

H2: Opportunity Assessment

Enhancing home thermal efficiency

Final report



RACE for Homes

Research Theme H2: Enhancing home thermal efficiency

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Project team

RMIT University

- P. Rajagopalan
- R. Horne
- T. Moore
- M.M. Andamon
- N. Willand
- J. Woo
- T. Simko
- K. Natarajan-Rajeswari

Climate KIC Australia

- K. Reynolds-Fox
- K. Vines

CSIRO

- A. Wright
- D. Cheng
- M. Ambrose

Technical Advisor

- A. Pears

Project Partners



CLIMATE KIC
Australia



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The authors of this report would like to respectfully acknowledge the Traditional Owners of the ancestral lands throughout Australia and their connection to land, sea and community. We recognise their continuing connection to the land, waters and culture and pay our respects to them, their cultures and to their Elders past, present, and emerging.

What is RACE for 2030?

RACE for 2030 CRC is a 10-year cooperative research centre with AUD350 million of resources to fund research towards a reliable, affordable, and clean energy future. <https://www.racefor2030.com.au>

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Executive summary

The RACE for 2030 Cooperative Research Centre (RACE for 2030) commissioned this Opportunity Assessment on *Enhancing home thermal efficiency* (Research Theme H2), to identify priority research areas to accelerate the adoption of home thermal efficiency. It was conducted through a combination of desktop research (systematic review of Australian and international literature), consultations with key stakeholders and Industry Reference Groups (IRG), and modelling of various home thermal efficiency retrofit scenarios. This research assessed the technologies and policy instruments which improve energy efficiency and thermal performance of homes, with a focus on low-cost solutions for existing homes. Findings from discussions with the IRG were followed through detailed review of literature, industry practices and modelling multiple retrofit scenarios.

Why is thermal efficiency important and how can it be achieved?

The energy used in residential buildings is responsible for a significant proportion of carbon emissions in Australia. In particular, heating and cooling accounts for a major portion of residential building energy consumption, and thus emissions. However, due to the relatively hidden nature of energy performance, it is found to be of a lower order concern for homeowners and buyers among many other factors such as cost, design, location, and convenience. Given the nature of climate change and the associated risk of more frequent extreme weather events, the need to increase the thermal efficiency of homes is becoming more important. Improving thermal efficiency has been proposed by researchers and policymakers around the world to reduce carbon emissions from the housing sector.

The former Council of Australian Governments (COAG) Energy Council report, *Trajectory for Low Energy Buildings* (2018), set goals for joint action by all levels of government to address multiple market failures that result in sub-optimal buildings from environmental and economic standpoints. The report presents a suite of initiatives for improving energy efficiency of existing buildings in Australia, some of which fall within the scope of this report.

In general, methods of achieving the appropriate thermal performance of a building can be categorised as:

- Passive, resulting from the design and construction of the building and local environment.
- Occupant-managed, where an occupant must actively manage aspects of the building such as opening windows, and shading;
- Reliant on infrastructure such as space conditioning equipment, district/shared systems for heating and cooling, and energy supply;
- Other factors such as policy and regulations, markets and financing, and skill capability.

The purpose of this Opportunity Assessment is to engage with industry stakeholders to examine and deliberate upon current issues and challenges related to home thermal efficiency improvements. This report presents the main findings and prioritises opportunities on improving home thermal performance. Twenty-two research opportunities revolving around eight research themes were identified, as illustrated in Figure 1. The eight research themes are: Technology and Envelope Performance; Assessment and Quality Assurance; Capacity Building and Delivery; Home Occupant Direct and Co-benefits; Home Occupant Engagement and Communication; Research, Development, and Innovation; Policy, Support, and Regulatory Framework; and Market, Funding (subsidies), and Financing.



Figure 1. Proposed research opportunities on home thermal performance

Research Priority Areas

To address the identified barriers examined through the assessment, key research topics were formulated. The research topics were further developed into specific research questions to clarify the perspectives of the project team and industry stakeholders on the critical and topical research to be conducted. The proposals were discussed, prioritised, and new research areas were welcomed. As recognised by the project team and IRG, many of the research hypotheses are interrelated (and so not mutually exclusive). This is also noted in the mapping of the opportunities and barriers, as these were found to address the same difficulties from multiple angles. The list of prioritised research areas is shown in Table 1. Specific Research questions for each research area are available in Section 9 of this report.

Table 1. Prioritised research areas on home thermal performance

<p>Building Fabric (Windows/glazing, air tightness, condensation, pre-cooling)</p> <p>Evaluation of new methods of retrofitting existing glazing (RQ5) Quantification/inclusion of air tightness in NatHERS (RQ6) Assessment of air tightness and condensation during construction and renovation (RQ7)</p>	High
<p>Existing Home Thermal Performance Assessment</p> <p>Tool selection for cost-efficient home retrofit strategies (RQ2) ‘One-stop shop’ for home retrofit program (RQ3)</p>	High
<p>Home Retrofits and Decarbonisation</p> <p>Support Australia’s decarbonisation target through home retrofit (RQ21) Identify the role of home thermal performance in the transition to electrification (RQ22)</p>	High
<p>Benefits Of Improved Thermal Performance</p> <p>Assessment of non-financial and co-benefits from improved home thermal performance (RQ1)</p>	High
<p>Skills and Trades Development</p> <p>Investigation of building specifications, practices, and workmanship for managing air tightness and condensation (RQ17) Mapping existing education, training, and continuing professional development (CPD) courses for home thermal performance (RQ18) Formulation of a framework to guide development of courses for home thermal performance (RQ19)</p>	Med
<p>Ventilation Strategies and Air Quality</p> <p>Baseline of ventilation and IAQ in Australian housing (RQ14) Optimisation of ventilation and energy consumption (RQ15) Use of heat recovery ventilation systems in Australian housing (RQ16)</p>	Med
<p>Thermal Comfort (vulnerable groups, extreme climate events)</p> <p>Examination of common heat management strategies during extreme hot days (RQ9) Thermal comfort and health under extreme weather conditions (RQ10) Risk assessment for extreme weather conditions (RQ10, RQ11) Examination of heat management for vulnerable groups (RQ10, RQ11) Evaluation of the ‘refuge rooms’ concept for extreme events (R12) Examination of the ASHRAE adaptive thermal comfort model in Australian homes across different climate zones (RQ13)</p>	Med
<p>Uptake of Incentives / Grants and Financing Options</p> <p>Public benefit campaigns for home retrofit incentives/grants (RQ20)</p>	Low
<p>Policy Evaluation - Impact of Energy Efficiency Disclosure</p> <p>Examination of lessons learned from the ACT energy efficiency disclosure requirement (RQ4)</p>	Low
<p>NatHERS Tool Update</p> <p>Promotion/inclusion of new design, technologies, and materials in NatHERS and/or alternative assessment tools (RQ8)</p>	Low

Scenario Modelling

For scenario modelling, a database of existing dwellings with Nationwide House Energy Rating Scheme (NatHERS) Star ratings, or a pseudo-old building stock covering all the states and territories, was developed based on 208,204 recent real dwelling designs submitted for NatHERS Star rating during year 2021. These sample dwellings represent around 90 per cent of the total 229,142 dwellings approved for construction during the same period in Australia. These dwellings were simulated without envelope insulation to represent pre-

1990s buildings. Energy efficiency and overheating risks for different building improvements were investigated under the current climate and projected future 2030 and 2050 climates. Three levels of building improvements were investigated in this study: rehabilitation, refurbishment, and major renovations.

Results show that overheating occurs in all improvement categories for both houses and apartments, and across each state and territory, under both future climate years modelled. In the current climate, the Northern Territory has the highest percentage of the Class 1¹ base designs experiencing overheating, at almost 100 per cent; Tasmania has the lowest (9.4%), with Queensland around 60 per cent. For most other states the percentage of Class 1 base designs experiencing overheating is close to 90 per cent. Class 2² base designs perform slightly better, but close to 100 per cent of dwellings Northern Territory, South Australia, and Western Australia are predicted to overheat.

Based on the calculated heating and cooling energy costs, the energy cost savings for different building improvement strategies were also estimated. Assuming improvements to 5 per cent of the entire building stock as Business-as-Usual Scenario, energy cost savings are estimated to be around AUD185 million, AUD207 million, and AUD439 million per year for rehabilitation, refurbishment, and major renovation, respectively in comparison with the base case (without any improvement). The CO₂ emission reductions are estimated to be 1.57 Mt, 1.76 Mt, and 3.6 Mt CO₂ per year, respectively. For an Accelerated Scenario (considering improvement 40 per cent of the entire stock), the total energy cost savings are estimated to be around AUD1.48 billion, AUD1.66 billion, and AUD3.51 billion, and the CO₂ emission reductions are estimated to be 12.58 Mt, 14.09Mt and 28.78 Mt CO₂ for rehabilitation, refurbishment, and major renovation respectively. While the difference between rehabilitation and refurbishment is relatively small at 12%, there is massive, 137% cost saving and emission reduction when comparing rehabilitation with major renovation.

Research Priorities

The research priorities identified through an extensive survey of literature and industry collaboration outlines eight main themes incorporating 22 research questions. Table 2 highlights a series of milestones to achieve by 2030 across three timeframes: short-term (1-3 years), medium-term (5years), and long-term (8-10 years). Each milestone is linked to the research questions and emerged after a detailed analysis of research priorities, industry development opportunities, and associated barriers.

¹ Class 1 - Class 1 buildings are houses. Typically, they are standalone single dwellings of a domestic or residential nature. These buildings can also be horizontally attached to other Class 1 buildings. When attached they are commonly referred to as duplexes, terrace houses, row houses, and town houses.

² Class 2 - Class 2 buildings are apartment buildings. They are typically multiunit residential buildings where people live above and below each other. The NCC describes the space considered as an apartment as a sole-occupancy unit (SOU).

