defined as a heat-impact even servicing all community and business sectors in Australia. CAWCR Technical Report, No. 060. , CSIRO and Australian Bureau of Meteorology**:** 96.

NSW Department for Health (2010). Closing the gap: 10 Years of Housing for Health in NSW. An evaluation of a healthy housing intervention, Aboriginal Environmental Health Unit, Population Health Division, NSW Department for Health.

NSW Government (2016). Future Directions for Social Housing in NSW, Family and Community Services.

Odgaard, T., S. P. Bjarløv and C. Rode (2018). "Interior insulation – Experimental investigation of hygrothermal conditions and damage evaluation of solid masonry façades in a listed building." Building and Environment **129**: 1-14.

Ormandy, D. and V. Ezratty (2012). "Health and thermal comfort: From WHO guidance to housing strategies." Energy Policy **49**: 116-121.

Osman, L. M., J. G. Ayres, C. Garden, K. Reglitz, J. Lyon and J. G. Douglas (2008). "Home warmth and health status of COPD patients." European Journal of Public Health **18**(4): 399-405.

Osman, L. M., J. G. Ayres, C. Garden, K. Reglitz, J. Lyon and J. G. Douglas (2010). "A randomised trial of home energy efficiency improvement in the homes of elderly COPD patients." Eur Respir J **35**(2): 303-309.

Phibbs, P. and S. Thompson (2011). The health impacts of housing: toward a policy-relevant research agenda, Australian Housing and Urban Research Institute.

Platt, S., R. Mitchell, J. Walker, J. Hopton, M. Petticrew, J. Corbett, S. Hope and C. Martin (2007). The Scottish Executive Central Heating Programme: Assessing Impacts on Health, Scottish Executive Social Research.

Platt, S. D., C. J. Martin, S. M. Hunt and C. W. Lewis (1989). "Damp housing, mould growth, and symptomatic health state." Bmj **298**(6689): 1673-1678.

Poortinga, W., S. Jiang, C. Grey and C. Tweed (2017a). "Impacts of energy-efficiency investments on internal conditions in low-income households." Building Research & Information: 1-15.

Poortinga, W., N. Jones, S. Lannon and H. Jenkins (2017b). "Social and health outcomes following upgrades to a national housing standard: a multilevel analysis of a five-wave repeated cross-sectional survey." BMC Public Health **17**(1): 927.

Preval, N., R. Chapman, N. Pierse and P. Howden-Chapman (2010). "Evaluating energy, health and carbon co-benefits from improved domestic space heating: A randomised community trial." Energy Policy **38**(8): 3965-3972.

Preval, N., M. Keall, L. Telfar-Barnard, A. Grimes and P. Howden-Chapman (2017). "Impact of improved insulation and heating on mortality risk of older cohort members with prior cardiovascular or respiratory hospitalisations." BMJ Open **7**.

PwC (2011). Protecting human health and safety during severe and extreme heat events: A national framework, PricewaterhouseCoopers Australia for Department of Climate Change and Energy and Efficiency.

Rawlinsons Group (2018). Rawlinsons Construction Cost Guide. Perth, Australia, Rawlinson Publishing, .

Remer, D. and A. Nieto (1995a). "A compendium and comparison of 25 project evaluation techniques. Part 1: Net present value and rate of return methods." International Journal of Production Economics **42**(1): 79-96.

Remer, D. and A. Nieto (1995b). "A compendium and comparison of 25 project evaluation techniques. Part 2: Ratio, payback, and accounting methods." International Journal of Production Economics **42**(2): 101-129.

Ren, Z., X. Wang and D. Chen (2014). "Heat stress within energy efficient dwellings in Australia." Architectural Science Review **57**(3): 227-236.

Rudge, J. and R. Gilchrist (2005). "Excess winter morbidity among older people at risk of cold homes: a population-based study in a London borough." Journal of Public Health **27**(4): 353-358.

Saman, W., J. Boland, S. Pullen, R. d. Dear, V. Soebarto, W. Miller, B. Pocock, M. Belusko, F. Bruno, D. Whaley, J. Pockett, H. Bennetts, B. Ridley, J. Palmer, J. Zuo, T. Ma, N. Chileshe, N. Skinner, J. Chapman, N. Vujinovic, M. Walsh, C. Candido and M. Deuble (2013). A framework for adaptation of Australian households to heat waves. Gold Coast, National Climate Change Adaptation Research Facility,.