Table 2. Research priorities for home thermal performance

RESEARCH THEMES	MILESTONES		
	2025	2028	2030
Technology and envelope performance	<ul style="list-style-type: none"> • Baseline of ventilation and IAQ in Australian housing (RQ14) • Use of heat recovery ventilation systems in Australian housing (RQ16) • Examination of vapour management (RQ7) 	<ul style="list-style-type: none"> • Optimisation of ventilation and energy consumption (RQ15) 	
Assessment and quality assurance	<ul style="list-style-type: none"> • Identification of reliable assessment tools for home thermal performance (RQ2) • Assessment of air tightness and condensation during construction and renovation (RQ7) 	<ul style="list-style-type: none"> • Tool selection for cost-efficient home retrofit strategies (R2) 	<ul style="list-style-type: none"> • Widespread adoption of home retrofit Tools (R2)
Capacity building and delivery	<ul style="list-style-type: none"> • Investigation of building specifications, practices, and workmanship for managing air tightness and condensation (RQ17) 	<ul style="list-style-type: none"> • Mapping existing education, training, and continuing professional development (CPD) courses for home thermal performance (RQ18) 	<ul style="list-style-type: none"> • Formulation of a framework to guide development of courses for home thermal performance (RQ19)
Home occupant direct- and co-benefits	<ul style="list-style-type: none"> • Risk assessment for extreme weather conditions (RQ10, RQ11) • Assessment of non-financial and co-benefits from improved home thermal performance (RQ1) 	<ul style="list-style-type: none"> • Examination of heat management for vulnerable groups (RQ10, RQ11) 	<ul style="list-style-type: none"> • Development of guidelines for heat management of vulnerable groups (RQ9)
Home occupant engagement and communication	<ul style="list-style-type: none"> • Public awareness of adopting advanced high-performance window systems (RQ5) • ‘One-stop shop’ for home retrofit program (RQ3) 		<ul style="list-style-type: none"> • Public benefit campaigns for home retrofit incentives/grants (RQ20)
Research, development, and innovation	<ul style="list-style-type: none"> • Examination of the ASHRAE adaptive thermal comfort model in Australian homes across different climate zones (RQ13) • Examination of common heat management strategies during extreme hot days (RQ9) • Thermal comfort under extreme weather conditions (RQ10) 	<ul style="list-style-type: none"> • Evaluation of the ‘refuge rooms’ concept for extreme events (R12) • Evaluation of new methods of retrofitting existing glazing (RQ5) 	<ul style="list-style-type: none"> • Quantification/inclusion of air tightness in NatHERS (RQ6)
Policy support and regulatory framework	<ul style="list-style-type: none"> • Examination of lessons learned from the ACT energy efficiency disclosure requirements (as being discussed in the Residential Energy Efficiency Disclosure Initiative government forum) (RQ4) 	<ul style="list-style-type: none"> • Promotion/inclusion of new design, technologies, and materials in NatHERS and/or alternative assessment tools (RQ8) 	<ul style="list-style-type: none"> • Support Australia’s decarbonisation target through home retrofit (RQ21)

	<ul style="list-style-type: none"> • Identify the role of home thermal performance in the transition to electrification (RQ22) • Review of mandatory energy efficiency schemes and gap analysis for maximum impact for households (RQ4) 	<ul style="list-style-type: none"> • MEPS for homes at point of sale & rental (RQ4) 	
Market, funding (subsidies) and financing	<ul style="list-style-type: none"> • Impact assessment of rolling out mandatory residential energy efficiency disclosure in other states (RQ4) 	<ul style="list-style-type: none"> • Encourage the industry to supply more affordable products. Explore sources of funding – existing and new (e.g., EUAs in Vic for homes) (RQ20) 	<ul style="list-style-type: none"> • Suitable financing options and incentives available for each type of household and ownership models (private & public renters; landlords; owner-occupiers; those experiencing financial hardship; indigenous housing) (RQ20)

Glossary

ABCB	Australian Building Codes Board
ABS	Australian Bureau of Statistics
ACEEE	American Council for an Energy-Efficient Economy
ACH	Air changes per hour
ACOSS	Australian Council of Social Service
ACT	Australian Capital Territory
ACTHERS	Australian Capital Territory House Energy Rating Scheme
AEER	Australian Energy Employment Report
AER	Australian Energy Regulator
AGWA	Australian Glass & Window Association
ARHCD	Australian Rental Housing Conditions Dataset
ASHP	Air Source Heat Pump
AUD	Australian Dollar
BASIX	Building Sustainability Index
BCA	Building Code of Australia
BERS Pro	Building Energy Rating Scheme computer program
BoM	Bureau of Meteorology
BSRIA	Building Services Research and Information Association
CBA	Cost Benefit Analysis
CEC	California Energy Commission
CHBA	Canadian Home Builders' Association
CIBSE	Chartered Institution of Building Services Engineers
CO ₂	Carbon dioxide
CO ₂ e	Carbon dioxide equivalent
COAG	Council of Australian Governments (Now Energy and Climate Change Ministerial Council)
CPD	Continuing Professional Development
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSOG	Concrete Slab on Ground
CZ	Climate Zone
DCCEEW	Australian Government Department of Climate Change, Energy, the Environment and Water
DELWP	Victoria Department of Environment, Land, Water and Planning (recently changed to Department for Energy Efficiency and Climate Action (DEECA))
DEWHA	Department of the Environment Water Heritage and the Arts,
DI	Discomfort Index
DISER	Department of Industry, Science, Energy and Resources,
DMN	Design Matters National
DoEE	Australian Government Department of the Environment and Energy
DPIE	New South Wales Department of Planning and Environment (now OECC - Office of Energy and Climate Change, within Dept of Treasury)
EC	Electrochromic
ECA	Energy Consumers Australia
EEC	Energy Efficiency Council

EED	Energy Efficiency Directive
EEIS	Energy Efficiency Improvement Scheme
EER	Energy Efficiency Rating
EPA	Environmental Protection Agency
EPBD	European Energy Performance of Buildings Directive
EPCs	Energy Performance Certificates
ERV	Energy Recovery Ventilation
ESS	Energy Savings Scheme
EU	European Union
EUAs	Environmental Upgrade Agreements
FY	Financial Year
GSHP	Ground Source Heat Pump
HEMS	Home Energy Management System
HERO	Home Energy Rating & Optimisation
HIA	Housing Industry Association
HRV	Heat Recovery Ventilation
IAQ	Indoor Air Quality
IEA	International Energy Agency
IPECC	International Partnership for Energy Efficiency Cooperation
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
LIEEP	Low Income Energy Efficiency Program
MEPS	Minimum Energy Performance Standards
MHCLG	Ministry of Housing Communities and Local Government
MJ	Mega Joules
NAAs	Non-Accredited Energy Efficiency Assessors
NABERS	National Australian Built Environment Rating System
NatHERS	Nationwide House Energy Rating Scheme
NCC	National Construction Code
NSW	New South Wales
NT	Northern Territory
NZ	New Zealand
NZD	New Zealand Dollar
NZE	Net Zero Energy
OA	Opportunity Assessment
PCM	Phase Change Material
PDLC	Polymer dispersed liquid crystal
PDRS	Peak Demand Reduction Scheme
PM	Particulate Matter
PV	Photovoltaic
QLD	Queensland
REPS	South Australian government's Retailer Energy Productivity Scheme
RESNET	Residential Energy Services Network
RMI	Rocky Mountain Institute

SHGC	Solar Heat Gain Coefficient
SHW	Solar Hot Water
SPC/H	Solar Pre-Cooling and Pre-Heating
SPD	Suspended Particle Device
SV	Sustainability Victoria
TAS	Tasmania
UK	United Kingdom
uPVC	Unplasticized Polyvinyl Chloride
US DOE	United States Department of Energy
USA	United States of America
USD	United States Dollar
VEU	Victorian Energy Upgrades program
VIC	Victoria
VOC	Volatile Organic Compound
WA	Western Australia
WHO	World Health Organisation

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1 Introduction

The majority of Australia's existing housing stock and some new residential construction lack optimal thermal and energy performance necessary to transition to a low energy and net zero carbon future. An oversight of building fabric construction is particularly an issue with older housing stock, with minimum insulation requirements only introduced in some jurisdictions in the 1990s, and nationally since 2003. Even homes constructed since the introduction of national energy performance standards are likely to be sub-optimal from an energy economics perspective (Moore, 2012; Berry & Davidson, 2015). Furthermore, older housing stock is diverse and there is no central database that accurately records conditions relative to energy efficiency, quality, or opportunities for improvement. Improving dwelling thermal efficiency in both existing and new housing is a critical opportunity area for low energy and net zero carbon transition. There is considerable research presented about the potential to radically reduce heating and cooling energy – the single largest source of energy demand in housing, through proven, cost-effective design improvements and use of materials and technologies (ACIL Allen, 2021; Sustainability Victoria, 2020; Tony Isaacs Consulting, 2021). Despite this evidence, there has been limited uptake of energy retrofits and lack of progress towards wider adoption, indicating a pressing need to overcome significant barriers (Ambrose & Syme, 2015; BSL, 2020). Home energy performance is frequently a lower order concern in real estate transactions due to the intangible and uncertain nature of energy (Aune, 2012), or the relative importance of other considerations such as outward design, location, convenience, and cost (Edwards & Pocock, 2011). Oftentimes, housing is delivered with fewer private and public advantages because of market failures, such as split incentives, information asymmetry, lack of public goods, and unforeseen externalities (Gerarden et al., 2017; Horne, 2018; Hurlimann et al., 2018; Martek et al., 2019; Moore et al., 2019).

The objective of cooperative action by all levels of government to address various market failures leading to buildings that are suboptimal from environmental and economic standpoints was reinforced by the former COAG Energy Council (now Energy and Climate Change Ministerial Council) in the report *Trajectory for Low Energy Buildings* (COAG Energy Council, 2018b). The *Trajectory* report offers recommendations for changes to the National Construction Code (NCC) for brand new buildings for 2022 (increased stringency for thermal comfort) and 2025 (technology improvements for lighting, space conditioning, and renewable energy), followed by triennial cost-effective revisions to the NCC in accordance with the goal of zero energy buildings. The *Trajectory* report reaffirms prior agreement for a nationwide collaborative approach to residential building ratings and disclosure about existing buildings. The National Energy Performance Strategy announced by the Albanese government in October 2022 (consultation open till 3 February 2023) focused on easing pressure on energy bills, improving energy reliability, and reducing emissions.

Improved thermal efficiency of homes can reduce energy bills, increase property value, enhance health and well-being of occupants, and reduce greenhouse gas emissions and energy infrastructure costs (DCCEEW, 2022c). Options for improving thermal efficiency can range from simple techniques such as installing door seals to automated smart home control technologies. In improving thermal efficiency in Australian homes, it is important to consider the large range of housing stock across Australia's diverse climate zones, markets (for example, owner occupied, rental), and building types (for example, detached homes, apartments). Policy instruments, standards, and the socioeconomic landscape within regulatory boundaries play a major role in enhancing thermal efficiency of homes with the support of available home improvement technologies. The impact of occupants' behaviour in buildings must also be investigated given the need to address climate

change challenges. The main challenge is the complexity and dynamic nature of occupant energy behaviour, which is influenced by various internal and external, individual and contextual factors (Delzendeh et al., 2017).

This Opportunity Assessment is a scoping study to investigate technologies and policy instruments to improve the thermal efficiency of homes in Australia – both existing housing stock and new dwellings. Cognisant that no single, one-size-fits-all approach will address energy efficiency and thermal requirements of Australia’s existing housing, this report explores potential opportunities for enhancing home thermal efficiency through a systematic and in-depth survey of the literature. It also addresses the imperative for compelling immediate action to identify technologies, regulatory policies, and other instruments to progress a home thermal energy efficiency agenda for Australia, which focuses on housing across the diverse climate zones, markets, and building typologies. Taking on the current national policy discourse on new housing performance requirements, this report centres on the task of retrofitting existing housing, although it references wider housing and construction industries where relevant – for example, where labour, skills, materials, and products might be needed across both new build and retrofit. This report also reviews the state of technology and the market for thermally efficient homes, with the aims of providing information, guidelines, and tools for homeowners and the building industry, and assisting policy makers to assess macrolevel impacts of deploying retrofitting at a large-scale.

2 Scope of study

2.1 Background

Buildings use an estimated 30 per cent of the energy consumed worldwide (UNEP 2020). Energy consumption in residential buildings is a major contributor to global anthropogenic carbon emissions (IPCC, 2014). In Australia, buildings account for around 19 per cent of the total energy use and 18% of direct carbon emissions (Commonwealth of Australia, 2023). Residential buildings account for approximately 8.4 per cent of total energy use (Commonwealth of Australia, 2022a), 24 per cent of overall electricity use and 12 per cent of total carbon emissions (DCCEEW, 2022c). Depending on the climate zone, heating and cooling can account for 20-50 per cent of energy used in residential buildings (DCCEEW, 2022b). Given the nature of climate change experienced and anticipated in Australia, energy used to maintain human thermal comfort in the existing housing stock is expected to increase unless there is significant and widespread retrofit action.

As early as 1990, the residential sector was highlighted as an integral part of the strategy to reduce greenhouse gas emissions, and a key feature in developing Australian climate change mitigation policy. Specific actions and approaches at state and federal levels have varied over time to include voluntary and mandatory approaches, awareness and disclosure programs, industry education and training programs, demonstration projects, providing financial incentives, and developing technical tools as outlined in the *Trajectory for Low Energy Buildings* (COAG Energy Council, 2018b). Governments have encouraged or required entities such as local councils and energy retailers to take action to deliver residential energy efficiency (COAG Energy Council, 2022).

In January 2003, the Australian Building Codes Board introduced into the Building Code of Australia (BCA) minimum energy performance requirements for houses. The BCA now forms part of the NCC and has been adopted by all Australian states and territories. New residential buildings in Australia must comply with the NCC's energy efficiency provisions prescribed in the building permit. The majority of new residential buildings demonstrate compliance using a Nationwide House Energy Rating Scheme (NatHERS) accredited software tool (replaced with BASIX in NSW). NatHERS estimates the thermal performance of a building shell based on its structure, design, construction materials, and the climate where it is built (DoEE, 2019). The Star rating system provides estimates of a home's thermal performance – that is how much energy is required for heating and cooling. The higher the Star rating, the less energy is needed to heat and cool the home to keep it comfortable. A Star rating of 6 or above is required in most parts of Australia for detached dwellings, with some jurisdictions moving to 7 Stars under provisions of NCC 2022 for adoption from 1 May 2023 (ABCB, 2022a, 2022b). In addition to requirements for 7-Star ratings, changes in NCC include introducing an 'energy budget' for major appliance, equipment, and rooftop solar energy performance. Subsequent Building Code updates in 2025 and 2028 address the need for net zero carbon ready buildings by 2030, including consideration of embodied energy (COAG Energy Council, 2018b). However, embodied energy is not within this study's scope. The climate files in NatHERS-accredited software tools were updated in 2022 with more recent and more accurate weather data. New Star bands have been included in NatHERS-accredited software tools (BERS Pro, HERO, FirstRate5) to minimise potential impacts of climate change on energy Star ratings. To comply with NCC 2022 standards, NatHERS software has been updated to include a thermal bridging capability, and the revisions require that steel-framed construction energy rating calculations match the thermal performance of timber-framed construction (NatHERS, 2022b).

Australian housing energy standards have improved at various points in time, but they still fall short of world’s best practice, both as a minimum performance target, and in what is required to transition to a more energy efficient and environmentally sustainable built environment (ACIL Allen, 2021). Residential buildings in Australia are typically not built to provide a high quality of thermal comfort, and indoor winter temperatures of homes are often lower than in considerably colder countries that require higher minimum standards for insulation, weatherproofing, and energy efficient appliances. Poor thermal efficiency increases energy costs, escalates respiratory and cardiovascular ailments, and exacerbates some mental health conditions (Dignam & Barrett, 2022a, 2022b). Research has shown that Australian homes are generally significantly less energy-efficient than homes in the USA, Canada, and the UK (Horne & Hayles, 2008), and climate regions like Australia have increased mortality rates due to unnecessarily low indoor temperatures (Eurowinter Group, 1997). Renters are often significantly affected by poor housing conditions as owners are not motivated to address the situation, whereas in owner-occupied homes there is greater incentive and opportunity to make homes thermally comfortable (Liu et al., 2019; QCOSS, 2019).

The 2022 International Energy Efficiency Scorecard of the American Council for an Energy-Efficient Economy (ACEEE) ranks Australia 12th in building energy efficiency among the world’s 25 largest energy users. This is a fall from its 10th place in the 2018 rankings (Subramanian et al., 2022). Australia’s 2022 scores for buildings in various categories were lower than for 2018 for most of the categories, including residential building codes, appliances and equipment, building retrofit policies, and energy intensity in residential buildings (Table 3). Furthermore, current spending on research and development in energy efficiency is AUD0.94 per capita, whereas the highest score achieved is AUD6.76 per capita (for Canada) (ACEEE, 2022; Subramanian et al., 2022).

Table 3. Australia’s scores for residential building-related metrics according to the ACEEE International Energy Efficiency Scorecard (ACEEE, 2022)

Metric	Points in 2018	Points in 2022
Residential building codes	3 out of 3	2.5 out of 3
Appliances and equipment standards	2 out of 5	1.5 out of 5
Appliances and equipment labelling	1.5 out of 2	1.5 out of 2
Building retrofit policies	3 out of 4	2 out of 4
Building rating and disclosure	1 out of 2	1 out of 2
Energy intensity in residential building	1 out of 3	0.5 out of 3

2.2 Trajectory for Low Energy Buildings

This report also reviewed progress made against opportunities identified in the Energy and Climate Change Ministerial Council report *Trajectory for Low Energy Buildings* (COAG Energy Council, 2022). The report reinforces the goal of cooperative action by all levels of government to address multiple market failures that are delivering buildings that are sub-optimal from environmental and economic perspectives. The report, published by the former COAG Energy Council (COAG Energy Council, 2018b), provides direction and greater certainty for industry by setting out a trajectory towards ‘zero energy (and carbon) ready buildings’ (see Figure 2). For new buildings, the *Trajectory* provided guidance for changes to the NCC to be introduced in 2022. For existing buildings, the *Trajectory* reiterates the previous agreement for a national collaborative approach to

residential building ratings and disclosure and includes, on a voluntary basis a trial of the assessment tool of Victoria’s Residential Efficiency Scorecard. The *Trajectory* does not provide a timeline for mandating residential energy performance disclosure (COAG Energy Council, 2019b).

The *Trajectory* also supports information sharing between jurisdictions about various programs and policy initiatives, including those for low-income households, with the intent of informing future policy development. For appliances and equipment, the *Trajectory* notes the need to increase minimum energy performance standards for air-conditioners, domestic refrigerators and freezers, hot water systems, industrial products, lighting, non-domestic fans, refrigerated storage and display cabinets, swimming pool pumps, and televisions. A recommendation for further investment in the NatHERS is highlighted, given the need to update climate data files (to better reflect the current, and potentially future, climate) and expand accredited ‘whole-of-home’ tools to verify NCC requirements (COAG Energy Council, 2018a). By 2030, stronger energy efficiency requirements for a new building ‘envelope’ (including walls, roof, floors, and windows), and major energy-using equipment (including lights, hot water heaters and air-conditioners), could reduce average energy consumption by 19-25 per cent, even with conservative improvement in code for new residential buildings (ClimateWorks Australia, 2018b).

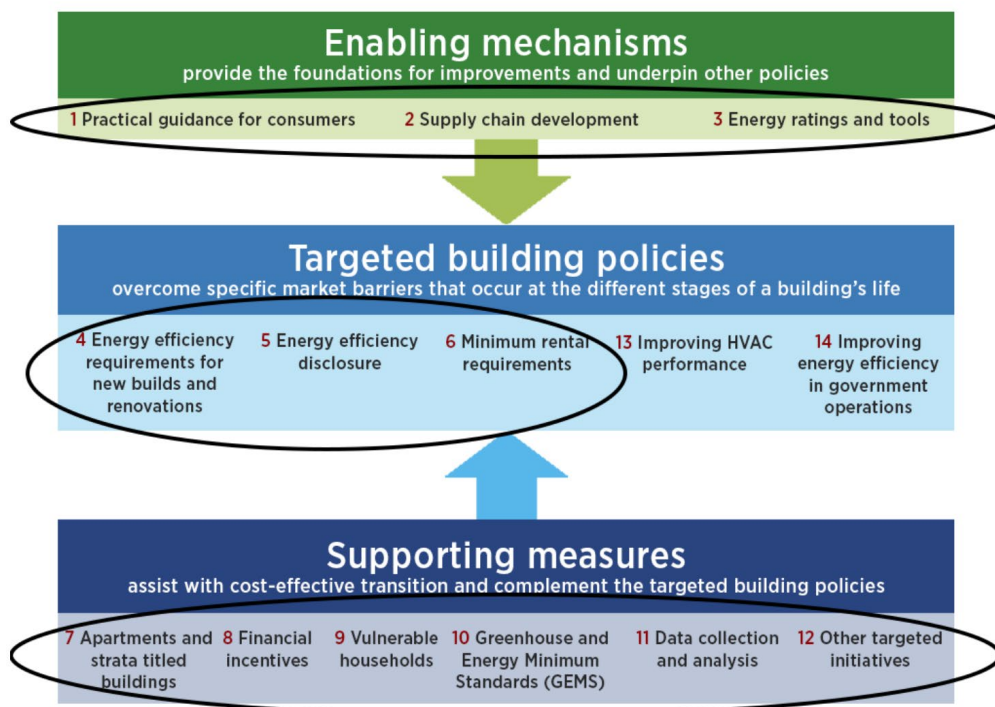


Figure 2. Trajectory for Low Energy Buildings – Suite of residential policies

3 Methodology

This Opportunity Assessment was conducted through a mix of desktop research (review of Australian and international literature), consultations with key stakeholders and an Industry Reference Group (IRG), as well as modelling various retrofit scenarios. Insights from consultations with the IRG fed into the in-depth literature review and scenario modelling. Figure 3 illustrates the various steps involved, including preliminary literature review, IRG workshops, scenario modelling, and detailed literature review.