Sauni, R., J. H. Verbeek, J. Uitti, M. Jauhiainen, K. Kreiss and T. Sigsgaard (2015). "Remediating buildings damaged by dampness and mould for preventing or reducing respiratory tract symptoms, infections and asthma." Cochrane Database of Systematic Reviews(2).

Semenza, J. C., J. E. McCullough, W. D. Flanders, M. A. McGeehin and J. R. Lumpkin "Excess hospital admissions during the July 1995 heat wave in Chicago." American Journal of Preventive Medicine **16**(4): 269-277.

Shapiro, Y. and Y. Epstein (1984). "Environmental Physiology and Indoor Climate Thermoregulation and Thermal Comfort." Energy and Buildings **7**: 29 - 34.

Sharpe, R. A., C. R. Thornton, V. Nikolaou and N. J. Osborne (2015). "Fuel poverty increases risk of mould contamination, regardless of adult risk perception & ventilation in social housing properties." Environment international **79**: 115-129.

Shone, C., G. Hamilton and K. Johns (2016). "Healthy Homes: Investing in Outcomes."

Shortt, N. and J. Rugkasa (2007). ""The walls were so damp and cold" fuel poverty and ill health in Northern Ireland: results from a housing intervention." Health Place **13**(1): 99-110.

Shrubsole, C., A. Macmillan, M. Davies and N. May (2014). "100 Unintended consequences of policies to improve the energy efficiency of the UK housing stock." Indoor and Built Environment **23**(3): 340-352.

Somerville, M., I. Mackenzie, P. Owen and D. Miles (2000). "Housing and health: does installing heating in their homes improve the health of children with asthma?" Public Health **114**(6): 434-439.

Sorrell, S., J. Dimitropoulos and M. Sommerville (2009). "Empirical estimates of the direct rebound effect: A review." Energy Policy **37**(4): 1356-1371.

Steffen, W., L. Hughes and S. Perkins (2014). Heatwaves: Hotter, Longer, More Often, Climate Council of Australia.

Sullivan, D. (2017). Home Energy Efficiency Upgrade Program Final Report, Brotherhood of St Laurence,.

Sustainability Victoria (2016a). Cavity Wall Insulation Retrofit Trial. Melbourne, Sustainability Victoria,.

Sustainability Victoria (2016b). Clothes Dryer Retrofit Trial Melbourne, Sustainability Victoria,.

Sustainability Victoria (2016c). Draught Sealing Retrofit Trial. Melbourne, Sustainability Victoria,.

Sustainability Victoria (2016d). Energy Efficiency Upgrade Potential of Existing Victorian Houses. Melbourne, Sustainability Victoria,.

Sustainability Victoria (2016e). Gas Water Heater Retrofit Trial. Melbourne, Sustainability Victoria,.

Sustainability Victoria (2016f). Halogen Downlight Retrofit. Melbourne, Sustainability Victoria,.

Sustainability Victoria (2016g). Swimming Pool Pump Retrofit Trial. Melbourne, Sustainability Victoria,.

Sustainability Victoria (2017a). Refrigerator retrofit trial. Melbourne, Sustainability Victoria,.

Sustainability Victoria (2017b). Window Film Secondary Glazing Retrofit Trial. Melbourne, Sustainability Victoria,.

Sustainability Victoria (2018). Outcomes evaluation of the Victorian Healthy Homes Program: a staggered parallel group cluster randomised controlled trial assessing the thermal comfort and health benefits of home energy efficiency improvements. Sydney Australian New Zealand Clinical Trials Registry.

The Office of the Deputy Prime Minister (2006). Housing Health and Safety Rating System: Operating Guidance. London, Office of the Deputy Prime Minister.

Thomas, S. (2011). Retrofitting Buildings form Energy Efficiency, University of Wollongong.

Thomson, H., S. Thomas, E. Sellstrom and M. Petticrew (2009). "The Health Impacts of Housing Improvement: A Systematic Review of Intervention Studies From 1887 to 2007." American Journal of Public Health **99**(3).

Thomson, H., S. Thomas, E. Sellstrom and M. Petticrew (2013). "Housing improvements for health and associated socio-economic outcomes." Cochrane Database Syst Rev(2): CD008657.

Ucci, M., P. Biddulph, T. Oreszczyn, D. Crowther, T. Wilkinson, S. E. C. Pretlove, B. Hart and I. Ridley (2011). "Application of a transient hygrothermal population model for house dust mites in beds: assessment of control strategies in UK buildings." Journal of Building Performance Simulation **4**(3): 285-300.