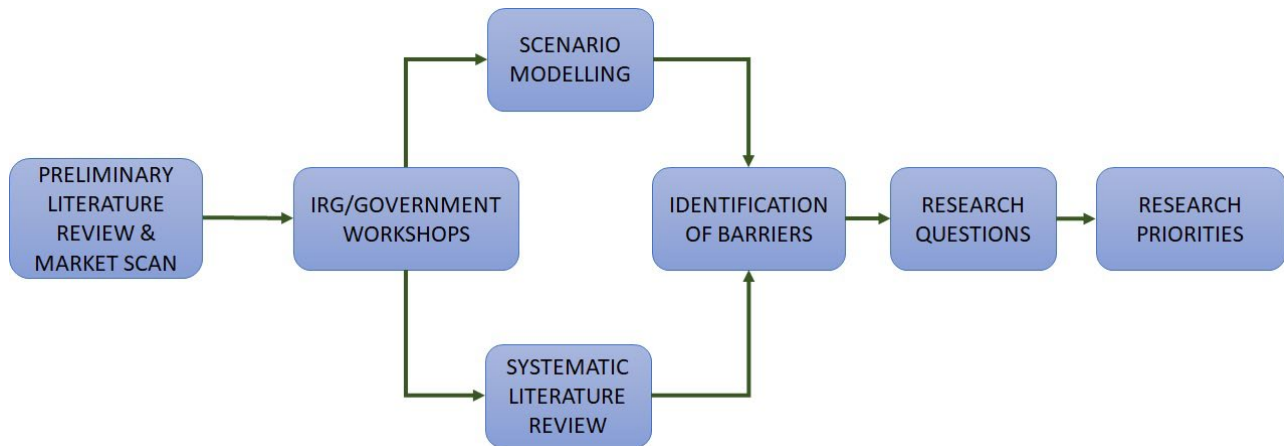


Figure 3. Methodology stages

3.1 Preliminary literature review and market scan

The initial orientation of the literature review was intended as a broad scan of the market to identify existing housing stock conditions and performance. This review was also aimed at understanding relevant policies on residential energy efficiency, current rates of construction and housing stock upgrade, as well as identifying Australian and international industry practices. Outcomes of work from the *Trajectory of Low Energy Buildings* (COAG Energy Council, 2022) were also reviewed to set the framework for this study. Available research, knowledge, and data were used to map current literature and identify data gaps. Key Australian and international resources were used, and existing technical know-how was leveraged (including emerging in-house data and expertise from several team members' research projects). Furthermore, resources and data were leveraged from energy efficiency programs of key industry partners (DELWP, CSIRO, DPIE, HIA)³.

3.2 Industry Reference Group (IRG) discussions

The IRG was made up of RACE partners, and representatives across the building and construction value chain. Members were chosen for their expertise and knowledge about the subject and included representatives from builders, builder associations, windows and weather resistant membrane manufacturers, glass and window associations, insulation industry associations, consumer associations, a professional body of building designers, and other peak organisations. Appendix 1 lists IRG members. A clear communication process was established, and expectations were clarified at the start of the project. IRG members were provided with relevant briefings,

³ Victoria Department of Environment, Land, Water and Planning (DELWP), Commonwealth Scientific and Industrial Research Organisation (CSIRO), New South Wales Department of Planning and Environment (DPIE), and Housing Industry Association (HIA).

including the proposed scope of the work and presentations on initial findings corresponding to various themes. Materials were circulated prior to each meeting to ensure a high level of engagement. Members were given the opportunity to provide feedback throughout various project stages. Specific comments provided by IRG members are shown in italics in following sections of this report.

IRG meetings were facilitated and chaired by Climate-KIC. Four workshops were held:

1. A kick-off workshop at project commencement which provided an understanding of the project and sought members' views on where the emphasis should be. Interviews were conducted with selected IRG members to gain insights about topics that needed in-depth investigation.
2. A government workshop to seek the views of various government and policy stakeholders.
3. A midway workshop to review progress to date and discuss details of assumptions and preliminary findings.
4. A final workshop towards project completion where a draft list of opportunities was shared and listed items ranked by priority.

3.3 Scenario modelling

The aim of the scenario modelling was to understand performance of existing housing stock, and to assess potential improvements in energy efficiency and overheating risks in current climate conditions, as well as in future projected climates. A database was developed of NatHERS Star rating files for existing dwellings, or a pseudo-old building stock, which covers all states and territories. The database included 208,204 recent dwelling designs submitted for NatHERS assessment during 2021. These sample dwellings represent around 90 per cent of the total 229,142 dwellings approved or built during 2021 in Australia. These dwellings were simulated without envelope insulation to represent pre-1990s buildings as thermal insulation as a contributor to energy efficient homes was introduced only after 1991. Building simulations were carried out for these dwellings to investigate energy efficiency and overheating risks with various potential building improvements under the current climate, and projected future 2030 and 2050 climates. Three levels of building improvements were investigated in this study, classified as 'rehabilitation,' 'refurbishment,' or 'major renovations.'

3.4 Systematic literature review

The systematic literature review involved in-depth investigation of each of the themes identified through the IRG workshops. An exhaustive list of barriers or challenges was developed through the detailed literature review. Stakeholders were interviewed for further clarification. To address the barriers, a list of research questions was developed, and this was summarised into eight themes. These research questions were presented to the IRG to better understand key industry priorities. The top ranked research priorities formed the essential framing elements of this Opportunity Assessment.

4 Technology and market status review

4.1 Existing building stock

The NatHERS scheme measures thermal comfort aspects of the NCC minimum energy performance requirement for residential building (ABCB, 2019d; DoEE, 2019). In 2020–21, around 90 per cent of building approvals used NatHERS for assessment (NatHERS, 2022a). Table 4 shows the housing condition data based on ‘as-design’ assessments. A majority of the assessments come from NatHERS and BASIX databases and were generated from submissions before a building is constructed. In NSW, there seems to be an increasing tendency to build units rather than detached dwellings, as shown in the BASIX database, with 56 per cent of new construction comprising apartments. In the NatHERS database, the average Star rating of new detached dwellings in Australia is 6.2 Stars, with ACT and Queensland having the highest ratings of 6.6 Stars. For apartments, the average rating is 6.6 Stars, with ACT apartments averaging 7.7 Stars. It should be noted that Queensland allows a credit of up to 1 additional Star for outdoor living facilities or use of photovoltaics.

Table 4. Existing housing condition datasets (‘as designed’) (CSIRO, 2022a; NSW Department of Planning, 2021a, 2021b)

Data type and assessment	Sample size and target group	Existing conditions																																	
Design data from BASIX (2018) – NSW; BASIX Single Dwelling Certificates 2011-2020	BASIX certificate data	<ul style="list-style-type: none"> • Apartments – 56 per cent of new dwellings • Average floor area – 106 m² in metropolitan NSW; 155 m² in regional areas • In 2017-18: <ul style="list-style-type: none"> – the number of units increased by over 300%, and detached dwellings decreased by 6%, compared to the previous year – low-rise apartment units (up to three storeys) decreased from 46% to 28% – 14% of certificates included a solar PV system, compared with 6% in 2016-17 – gas was the most common hot water system 																																	
Design data from CSIRO (2021) – all states; Australian Housing Data Portal (last 12 months)	Houses = 137,247, Apartment Units = 70,772; NatHERS data	<table border="1"> <thead> <tr> <th></th> <th colspan="2">Average Star ratings</th> </tr> <tr> <th></th> <th>Houses</th> <th>Apartments</th> </tr> </thead> <tbody> <tr> <td>ACT</td> <td>6.6</td> <td>7.7</td> </tr> <tr> <td>NSW</td> <td>6.0</td> <td>6.5</td> </tr> <tr> <td>NT</td> <td></td> <td>6.2 no data</td> </tr> <tr> <td>Queensland</td> <td>6.6</td> <td>6.6</td> </tr> <tr> <td>SA</td> <td>6.3</td> <td>6.9</td> </tr> <tr> <td>Tasmania</td> <td>6.5</td> <td>7.3</td> </tr> <tr> <td>Victoria</td> <td>6.2</td> <td>7.2</td> </tr> <tr> <td>WA</td> <td>6.2</td> <td>7.2</td> </tr> <tr> <td><i>Australia</i></td> <td>6.2</td> <td>6.6</td> </tr> </tbody> </table>		Average Star ratings			Houses	Apartments	ACT	6.6	7.7	NSW	6.0	6.5	NT		6.2 no data	Queensland	6.6	6.6	SA	6.3	6.9	Tasmania	6.5	7.3	Victoria	6.2	7.2	WA	6.2	7.2	<i>Australia</i>	6.2	6.6
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WA	6.2	7.2																																	
<i>Australia</i>	6.2	6.6																																	

NatHERS is now expanded to include 'Whole-of-Home' assessments to support the proposed NCC energy efficiency requirements for residential buildings (Department of the Environment and Energy, 2022). The Whole-of-Home energy assessment features energy performance of household appliances such as heating and cooling system, water heating, lighting, pool/spa, and on-site energy generation and storage.

Most Australian homes are only designed to the minimum energy efficiency requirements as required by the NCC, often missing cost-effective opportunities to reduce household energy bills. The decrease in prices of energy efficient technologies has been offset by increasing energy costs; hence consumers are failing to benefit (COAG Energy Council, 2022). There is no systematic process to make sure they are built as designed, and often houses not being built as expected is one of the barriers (Wang et al., 2020; Winter, 2016).

Owing to impacts of climate change, heating and cooling requirements are constantly changing across Australia. Increasing temperatures and frequency of heatwaves in Australia have become a public health concern (Duckett et al., 2020 ; Steffen et al., 2014; Zander et al., 2021).

In addition, urban areas are more vulnerable to such events because of heat island effects (Hooyberghs et al., 2017). For example, a 1.5°C rise in global temperature would impact the health of people in Melbourne by increasing hospitalisation from heat related illnesses. As high ambient temperatures cause buildings to retain heat, poorly designed homes become uninhabitable if there is a power outage during a heatwave. Heatwaves are occurring more frequently and with greater intensity due to climate change. The social impacts of building thermal performance during heatwaves and extreme weather need to be considered because some members of our community, particularly very young children, older people, and those with underlying health problems, are more at risk. Low-income households and renters have less ability to retrofit their homes to save energy and maintain thermal comfort. Many Australian cities are promoting strategies to address rising temperatures associated with the urban heat island effect: for example, the Urban Forest Strategy under Melbourne Climate Change Mitigation Strategy 2050.

As local climate in different locations varies, annual thermal energy modelled for 6-Star rating in different locations varies significantly. Seasonal (heating and cooling seasons) requirements were introduced in NCC 2019 to address the situation where, in some climate zones, design features could improve performance in one season but adversely affect it at other times of year, yet result in a reduced net annual energy use. For example, a dwelling with a black roof and no eaves in Melbourne (climate zone 6) would experience improved winter performance due to heat gain through the roof and unshaded walls. These features would adversely affect summer performance but could achieve a net improvement in annual energy consumption because winter energy use in this climate is far greater than during summer. The goal of the change to seasonal targets is to ensure all new homes are thermally comfortable in each season.

It is important to note that the Star rating scheme is not linear. This means an improvement from 1 to 2 Stars achieves a much larger energy saving than an improvement from 5 to 6 Stars, to some degree reflecting the relative cost in achieving that additional Star (Pears, 2022a). For example, for Melbourne, a shift from 1 to 2 Stars saves five times as much energy as a shift from 5 to 6 Stars: 175 MJ/m² compared with a shift from 5 to 6 Stars which saves 35 MJ/m². This means research studies using Star ratings as a metric for improvement potentially distort perceptions of energy outcomes. A one-Star improvement in existing 1-2 Star (low performance) homes is far more significant than upgrading the performance of a 5-Star dwelling.

NatHERS modelling includes many assumptions of human behaviour, and internal heat loads that impact the relative importance of particular design strategies and technologies. For example, thermostat settings at which

heating or cooling ‘switches on’ have a very significant impact on modelled energy use. Assumptions about the amount of heat released by cooking and other activities can also be significant in mild climate zones. As raised by IRG members, NatHERS requires regular updating to incorporate benefits of new technologies and improvements in knowledge of human behaviour, similar to other thermal energy performance modelling systems. Potential issues that require further research include considering thermal bridging (for example, heat flows from balconies via concrete slabs), a review of human behaviour during assumed sleeping periods, and incorporating impacts from mechanical energy recovery ventilation.

4.1.1 The net zero transition

Australia has set a target of achieving net zero emissions by 2050 for the whole economy. Residential buildings will need to play a part in achieving this goal. A Net Zero Energy (NZE) building, also known as a zero-energy building or zero-net energy building, is one in which the total amount of energy used on an annual basis is equal to the amount of renewable energy created onsite. This may involve some energy consumption in winter, offset by net exports of local electricity generation in summer. Australia lags behind other jurisdictions such as the UK and California in the implementation of NZE buildings. NZE buildings remain relatively uncommon in Australia owing to the concept’s obscurity to the general public (Wells et al., 2018). NZE buildings are becoming popular in other parts of the world as a means of reducing operational energy consumption and greenhouse gas emissions in the built environment.

The City of Melbourne’s Net Zero emissions strategy, introduced in 2014, sets goals focused on the operation of the Melbourne City Council, commercial buildings, residential, energy, transportation, and waste (Melbourne City Council, 2014). The goals set out in this strategy for residential buildings are less defined, with the strategy stating that long-term targets will be founded on a yet-to-be-developed baseline. Residential dwellings with energy efficient thermal shells and appliances, combined with renewable energy systems, have the potential to become zero energy homes (Dwyer, Pipkorn, et al., 2020). However, this is challenging for high-rise apartment buildings due to limited space for onsite renewable energy production, and complications arising from landlord-tenant and owners’ corporation issues. The report *Trajectory for Low Energy Buildings* released by the former COAG Energy Council (now Energy and Climate Change Ministerial Council) sets out a series of cost-effective revisions to the NCC with the goal of expanding the number of zero energy new buildings (COAG Energy Council, 2018b), although the pathway remains unclear for transitioning existing housing stock to zero energy performance.

4.1.2 Retrofitting opportunities

Residential structures in Australia account for 70 per cent of total building floor area (Gaterell & McEvoy, 2005). However, a major portion of residential stock is in poor condition and inefficient from a thermal performance perspective. Approximately two-thirds of extant structures are more than 30 years old, while approximately 40 per cent are more than 50 years old (Poel et al., 2007). Refurbishing and/or retrofitting existing residential buildings can be a valuable solution to enhancing the building sector’s environmental performance (Poel et al., 2007). Existing buildings outnumber new constructions, with new builds contributing to 1 per cent or less of the existing stock annually. With less than 2 per cent of Australia’s building stock replaced each year, there is a clear need to reduce carbon emissions in homes that have already been built and occupied (Whitehouse et al., 2019). More than 7 million Australia homes were built before energy efficiency standards were introduced into the NCC. Many of these homes are draughty and have insufficient insulation, especially in the walls (Murray-Leach, 2021). According to the data from CSIRO’s Australian housing data portal

the average existing house is rated 2.2 stars for energy efficiency (Cranney, 2022). The CRC for Low Carbon Living has published a Guide to Low Carbon Residential Buildings – Retrofit (Whitehouse et al., 2018) which provides a retrofit matrix for different climates and building types in Australia. Retrofitting older buildings offers significant potential for energy savings and other long-term social and economic advantages. An on-ground assessment study by Sustainability Victoria (2019a) identified significant energy saving and greenhouse gas abatement potential in Victoria’s existing housing stock from energy efficiency upgrades: average gas savings of 29,229 MJ per year (58 per cent of average household gas use), and average electricity savings of 5,563 MJ per year (33 per cent of average household mains electricity use). Section 4.2 discusses these studies in detail. Section 7 presents the improvements achieved from various levels of retrofitting (rehabilitation, refurbishment, and renovation) through scenario modelling. As discussed in Sections 4.2.4 and 4.3.4 respectively, there are unique challenges in retrofitting apartments and rented homes.

4.2 Studies on housing conditions and retrofits

For this report, databases were reviewed, including past studies analysing various housing stock upgrades and the benefits of uptake at affordable prices. The most notable outcomes are summarised below and analysed in detail in Appendix 6:

4.2.1 National studies

Housing conditions data

The Australian Housing Conditions Dataset (Baker et al., 2019) emphasises the need for reliable and up-to-date housing conditions data for different population groups and locations. For example, researchers and policy makers know very little about housing conditions, including their thermal efficiency, within Australia’s rental housing sector due to a lack of systematic, reliable data.

A survey was commissioned in collaboration with Australian universities to build this data infrastructure (Table 5). The self-reported data was extracted from phone interviews of a sample of 4,501 people from South Australia, NSW and Victoria (Baker et al., 2019). Eighty-four per cent of the houses were detached dwellings. Of the total sample, 90 per cent were owner occupied houses and 10 per cent renters. Only 12 per cent of the households reported to have major building problems, the majority of which were associated with cracks in walls. The information on building thermal efficiency was limited, involving a few questions about the main material used for the roof and external walls. Fifty-seven per cent of the households had gas as the main source of energy, and 94 per cent reported being able to keep their house sufficiently warm in winter and cool in summer. The most popular renovations were major kitchen and bathroom renovations. This was followed by installation of insulation and ceiling fans and outside awnings and shutters, as well as solar generation. Twenty-nine per cent replaced electric hot water with gas hot water, and only 6 per cent installed double-glazed windows (Baker et al., 2019; Baker et al., 2022).

Table 5. Existing housing condition datasets (Baker et al., 2019; Baker et al., 2022)

Data type and assessment	Sample size and target group	Existing conditions
Self-reported data (phone survey) (2018), all states; (Baker et al., 2019)	4501 households; random sampling includes rental	<ul style="list-style-type: none"> • Major building problems related with thermal efficiency: <ul style="list-style-type: none"> – mould: 1% – cracks in walls/floors: 6.1% – no major problems: 87.8% • Modifications made to the dwelling <ul style="list-style-type: none"> – replaced electric hot water system with gas hot water system: 24.6% – installed solar electricity: 24.2% – installed insulation: 30.1% – installed ceiling fans: 30.1% – installed outside awnings/shutters that improved energy efficiency: 25.2% • Comfort <ul style="list-style-type: none"> – comfortable during winter: 94.2% – comfortable during summer: 93.9% • Main sources of energy <ul style="list-style-type: none"> – electricity: 94.3% – mains gas: 56.4% – solar electricity or solar hot water: 16%
Self-reported data (phone survey) (2020), all states; (Baker et al., 2022)	15,004 rental households; random sampling	<ul style="list-style-type: none"> • Major building problems related to thermal efficiency <ul style="list-style-type: none"> – mould: 27% – cracks in walls/floors: 40% – walls, windows or floors not level: 20% – roof defect: 13% • Problems requiring urgent repair <ul style="list-style-type: none"> – dampness: 7.7% – mould: 10.9% – cracks in walls/floors: 7% – roof defect: 5.6% • Comfort <ul style="list-style-type: none"> – comfortable during winter: 76% – comfortable during summer: 71%

Data type and assessment	Sample size and target group	Existing conditions																																																																
Performance data (evidence based) (2022) (Dignam & Barrett, 2022a, 2022b)	75 rental households; specifically diverse sample of renters from all states	<p>Temperature and humidity tracking (quantitative data)</p> <ul style="list-style-type: none"> Proportion of recordings with the temperature below 18°C <table border="1"> <thead> <tr> <th>State / Territory</th> <th>Time below 18°C (%)</th> </tr> </thead> <tbody> <tr> <td>- Australia</td> <td>- 75.1%</td> </tr> <tr> <td>o NSW</td> <td>- 85.1%</td> </tr> <tr> <td>o VIC</td> <td>- 80.2%</td> </tr> <tr> <td>o SA</td> <td>- 79.2%</td> </tr> <tr> <td>o WA</td> <td>- 56.5%</td> </tr> <tr> <td>o TAS</td> <td>- 91.0%</td> </tr> <tr> <td>o QLD</td> <td>- 28.6%</td> </tr> <tr> <td>o ACT</td> <td>- 88.3%</td> </tr> <tr> <td>o NT (Darwin)</td> <td>- 0%</td> </tr> <tr> <td>o NT (0870)</td> <td>- 89.5%</td> </tr> </tbody> </table> Proportion of recordings with different RH ranges <table border="1"> <thead> <tr> <th>State / Territory</th> <th>Time above 60% RH (%)</th> <th>Time above 70% Relative Humidity (%)</th> </tr> </thead> <tbody> <tr> <td>- Australia</td> <td>- 69.3%</td> <td>- 38.2%</td> </tr> <tr> <td>o NSW</td> <td>- 82.8%</td> <td>- 53.4%</td> </tr> <tr> <td>o VIC</td> <td>- 65.4%</td> <td>- 35.2%</td> </tr> <tr> <td>o SA</td> <td>- 77.8%</td> <td>- 43.3%</td> </tr> <tr> <td>o WA</td> <td>- 78.0%</td> <td>- 38.6%</td> </tr> <tr> <td>o TAS</td> <td>- 78.2%</td> <td>- 43.0%</td> </tr> <tr> <td>o QLD</td> <td>- 59.2%</td> <td>- 33.3%</td> </tr> <tr> <td>o ACT</td> <td>- 42.0%</td> <td>- 16.1%</td> </tr> <tr> <td>o NT (Darwin)</td> <td>- 45.6%</td> <td>- 15.7%</td> </tr> <tr> <td>o NT (0870)</td> <td>- 0.1%</td> <td>- 0%</td> </tr> </tbody> </table> Owners and Renters comparison <table border="1"> <thead> <tr> <th>Group</th> <th>Time below 18°C (%)</th> <th>Average Relative Humidity (%)</th> </tr> </thead> <tbody> <tr> <td>Sydney renters (n=5)</td> <td>83.9%</td> <td>68.9%</td> </tr> <tr> <td>Sydney owners (n=3)</td> <td>2%</td> <td>47.2%</td> </tr> </tbody> </table> 	State / Territory	Time below 18°C (%)	- Australia	- 75.1%	o NSW	- 85.1%	o VIC	- 80.2%	o SA	- 79.2%	o WA	- 56.5%	o TAS	- 91.0%	o QLD	- 28.6%	o ACT	- 88.3%	o NT (Darwin)	- 0%	o NT (0870)	- 89.5%	State / Territory	Time above 60% RH (%)	Time above 70% Relative Humidity (%)	- Australia	- 69.3%	- 38.2%	o NSW	- 82.8%	- 53.4%	o VIC	- 65.4%	- 35.2%	o SA	- 77.8%	- 43.3%	o WA	- 78.0%	- 38.6%	o TAS	- 78.2%	- 43.0%	o QLD	- 59.2%	- 33.3%	o ACT	- 42.0%	- 16.1%	o NT (Darwin)	- 45.6%	- 15.7%	o NT (0870)	- 0.1%	- 0%	Group	Time below 18°C (%)	Average Relative Humidity (%)	Sydney renters (n=5)	83.9%	68.9%	Sydney owners (n=3)	2%	47.2%
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Rental properties

In Australia, rental homes account for 32 per cent of all homes (approximately 3 million homes) (Australian Bureau of Statistics, 2019). The Australian Rental Housing Conditions Dataset (ARHCD), with a sample size of 15,004, provides data for housing quality and conditions of rental houses across various demographics (Baker et al., 2022). Reported problems requiring urgent attention included mould and cracks in walls. Mould problems were reported by 25 per cent of participants. In contrast to the Australian Housing Condition

datasets, a majority of which included owner-occupied participants, in the rental housing dataset only 76 per cent of rental households were thermally comfortable during winter, and 71 per cent were comfortable during summer.