Urmee, T., S. Thoo and W. Killick (2012). "Energy efficiency status of the community housing in Australia." Renewable and Sustainable Energy Reviews **16**: 1916–1925.

van Loenhout, J. A. F., A. le Grand, F. Duijm, F. Greven, N. M. Vink, G. Hoek and M. Zuurbier (2016). "The effect of high indoor temperatures on self-perceived health of elderly persons." Environmental Research **146**: 27-34.

Waitt, G., K. Roggeveen, R. Gordon, K. Butler and P. Cooper (2016). "Tyrannies of thrift: Governmentality and older, low-income people’s energy efficiency narratives in the Illawarra, Australia." Energy Policy **90**: 37-45.

Wang, X. Y., A. G. Barnett, W. Yu, G. FitzGerald, V. Tippett, P. Aitken, G. Neville, D. McRae, K. Verrall and S. Tong (2012). "The impact of heatwaves on mortality and emergency hospital admissions from non-external causes in Brisbane, Australia." Occupational and Environmental Medicine **69**(3): 163.

Wickens, K., J. de Bruyne, M. Calvo, S. Choon-Kook, G. Jayaraj, C. K. Lai, J. Lane, R. Maheshwari, J. Mallol, S. Nishima, G. Purdie, R. Siebers, T. Sukumaran, M. Trakultivakorn and J. Crane (2004). "The determinants of dust mite allergen and its relationship to the prevalence of symptoms of asthma in the Asia-Pacific region." Pediatr Allergy Immunol **15**(1): 55-61.

Wilkinson, P., M. Landon, B. Armstrong, S. Stevenson, S. Pattenden, M. McKee and T. Fletcher (2001). Cold comfort The social and environmental determinants of excess winter deaths in England, 1986-96. Bristol, The Policy Press.

Willand, N. (2017). Residential energy efficiency and health – A mixed methods study of a quasi-randomised controlled trial of energy efficiency improvements of the homes of low-income Home and Community Care recipients near Melbourne, Australia. Doctor of Philosophy (Built Environment), RMIT University.

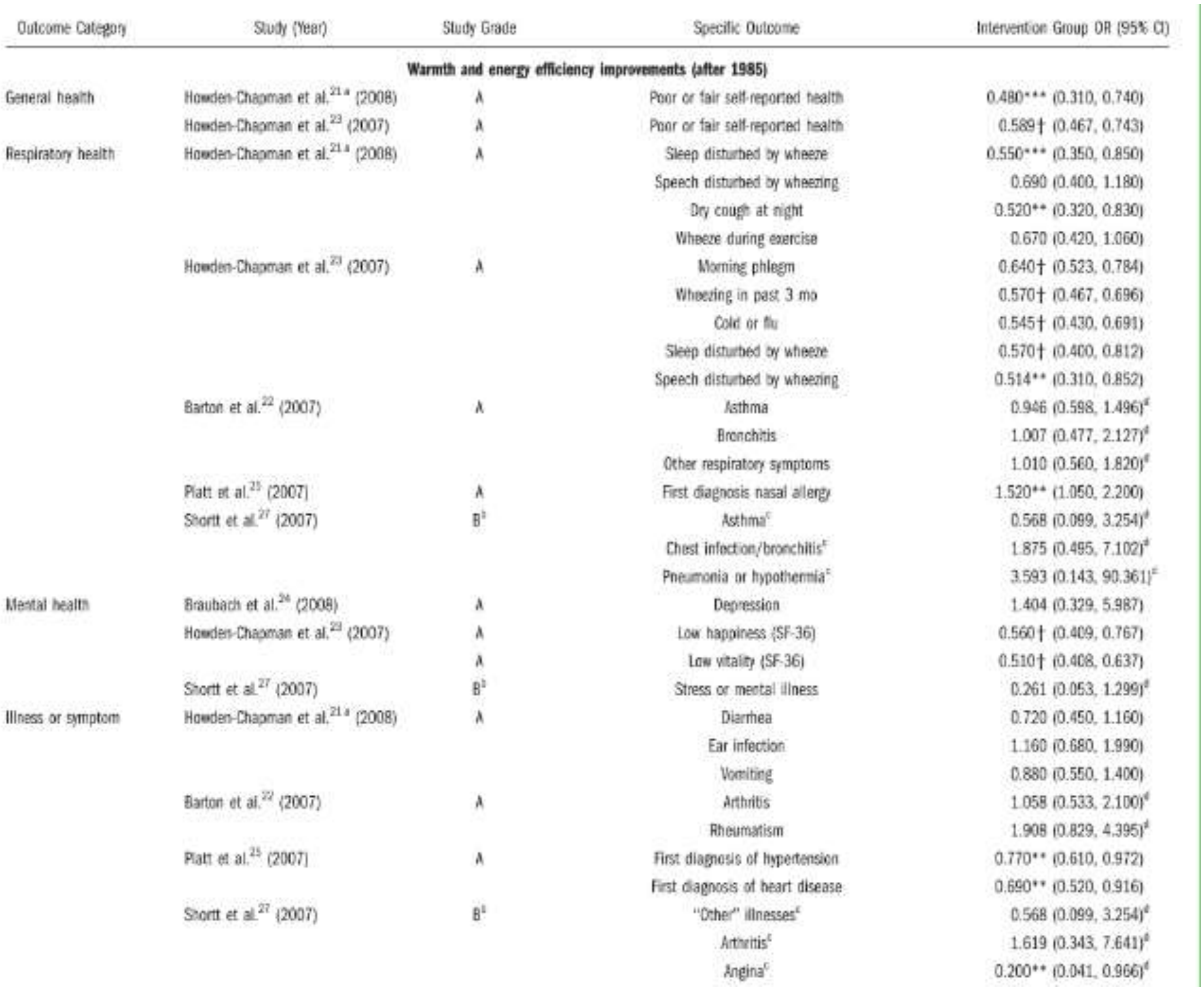
Willand, N., I. Ridley and A. Pears (2016). "Relationship of thermal performance rating, summer indoor temperatures and cooling energy use in 107 homes in Melbourne, Australia." Energy and Buildings **113**: 159-168.

Williamson, T., E. Grant, A. Hansen, D. Pisaniello and M. Andamon (2009). An Investigation of Potential Health Benefits from Increasing Energy Efficiency Stringency Requirements: Building Code of Australia Volumes One & Two. Adelaide, The University of Adelaide.

Yost, N., J. Lstiburek and T. Brennan (2002). What You Need to Know About Mold, Building Science Corporation.

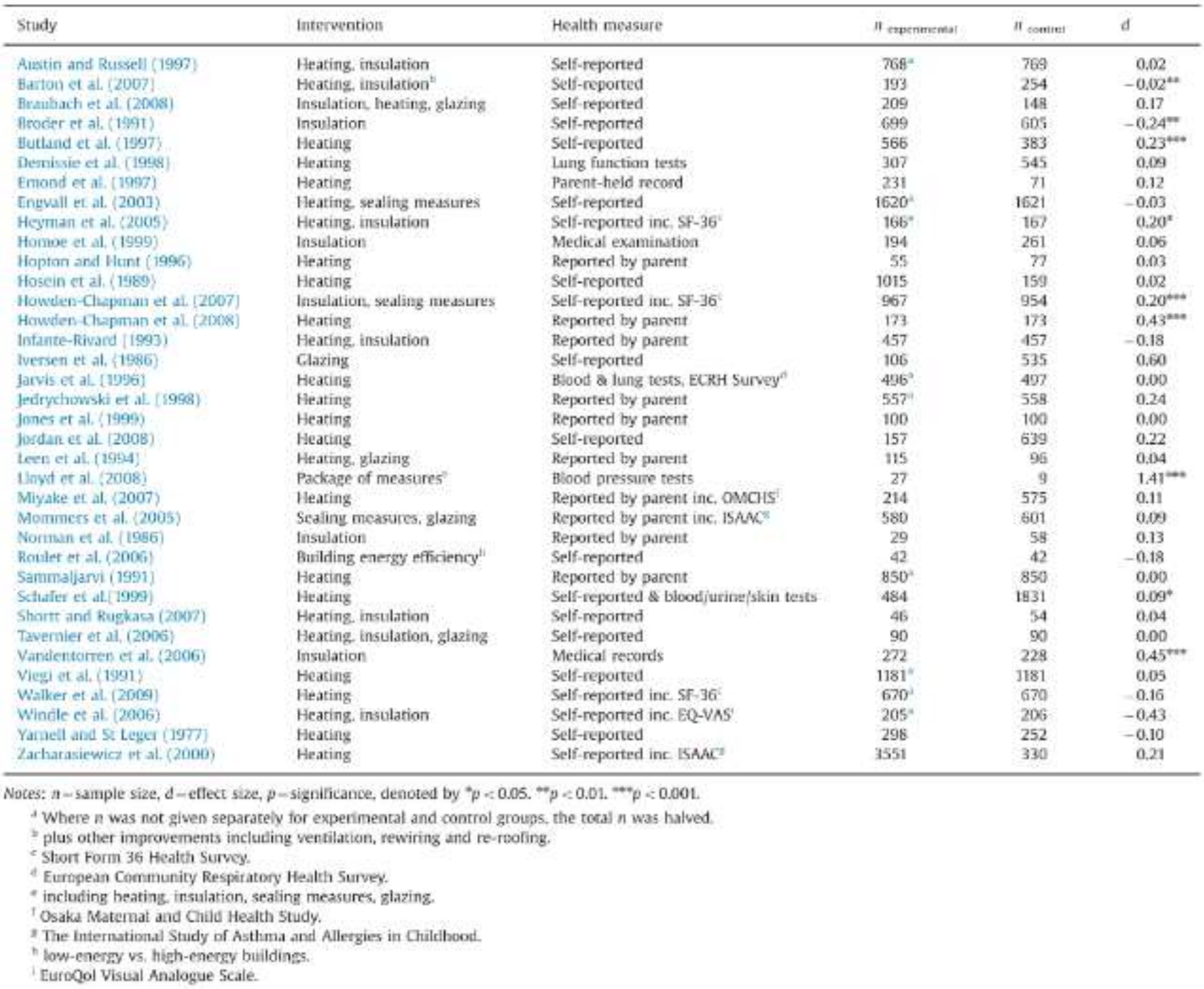
# Appendix A

Table 4. Measures of Standardised Effect (Intervention Group Compared With Control Group) Following Housing Improvement Interventions, reprinted from (Thomson *et al.* 2009). Note: odds ratio of 1 means no effect, lower odds ratio means lower prevalence of outcome in intervention group.



| Outcome Category | Study (Year) | Study Grade | Specific Outcome | Intervention Group OR (95% CI) |
|---|---|---|---|---|
| **Warmth and energy efficiency improvements (after 1985)** | | | | |
| General health | Howden-Chapman et al.[21][a] (2008) | A | Poor or fair self-reported health | 0.480*** (0.310, 0.740) |
| | Howden-Chapman et al.[23] (2007) | A | Poor or fair self-reported health | 0.589† (0.467, 0.743) |
| Respiratory health | Howden-Chapman et al.[21][a] (2008) | A | Sleep disturbed by wheeze | 0.550*** (0.350, 0.850) |
| | | | Speech disturbed by wheezing | 0.690 (0.400, 1.180) |
| | | | Dry cough at night | 0.520** (0.320, 0.830) |
| | | | Wheeze during exercise | 0.670 (0.420, 1.060) |
| | Howden-Chapman et al.[23] (2007) | A | Morning phlegm | 0.640† (0.523, 0.784) |
| | | | Wheezing in past 3 mo | 0.570† (0.467, 0.696) |
| | | | Cold or flu | 0.545† (0.430, 0.691) |