An evidence based quantitative and qualitative study (Dignam & Barrett, 2022a) was conducted with 75 specifically selected diverse sample of rental households on their experiences during winter relating to their housing conditions. Quantitative data of Temperature (°C)⁴ and Relative Humidity (RH%)⁵ was recorded using data loggers and it was coupled with qualitative data from participants drawn from surveys, phone interviews, and discussions. Qualitative data assisted in understanding consequences and impacts of the recorded temperature and humidity. Indoor temperatures were below the healthy temperature⁴ range 75 per cent of the time; 69 per cent of the time the RH% was more than 60 per cent, and 38 per cent of the time the RH% was more than 70 per cent. As a final input to understanding the difference between owner occupied homes and rental homes, 3 owner occupied homes in a similar climate were selected and compared with data from 5 rental households in the same area. The comparison indicated that the owners spent a negligible portion of their time in unhealthy ranges, whereas renters have unfavourable conditions more frequently.

Performance-based data

Appendix 6 presents the varied performance-based data collected using energy bills, on-ground assessment, and air infiltration testing. Further datasets were obtained by extrapolating ABS data. These datasets provide several opportunities to benchmark energy performance and retrofit potential, and to extract insights about them. The Australian Energy Regulator (AER) has available a large database of consumption data for 6,465 electricity and 3,148 gas consumers; it may also be possible for AER to use the database to compare the usage of these consumers with similar households within a geographic area (Frontier Economics Pty Ltd, 2020).

Air tightness

Another study was conducted by monitoring airtightness and insulation quality for a sample of three-year-old existing houses that are assumed to be NatHERS 6-Star rated (Ambrose & Syme, 2015, 2017). Findings of the study demonstrated that airtightness levels varied significantly, ranging from well-sealed homes to poor performing leaky homes (Ambrose, 2019). The insulation quality was average in 39 per cent of homes, and 10 per cent had poor levels of insulation, with prominent gaps around openings, pipes, and similar penetrations, or missing insulation in some places. The findings highlighted problems with build quality, lack of attention to detail during construction, and lack of suitable post-construction audit processes. Interestingly, for that sample, houses with uPVC window frames recorded much lower air change rates than most other houses.

4.2.2 Victorian studies

Victoria is ahead of other states in terms of on-ground home retrofit studies, including several studies conducted by Sustainability Victoria between 2011 and 2015. One of these studies focused on 60 existing Class 1 dwellings (i.e., houses) that were built prior to 2005, when the 5-Star rating requirement was introduced, and

⁴ Healthy Temperature - WHO recommends 18°C as the minimum healthy indoor temperature for countries with temperate or colder climates.

⁵ Healthy Relative Humidity - The healthiest RH range is 40-60%. RH above 70% encourages condensation, and thus dampness and mould.

these houses had an average of 1.8 Stars rating. Air leakage was one of the key reasons for the low level of energy performance of the houses. In addition to the poor performing building fabric, the houses had poor-performing appliances that were remarkably less efficient than average new appliances. The average House Energy Rating was 1.57 Stars for houses constructed prior to 1990, and 3.14 Stars for houses constructed between 1990 and 2005 when basic insulation regulations were in place (Sustainability Victoria, 2015). The same project also investigated energy efficiency upgrade potential of building shells in five main stages over a number of years. Though ceiling insulation measures had a large impact, they had a much lower-level applicability, as most of the houses already had a certain level of ceiling insulation. With application of building shell improvement, the ratings of houses constructed prior to 1990 increased by an average of 3.42 Stars, while ratings of houses constructed post-1990 increased by an average of 2.23 Stars. The draught sealing retrofit trials involving 16 houses (Sustainability Victoria, 2016b) showed that natural air leakage reduced from an average of 1.8 to 0.83 air changes per hour (ACH), with an average retrofit cost of AUD1,001. The average heating energy saving was 13.2 per cent. A cavity wall insulation retrofit trial involved 15 houses with cavity wall construction, where insulation was pumped into the wall cavities (Sustainability Victoria, 2016a). This retrofit trial resulted in a 15.5 per cent reduction in heating energy and improved the perceived occupant thermal comfort in winter. Window film secondary glazing retrofit trials (Sustainability Victoria, 2017) involved eight houses with large single-glazed windows and resulted in a 3-4 per cent reduction in heating energy, and a slight increase in thermal comfort. A subsequent study involving lighting and appliances upgrades showed that lighting and appliance upgrades are more cost-effective (cost AUD5,882 and AUD558 saving per year) than building shell upgrades (cost AUD9,392 and AUD430 saving per year), although they do not address the fundamental issue of thermal efficiency (Sustainability Victoria, 2015). A ductwork retrofit study involving eight houses with older gas ducted heating systems resulted in an average heating energy saving of 14.1 per cent (Sustainability Victoria, 2016c).

A separate retrofit trial consisting of 93 low-income households in Victoria (Sullivan et al., 2017) involved upgrading to more efficient hot water systems including heat pump, solar, instant gas, and gas storage. Appendix 6 shows the upgrade path, yielding significant energy savings. One of the more comprehensive sets of performance data collected so far is through the Victorian Energy Efficiency Scorecard. The scorecard is used to measure and improve the energy cost and comfort of homes (DELWP, 2019). The study showed that 75 per cent of houses assessed had a low building shell rating, mainly because of poor insulation and low air tightness.

The savings documented in the studies above were based only on the direct energy savings achieved from the upgrades. Costs associated with the greenhouse gas savings, or comfort or health improvements were not included as there was limited evidence base for incorporating these additional benefits. The recent Victorian Healthy Homes Program (Sustainability Victoria, 2022c) delivered thermal comfort and energy efficiency upgrades to 1000 homes of low-income Victorians with a health or social care need. It ran over three study years (2018, 2019, 2020) across western Melbourne and the Goulburn Valley. The purpose of the trial was to evaluate the difference between groups over winter on thermal comfort, energy use, healthcare utilisation, health, and quality of life (Campbell et al., 2022). The results showed that the average indoor temperature increased by 0.33°C, with increases particularly strong in the morning when temperatures are lowest. Exposure to cold temperatures (<18°C) was reduced by an average of 43 minutes per day. Thermal comfort and energy efficiency upgrades with an average cost of AUD2,809 provided various benefits like increase in indoor temperature during winters, householders reporting greater warmth, improved quality of life, reduction in condensation, reduction in gas usage and energy bills (AUD85 energy cost savings), and a major reduction in

greenhouse gas emissions. Healthcare data showed that people in upgraded homes used fewer services and spent less on healthcare with a 3-month saving of about AUD887. The payback for the upgrades was estimated to be within three years, even under the most conservative assumptions (Campbell et al., 2022; Sustainability Victoria, 2018, 2022b). Victorian studies provided sufficient evidence that by improving winter warmth with thermal fabric and energy efficiency upgrades, householders and the broader community can reap several significant benefits on home liveability and health impacts. Significant energy and health care savings were identified, with the average payback period being less than three years (Sustainability Victoria, 2022d)

4.2.3 Cost and benefits of retrofits

The modelling performed in the final report of the RACE *H2 Pathways to scale: Retrofitting One Million+ Homes* (Fox-Reynolds et al., 2021) demonstrated that retrofitting existing Australian homes across five years reduces average home energy use by up to 9,000 kWh per year, reduces average home emissions by up to 5.8 tonnes CO₂e per year, and could create up to AUD55 billion of private finance investment opportunity. It concluded that a customised home retrofit program through a whole-of-home assessment could address the identified needs and reduce an average home energy bill by up to AUD1,600 per year.

Table 6 summarises the cost-benefit normalised values for building shell, and heating and cooling appliance retrofit trials, undertaken by Sustainability Victoria in multiple stages over several years. The costs estimated include only the commercial costs and not any government incentives. The measure with lowest average cost was ceiling insulation (easy) with a payback period of 4.1 years. Draft sealing measures had a payback period of 6.6 years whereas difficult ceiling insulation had a payback period of 8.2 years. The savings and total cost of upgrades are all based on prices current during the time of the study. As electricity and gas prices have increased substantially since 2015, further research and analysis are required to match current prices and payback periods rates. Understanding the relative impacts of behaviour, systems performance, and building fabric is important in identifying cost-effective retrofit solutions. For example, during the retrofit or refurbishment stage, it is important for the assessor to look at home energy bills as well as the building and its energy systems to establish whether structural or behavioural reasons cause the issues encountered.

Health and well-being benefits of retrofitting outweigh the financial benefits. A thermally efficient home will moderate temperatures and keep more people safe at home during extreme events such as heatwaves. Furthermore, higher quality homes result in people taking fewer days off work and school due to illness, and reduce visits to doctors and hospitals (Tidemann, Hutlet, et al., 2022). As demonstrated by a retrofit trial in New Zealand as part of the Warm Up NZ: Heat Smart program, for every NZD1 spent insulating houses, there is a return to society of NZD3.88 (Grimes et al., 2012). The Victorian Health Home Program Sustainability Victoria (2022c) found that improving winter warmth through thermal shell and energy efficiency upgrades provided multiple important benefits, both for householders and the broader community. The health impacts are further discussed in Section 6.5.2.

Table 6. Cost-benefit analysis of on-ground assessment and retrofit trials (Sustainability Victoria, 2015)

Measures	Average	Average energy savings			Average	Energy rating
	cost	Gas	Elec	Total	payback	improvement
	(AUD)	(MJ/year)			(Years)	(Stars)
Ceiling insulation (easy)	673	8,210	277	8,487	4.1	0.84
Draught sealing	1,037	7,942	225	8,167	6.6	0.69
Ceiling insulation (difficult)	835	4,891	204	5,095	8.2	1.14
Reduce sub-floor ventilation	769	2,720	53	2,773	14.9	0.26
Seal wall cavity	541	1,806	48	1,854	15.3	0.16
Ceiling insulation top-up	774	1,970	50	2,020	20.3	0.39
Underfloor insulation	1,962	4,507	25	4,532	24.3	0.34
Wall insulation	4,167	5,561	136	5,697	39	1.02
Drapes & pelmets	2,036	2,209	54	2,263	47	0.58
Double glazing	12,145	2,278	66	2,344	270	0.63
External shading	1,464	–	27	27	694	0.01
Heating	1,110	6,239	215	6,454	8.8	–
Water heater – high efficiency gas	477	460	1,004	1,463	8.2	–

4.2.4 Performance of apartments

Apartments, including high-rise developments, comprise an increasing share of housing (Shoory, 2016). Rapid urbanisation and growing population are increasing demand for high-rise residential apartment buildings which are more energy intensive than low-rise residential dwellings. Moreover, reducing the emissions footprint of the high-rise-built form is challenging. Apartment buildings may have a single external façade, often with a large area of glazing. Orientation, inappropriate specification of window treatments (for example, dark coloured blinds), landlord attitudes, or Owners Corporation rules, may constrain the capacity of an occupant to manage solar gain. Effective ventilation of apartments can also be a challenge if cross-ventilation is not possible. Heat flows from adjacent apartments, or unconditioned areas at significantly different temperatures from adjacent areas, can impact thermal conditions.