| | | | Sleep disturbed by wheeze | 0.570† (0.400, 0.812) |
| | | | Speech disturbed by wheezing | 0.514** (0.310, 0.852) |
| | Barton et al.[22] (2007) | A | Asthma | 0.946 (0.598, 1.496)[d] |
| | | | Bronchitis | 1.007 (0.477, 2.127)[d] |
| | | | Other respiratory symptoms | 1.010 (0.560, 1.820)[d] |
| | Platt et al.[25] (2007) | A | First diagnosis nasal allergy | 1.520** (1.050, 2.200) |
| | Shortt et al.[27] (2007) | B[b] | Asthma[c] | 0.568 (0.099, 3.254)[d] |
| | | | Chest infection/bronchitis[c] | 1.875 (0.495, 7.102)[d] |
| | | | Pneumonia or hypothermia[c] | 3.593 (0.143, 90.361)[e] |
| Mental health | Braubach et al.[24] (2008) | A | Depression | 1.404 (0.329, 5.987) |
| | Howden-Chapman et al.[23] (2007) | A | Low happiness (SF-36) | 0.560† (0.409, 0.767) |
| | | A | Low vitality (SF-36) | 0.510† (0.408, 0.637) |
| | Shortt et al.[27] (2007) | B[b] | Stress or mental illness | 0.261 (0.053, 1.299)[d] |
| Illness or symptom | Howden-Chapman et al.[21][a] (2008) | A | Diarrhea | 0.720 (0.450, 1.160) |
| | | | Ear infection | 1.160 (0.680, 1.990) |
| | | | Vomiting | 0.880 (0.550, 1.400) |
| | Barton et al.[22] (2007) | A | Arthritis | 1.058 (0.533, 2.100)[d] |
| | | | Rheumatism | 1.908 (0.829, 4.395)[d] |
| | Platt et al.[25] (2007) | A | First diagnosis of hypertension | 0.770** (0.610, 0.972) |
| | | | First diagnosis of heart disease | 0.690** (0.520, 0.916) |
| | Shortt et al.[27] (2007) | B[b] | "Other" illnesses[c] | 0.568 (0.099, 3.254)[d] |
| | | | Arthritis[c] | 1.619 (0.343, 7.641)[d] |
| | | | Angina[c] | 0.200** (0.041, 0.966)[d] |