According to Australian Bureau of Statistics (2016) census data, the proportion of high-rise housing complexes increased from 18 per cent of new dwellings in the 2006 census to 38 per cent in 2016. Melbourne, Sydney and Brisbane have accounted for more than 75 per cent of apartment developments constructed in Australia between 2011 and 2015 (Shoory, 2016). BASIX was first introduced in 2004, initially in Sydney, NSW, as a mandatory standard for new dwellings. It was extended to all NSW, and all forms of dwellings, including apartments. Of the residential developments certified in BASIX, 27.3 per cent were high-rise units, 19.5 per cent were mid-rise units, and 18.1 per cent were low-rise units; the remaining 35.1 per cent comprised detached or attached houses (NSW Department of Planning, 2011).

The latest forecasts by the Housing Industry Association (2022b) show that detached home building will remain at capacity until June 2023, with an increased volume of apartment commencements. Therefore, apartments will again make up a sizeable proportion of new homes (Figure 4). This highlights the importance of building energy efficiency policy for apartments, particularly when apartment retrofits pose more challenges in comparison to detached houses (COAG Energy Council, 2018a). Heffernan et al. (2015) note that legislation is the key driver for addressing energy efficiency of new-build apartment developments.

HIA Forecast - Australia

Source: HIA Economics

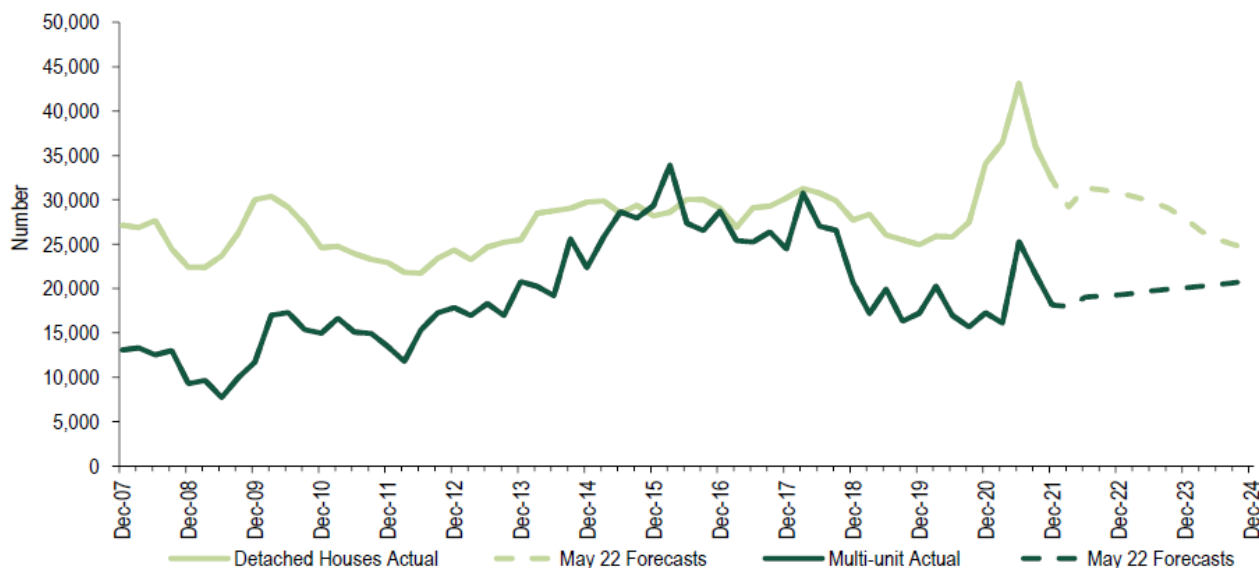


Figure 4. Forecast of detached houses and apartments in Australia to December 2024 (HIA, 2022b)

NABERS (2022) ratings for apartment buildings quantify the building’s energy and water performance with a Star rating from 1-6 Stars for shared services such as carparks, lobbies, gyms, pools, and water features. The rating of individual buildings for NABERS Energy is relatively low but has increased consistently every year from 100 in 2019 to 181 in 2021. The average Star rating of all apartments certified in the states of NSW, Victoria, and Western Australia increased from 2.9 Stars in financial year 2019-20 (FY20) to 3.1 Stars in FY21. The number of buildings that achieved more than a 5-Star rating increased from two buildings in FY20 to nine buildings in FY21. The average Star rating of apartment buildings in FY21 was 3.6 Stars in NSW and 0.5 Stars in Victoria. The number of NABERS Energy certified apartment buildings in NSW is 49, with more than 50 per cent of buildings having a Star rating greater than 3.5 Stars, whereas in Victoria only two buildings were rated in FY21 – one building did not receive a Star and one building received 1 Star. There were no NABERS Energy and Water for Apartment buildings ratings undertaken in ACT, Queensland, NT, South Australia, Tasmania or Western Australia (NABERS, 2022). However, as NABERS only certified the common areas of apartment buildings, rather than individual apartments, it is not possible at present to get a home energy efficiency Star rating under that scheme.

A report by Pitt & Sherry (2016) found that net zero apartment buildings are technically feasible and highly cost-effective from a societal perspective. However, significant gaps and weaknesses in our energy efficiency and climate policy frameworks will slow down commercial uptake, while a collaborative and strategic approach by industry and government could rapidly transform Australia’s market. It was found that energy efficiency

measures are extremely effective, and modelling shows that average Star ratings in Sydney could jump from 4.4 to 9.2, and in Melbourne from 6.5 to 9.3. Figure 5 and Figure 6 show the Base Case's elemental energy contribution to high-rise buildings, and the reductions designed for the Sydney and Melbourne areas, using examples from buildings in the Australian Excellence and Global Excellence cases. Recommendations for future work which arise from the research were to investigate the associated incremental costs, establish a cost-optimised pathway, and quantify societal willingness to spend for net zero performance. In assessing the feasibility of net zero high-rise residential buildings in all Australian climates, Alawode and Rajagopalan (2022) found that existing building technologies, in combination with passive design strategies, can meet the requirements necessary to achieve net zero energy performance, though climate zone 1 (hot humid summer and warm winter; for example, Darwin) and climate zone 7 (cool temperate climate; for example, Canberra) were found to be more challenging. However, a rating tool, such as NatHERS, needs to be developed to accurately assess individual apartments in a complex, as opposed to NABERS which just assesses the common areas.

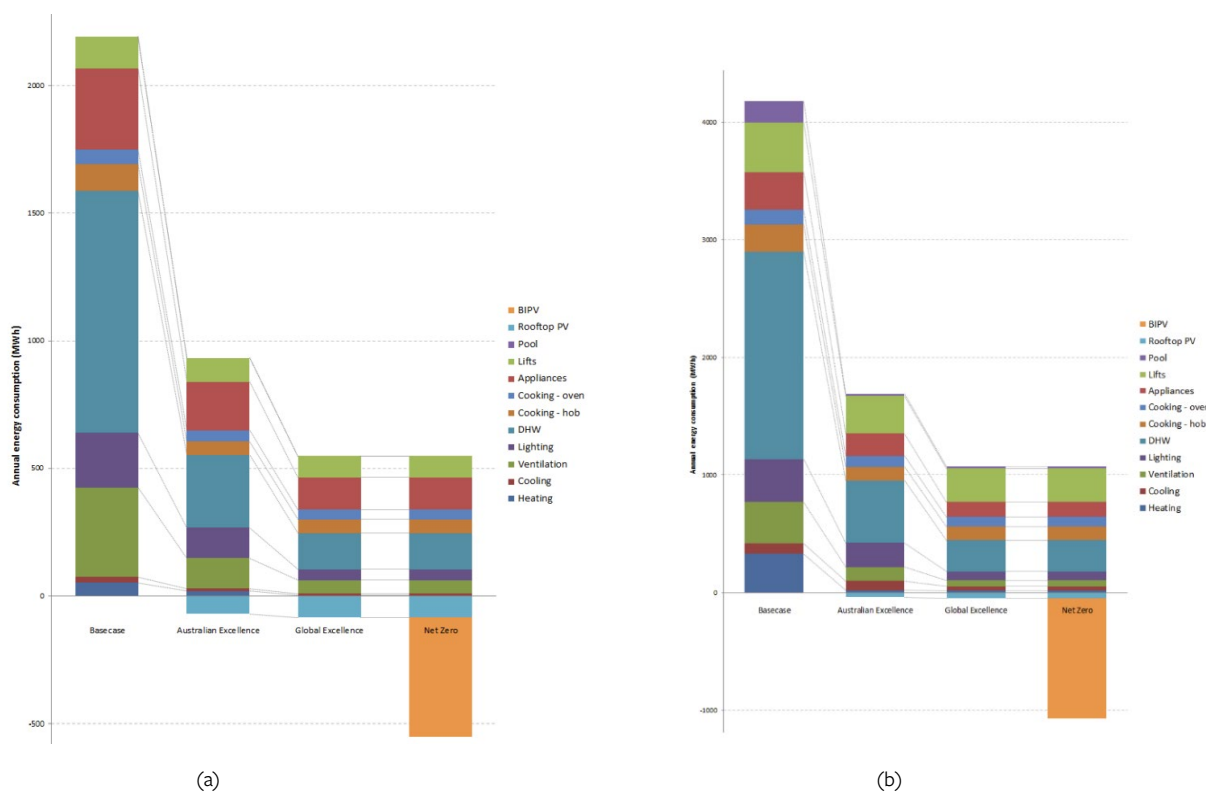


Figure 5. Shares of energy use and savings by performance scenario (a) SYDNEY (b) MELBOURNE (Pitt & Sherry, 2016)

Existing apartment buildings pose many challenges for retrofitting, including the need to work with strata committees and strata management companies, where owners typically require 75 per cent consensus to undertake significant upgrade works. There may be owners who either do not wish to take part or do not understand the benefits of upgrade proposals (Leshinsky & Rex, 2012). Educating strata communities about the benefits and possibilities of environmental upgrades is challenging.