Table 5. Sample-weighted effect size for health impacts of energy efficiency measures, reprinted from Maidment *et al.* (2014).



| Study | Intervention | Health measure | $n_{experimental}$ | $n_{control}$ | d |
|---|---|---|---|---|---|
| Austin and Russell (1997) | Heating, insulation | Self-reported | 768[a] | 769 | 0.02 |
| Barton et al. (2007) | Heating, insulation[b] | Self-reported | 193 | 254 | −0.02** |
| Braubach et al. (2008) | Insulation, heating, glazing | Self-reported | 209 | 148 | 0.17 |
| Broder et al. (1991) | Insulation | Self-reported | 699 | 605 | −0.24** |
| Butland et al. (1997) | Heating | Self-reported | 566 | 383 | 0.23*** |
| Demissie et al. (1998) | Heating | Lung function tests | 307 | 545 | 0.09 |
| Emond et al. (1997) | Heating | Parent-held record | 231 | 71 | 0.12 |
| Engvall et. al. (2003) | Heating, sealing measures | Self-reported | 1620[a] | 1621 | −0.03 |
| Heyman et al. (2005) | Heating, insulation | Self-reported inc. SF-36[c] | 166[a] | 167 | 0.20* |
| Homoe et al. (1999) | Insulation | Medical examination | 194 | 261 | 0.06 |
| Hopton and Hunt (1996) | Heating | Reported by parent | 55 | 77 | 0.03 |
| Hosein et al. (1989) | Heating | Self-reported | 1015 | 159 | 0.02 |
| Howden-Chapman et al. (2007) | Insulation, sealing measures | Self-reported inc. SF-36[c] | 967 | 954 | 0.20*** |
| Howden-Chapman et al. (2008) | Heating | Reported by parent | 173 | 173 | 0.43*** |
| Infante-Rivard (1993) | Heating, insulation | Reported by parent | 457 | 457 | −0.18 |
| Iversen et al. (1986) | Glazing | Self-reported | 106 | 535 | 0.60 |
| Jarvis et al. (1996) | Heating | Blood & lung tests, ECRH Survey[d] | 496[a] | 497 | 0.00 |
| Jedrychowski et al. (1998) | Heating | Reported by parent | 557[a] | 558 | 0.24 |
| Jones et al. (1999) | Heating | Reported by parent | 100 | 100 | 0.00 |
| Jordan et al. (2008) | Heating | Self-reported | 157 | 639 | 0.22 |
| Leen et al. (1994) | Heating, glazing | Reported by parent | 115 | 96 | 0.04 |
| Lloyd et al. (2008) | Package of measures[e] | Blood pressure tests | 27 | 9 | 1.41*** |
| Miyake et al. (2007) | Heating | Reported by parent inc. OMCHS[f] | 214 | 575 | 0.11 |
| Mommers et al. (2005) | Sealing measures, glazing | Reported by parent inc. ISAAC[g] | 580 | 601 | 0.09 |
| Norman et al. (1986) | Insulation | Reported by parent | 29 | 58 | 0.13 |
| Roulet et al. (2006) | Building energy efficiency[h] | Self-reported | 42 | 42 | −0.18 |
| Sammaljarvi (1991) | Heating | Reported by parent | 850[a] | 850 | 0.00 |
| Schafer et al.(1999) | Heating | Self-reported & blood/urine/skin tests | 484 | 1831 | 0.09* |
| Shortt and Rugkasa (2007) | Heating, insulation | Self-reported | 46 | 54 | 0.04 |
| Tavernier et al. (2006) | Heating, insulation, glazing | Self-reported | 90 | 90 | 0.00 |
| Vandentorren et al. (2006) | Insulation | Medical records | 272 | 228 | 0.45*** |
| Viegi et al. (1991) | Heating | Self-reported | 1181[a] | 1181 | 0.05 |
| Walker et al. (2009) | Heating | Self-reported inc. SF-36[c] | 670[a] | 670 | −0.16 |
| Windle et al. (2006) | Heating, insulation | Self-reported inc. EQ-VAS[i] | 205[a] | 206 | −0.43 |
| Yarnell and St Leger (1977) | Heating | Self-reported | 298 | 252 | −0.10 |
| Zacharasiewicz et al. (2000) | Heating | Self-reported inc. ISAAC[g] | 3551 | 330 | 0.21 |

*Notes:* $n$ – sample size, $d$ – effect size, $p$ – significance, denoted by $^*p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.001$.

[a] Where $n$ was not given separately for experimental and control groups, the total $n$ was halved.

[b] plus other improvements including ventilation, rewiring and re-roofing.

[c] Short Form 36 Health Survey.

[d] European Community Respiratory Health Survey.

[e] including heating, insulation, sealing measures, glazing.

[f] Osaka Maternal and Child Health Study.

[g] The International Study of Asthma and Allergies in Childhood.

[h] low-energy vs. high-energy buildings.

[i] EuroQol Visual Analogue Scale.

Table 6. Cost-benefit of modelling energy interventions, reprinted from Sustainability Victoria (2016d)

| | | Av. Energy Saving (MJ/Yr) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Across stock** | **% Houses Applied To** | **Gas** | **Elec** | **Total** | **Av. GHG Saving (Kg/Yr)** | **Av. Saving ($/Yr)** | **Av. Cost ($)** | **Av. Payback (Yrs)** |
| LF Shower Rose | 56.7% | 1,333 | 69 | **1,402** | 95 | $57.9 | $48.8 | 0.8 |
| Ceiling Insulation (easy) | 11.7% | 958 | 32 | **990** | 64 | $19.3 | $78.6 | 4.1 |
| Lighting | 93.3% | - | 1,202 | **1,202** | 365 | $93.5 | $535.8 | 5.7 |
| Draught Sealing | 98.3% | 7,809 | 221 | **8,030** | 496 | $153.9 | $1,019.8 | 6.6 |
| Clothes Washer | 55.0% | 135 | 16 | **152** | 12 | $24.9 | $190.9 | 7.7 |
| Water Heater – High Eff. Gas | 58.3% | 460 | 1,004 | **1,463** | 330 | $58.2 | $477.3 | 8.2 |
| Ceiling Insulation (difficult) | 33.3% | 1,630 | 68 | **1,698** | 111 | $33.8 | $278.2 | 8.2 |
| Heating | 80.0% | 6,239 | 215 | **6,454** | 411 | $125.9 | $1,110.6 | 8.8 |
| Refrigerator | 86.7% | - | 1,202 | **1,202** | 365 | $93.5 | $1,103.7 | 11.8 |
| Reduce Sub-Floor Ventilation | 21.7% | 589 | 12 | **601** | 36 | $11.2 | $166.7 | 14.9 |
| Seal Wall Cavity | 50.0% | 903 | 24 | **927** | 57 | $17.6 | $270.4 | 15.3 |
| TV | 95.0% | - | 696 | **696** | 273 | $54.1 | $964.3 | 17.8 |
| Ceiling Insulation (Top Up) | 43.3% | 853 | 22 | **875** | 54 | $16.6 | $335.3 | 20.2 |
| Underfloor Insulation | 40.0% | 1,803 | 10 | **1,813** | 102 | $32.4 | $784.7 | 24.3 |
| Dishwasher | 43.3% | - | 112 | **112** | 34 | $10.4 | $258.1 | 24.9 |
| Clothes Dryer – Heat Pump | 45.0% | - | 353 | **353** | 107 | $27.5 | $727.7 | 26.5 |
| Cooling | 40.0% | - | 160 | **160** | 49 | $12.5 | $464.8 | 37.3 |
| Wall Insulation | 95.0% | 5,283 | 130 | **5,412** | 331 | $102.5 | $3,958.7 | 38.6 |
| Drapes & Pelmets | 100.0% | 2,209 | 54 | **2,263** | 139 | $42.9 | $2,035.9 | 47.5 |
| Double Glazing | 100.0% | 2,278 | 66 | **2,344** | 146 | $45.0 | $12,145 | 270 |
| External Shading | 31.7% | - | 9 | **9** | 3 | $0.7 | $463.6 | 694 |
| **Total (ex Double Glazing)** | | **30,203** | **5,610** | **35,813** | **3,434** | **$989** | **$15,274** | **15.4** |
| **Total (ex Drapes)** | | **30,273** | **5,621** | **35,894** | **3,441** | **$991** | **$25,383** | **25.6** |

Table 7. Relative impact of different draught sealing measures across all houses, reprinted from Sustainability Victoria (2016c).

| | | Air Leakage Reduction | | Cost | | |
|---|---|---|---|---|---|---|
| **Draught sealing measure** | **% of Houses Applied To** | **Total Reduction ($m^3$/hr)** | **% of Total Reduction** | **Total Cost ($)** | **% of Total Cost** | **$ per $m^3$/hr** |
| General caulking | 87.5% | 1,750 | 26.1% | $4,947 | 30.9% | $2.83 |
| Evaporative cooler outlets | 56.3% | 1,343 | 20.0% | $2,695 | 16.8% | $2.01 |
| Exhaust fans/vents | 87.5% | 1,040 | 15.5% | $1,742 | 10.9% | $1.67 |
| Seal external door | 68.8% | 800 | 11.9% | $1,891 | 11.8% | $2.36 |
| Seal wall vents | 62.5% | 447 | 6.7% | $815 | 5.1% | $1.82 |
| Caulking heating/cooling[16] | 50.0% | 275 | 4.1% | $731 | 4.6% | $2.66 |
| Combined[17] | 12.5% | 225 | 3.4% | $637 | 4.0% | $2.83 |
| Seal chimney | 18.8% | 206 | 3.1% | $241 | 1.5% | $1.17 |
| Seal larger gap or hole | 25.0% | 174 | 2.6% | $223 | 1.4% | $1.28 |
| Seal louver window | 6.3% | 120 | 1.8% | $66 | 0.4% | $0.55 |
| Seal downlights | 43.8% | 98 | 1.5% | $1,287 | 8.0% | $13.07 |
| Seal windows | 25.0% | 67 | 1.0% | $423 | 2.6% | $6.30 |
| Seal manhole cover | 12.5% | 52 | 0.8% | $67 | 0.4% | $1.31 |
| Tape leaking ductwork | 6.3% | 43 | 0.6% | $39 | 0.2% | $0.91 |
| Seal sliding door | 12.5% | 25 | 0.4% | $106 | 0.7% | $4.26 |
| Caulk ceiling rose | 6.3% | 25 | 0.4% | $69 | 0.4% | $2.80 |
| Seal plumbing penetrations | 6.3% | 23 | 0.3% | $42 | 0.3% | $1.81 |
| **Total** | | **6,713** | **100.0%** | **$16,021** | **100.0%** | **$2.39** |

Table 8. Average air leakage reduction per unit of draught sealing measure applied, reprinted from Sustainability Victoria (2016c)

| Draught sealing measure | Unit | Air leakage reduction per unit ($m^3$/hr) | Cost per unit ($) |
|---|---|---|---|
| Seal louver window | Per window | 120.2 | $66.0 |
| Tape leaking ductwork | Per duct system | 42.8 | $39.0 |
| Seal chimney | Per chimney | 41.1 | $48.2 |
| Seal external door | Per door | 38.1 | $90.1 |
| Exhaust fans/vents | Per fan/vent | 28.1 | $47.1 |
| Seal plumbing penetrations | Per instance | 23.4 | $42.4 |
| Evaporative cooler outlet | Per outlet | 22.4 | $44.9 |
| Seal larger gap or hole | Per instance | 21.7 | $27.9 |
| Caulk heating/cooling | Per instance | 18.3 | $48.7 |
| Seal manhole cover | Per cover | 17.2 | $22.4 |
| Caulk ceiling rose | Per rose | 12.3 | $34.4 |
| Seal sliding door | Per door | 8.3 | $35.3 |
| Seal wall vents | Per vent | 3.7 | $6.8 |
| Combined | Per measure implemented | 3.3 | $9.4 |
| Seal windows | Per window | 2.7 | $16.9 |
| Seal downlights | Per downlight | 1.3 | $16.7 |
| General caulking[21] | Per metre | 1.0 | $2.8 |