There have been a few attempts to improve the performance of apartment buildings. The City of Sydney's Smart Green Apartments program (City of Sydney, 2022) provides financial assistance to owner corporations aiming to improve the environmental efficiency and cost-efficiency of apartment buildings across the local government area. The NABERS rating tool is used in this context to measure the performance of common areas. Participating building owners and managers receive a free water and energy audit and action plan, with

retrofitting recommendations. The participants can also get information on capital cost and projected savings, in addition to knowledge and capacity building. North Sydney Council's Futureproofing Apartments program (Wattblock, 2019) targets small to medium-sized strata properties. Waverly Council's Building Futures program (Waverly Council, 2019) aims to reduce shared energy use in community apartments. Very little work has been done in other states on energy benchmarking and retrofitting of apartments.

Environmental Upgrade Agreements (EUAs) are another way apartment owners could access capital in the future to make energy efficiency upgrades to apartment buildings. Currently only available to commercial building owners, EUAs are simple loans repaid to the local council over an agreed period of up to 20 years, utilising savings from the upgrade. More research is required to see how EUAs can be leveraged for apartment buildings and strata units (Sustainable Australia Fund, 2022).

4.3 National plans and policies

Revisions to NCC energy efficiency requirements in 2022 include a more holistic approach to residential energy efficiency standards by increasing the thermal performance requirement to 7 Stars (ACIL Allen, 2021) and combining this with rating of appliances for a whole-of-home assessment. Each State and Territory jurisdiction is responsible for timely adoption of NCC 2022 changes which come into effect on 1 May 2023. The cost-benefit analysis of increasing building fabric rating levels from 6 to 7 Stars demonstrates that benefits or positive impacts outweigh costs required for the improvements for most households (Tony Isaacs Consulting, 2021). Another study by ClimateWorks Australia (2018a) calculated that the delay in increasing residential energy efficiency requirements from 2019 to 2022 has cost AUD1.1 billion (to 2050) in household energy bills, which could have been avoided, along with emission of an additional 3 million tonnes of greenhouse gases.

4.3.1 Skills development

As awareness of the need to address energy efficiency and climate change has increased, government and industry have responded through developing technical guide materials and associated training courses. For example, the HIA Greensmart initiative and the Your Home Technical Manual were developed in the early 2000s to support skills development in the residential building sector, and similar programs were developed for other building sector professionals and trades.

Skills development resources continue to be actively delivered to train the industry for changing energy efficiency requirements, and as best practice methods by government programs, and professional and industry organisations. These resources are also delivered through continuing professional development (CPD), video demonstrations, short courses, and tertiary education (DISER, 2022a). The training resources can be accessed through *Energy efficiency training* (DISER, 2022a).

However, as expressed in the initial IRG meeting (13 April 2022), the lack of regulatory requirements to improve skills is a barrier. In addition, the range of training resources are not marketed to trades, and these are not in a format that can be communicated easily to homeowners. In addition, design and energy rating professionals often overlook cost sensitivity when specifying energy efficiency products. During procurement and construction stages, cost is a key selection criterion for trades and material procurement, a result of which alternative products are often used which can adversely impact building energy efficiency performance (Gram-Hanssen et al., 2018; Zou et al., 2018b). An industry focus group organised by the Design Matters National (DMN) noted that some builders and users can be cost-driven, not driven by consumers' longer term energy

efficiency and home liveability gains. Divergence in the perspectives of building designers and home builders in assessing the cost of energy efficient materials can be bridged by providing builders, designers, and homeowners with adequate training materials and up-to-date information. However, though training is essential, it is insufficient to transform perspectives. Engagement of various stakeholders depends on policy measures and consumer attitudes, and designing and implementing policies and legislations are important. It is essential for all trades, design professionals and energy raters to have certification, accreditation, and CPD, just as it is mandatory for solar installers.

Developing the future energy workforce is essential to the rollout of energy efficiency upgrades at scale, in order to transition to net-zero emissions. The RACE for 2030 E3 Opportunity Assessment Project *Developing the Future Energy Workforce* looked at the fundamental questions for Australia's current energy sector workforce and what needs to happen for a transition to net zero emissions across the economy. The issues included how to measure workforce size, how training and skills can be fit for the future, and how to strengthen Australia's innovation pathways (Rutovitz et al., 2021). Both qualitative and quantitative methods were used in the assessment of mapping skills required for the energy sector (Rutovitz et al., 2021).

A particular finding related to home thermal efficiency is that the current size of the thermal workforce (in particular insulation and glazing) is unknown considering the Australian Bureau of Statistics does not measure this workforce as part of the energy sector workforce. Without understanding current workforce size, it becomes difficult to determine the scale of the future workforce required to meet growth in energy efficiency demands to achieve emissions reduction goals. RACE for 2030 is working on research, with stakeholders through the E3 theme, to resolve these challenges, including ways of defining energy efficiency roles in the Australian government's planned Australian Energy Employment Report, and measuring the 'hidden workforce' of people who work in this field and related demand-management roles. To give a sense of the scale of the potential workforce required, the recently released *Australian Electricity Workforce for the 2022 Integrated System Plan: Projections to 2050* suggests that, while there is a lack of information on the current and future scale of this workforce, estimates for 2030 currently vary from 200,000 to 400,000. To give a sense of the scale of the potential workforce required, the recently released *Australian Electricity Workforce for the 2022 Integrated System Plan: Projections to 2050* suggests that, while there is a lack of information on the current and future scale of this workforce, estimates for 2030 currently vary from 200,000 to 400,000. Even the lower end of this range would be four times the 2030 electricity sector projection requirements for large-scale renewable generation and network asset installation (Rutovitz et al., 2022). A significant scaling up of workforce training will be required to meet this need.

To meet these requirements, *Developing the Future Energy Workforce* Opportunity Assessment recommends:

- Detailed future occupation and skills mapping, aligned with pathways to net zero by 2050;
- Pathways for developing cross-cutting skills for both traditional and non-traditional energy professionals;
- Improved coordination between educational providers and industry to fill the talent pipeline;
- Understanding the role women can play to diversify, and boost numbers in, the workforce;
- That there is a significant opportunity to map occupations and skills of fossil fuel workers to understand their workforce transition potential.

An industry-led roadmap for quality control and safety in insulation installation has been developed by the Energy Efficiency Council, in collaboration with several industry associations and organisations. Several organisations have committed to work with government to ensure proper insulation installation (EEC, 2021).

The roadmap sets out actions that include information and guidelines, training and accreditation. It also proposes requirements for insulation installations supported by governments, compliance associated with new buildings and major renovations, and moving beyond an insulation-only approach (EEC, 2021).

The Energy Efficiency Council has also been working on developing professional certifications to develop Australia's future energy and related services workforce. Currently there are certifications for Emissions Reduction Leader for Commercial Buildings, Energy Management Systems Advisor, and Certified Insulation Installer (EEC Professional Certifications, 2023). A Certified Insulation Installer certificate (EEC Professional Certifications, 2023) replaces the previous certification program administered by the Clean Energy Council. HIA is also offering government subsidised training across a range of state and federal government supported courses and qualifications (HIA, 2022a). There are also views from industry organisations that governments are not spending enough to support upskilling the workforce.

As part of the *Trajectory for Low Energy Buildings* (COAG Energy Council, 2018b), and in response to recommendations by Rutovitz et al. (2021), the Department of Industry, Science, Energy and Resources has committed to delivering the inaugural *Australian Energy Employment Report* (AEER) (DCCEEW, 2022a). AEER represents global leadership, and Australia is the first country to count energy jobs and adopt the Gold Standard methodologies and extend them to energy management across the economy. As Australia's energy sector transitions to net zero, AEER will make it possible for business and the government to avoid skill shortages and take advantage of financial opportunities (DCCEEW, 2022c; Energy Efficiency Council, 2022). It is essential for the scope of the project to include thermal efficiency of homes, and the extent of training to be provided requires specific research.

4.3.2 Supply chain

In 2021, the impact of the global COVID-19 pandemic on the construction sector included supply chain shortages of key construction materials, including structural and finished timber, insulation, dry walling, bricks and other cladding materials (Australian Institute of Architects, 2021). Shortages are continuing across industries. It is crucial to develop materials and products less susceptible to international supply chain failures, and less dependent on suppliers vulnerable to impacts of global and extreme climate events. *The views of the IRG (13 April 2022) also reinforced the issue of supply chain shortages and noted that maturity (market, supply, pricing) is required for products such as affordable window solutions and under-slab insulation which are currently relatively high cost and with very little market pull.*

Australian Bureau of Statistics data showed structural timber prices increased by 11.7 per cent from June 2020 to June 2021, mainly due to key drivers such as competing overseas demand and 10 per cent plantation timber loss from domestic bushfire events (ABS, 2021). Major reliance on international suppliers for essential building supplies puts Australia's construction sector at risk, as the implications of the global COVID-19 pandemic have revealed. To expand national capacity and secure the provision of adequate, low-carbon construction materials, Australia should develop a national construction supply chain strategy. *The window supplier association indicated that some manufacturing industries, such as the window industry, are market-ready to face new advancements. (IRG meeting 1 – 13 April 2022).* However, the Australian window industry faces challenges in adopting what are considered to be conventional designs elsewhere (for example, North America and Europe) but are still viewed as advanced window features in Australia, such as double glazing (DG), low-E coatings, and highly insulating framing (for example, uPVC) (Cuce & Riffat, 2015; WERS, 2022a). In the case of

the window industry, despite the readiness of supply, barriers exist including logistic issues for handling heavier window products.

4.3.3 Impact of energy efficiency disclosure schemes

Energy efficiency disclosure in Australia has been limited to a few temporary voluntary regional trials and one long-term mandated scheme – the Australian Capital Territory House Energy Rating Scheme (ACTHERS) mandates disclosure of residential property energy efficiency performance at the point of sale and rent, creating an informed housing market (Berry et al., 2008b; Berry et al., 2022; Fuerst & Warren-Myers, 2018). Reducing greenhouse gas emissions to mitigate global climate change has been the primary policy motivation to hasten the uptake of increased efficiency standards and mandatory disclosure regulations (Harrington & Hoy, 2019; O'Neill & Gibbs, 2020). There is an increased uptake of measures that improve existing building stock in the ACT (ABS, 2011), which may be due in part to the mandatory disclosure requirements. Australian Bureau of Statistics (2008) shows that Energy Efficiency Rating (EER) has been positively associated with ACT house sale prices; house prices rose by an average of 1.23 per cent and 1.91 per cent in 2005 and 2006, respectively, for every half-Star improvement in EER, holding all other variables constant. Recent research (Berry et al., 2022) indicates that the market for houses above the minimum standard is unusually strong in the ACT, further supporting the argument that mandatory disclosure requirements have increased demand for homes with higher energy ratings, and that the market more highly values improved energy performance.

The trend of improving energy efficiency is not evident in the rental property market, which constitutes 30.9 per cent of residential properties in the ACT, and where there is minimal investment in upgrades by landlords (Fuerst & Warren-Myers, 2018; Pitt & Sherry, 2016). The ACT's *Residential Tenancies Act 1997* does not strictly enforce disclosure of the EER when a property is advertised for rent. Only 37.5 per cent of rental properties disclosed the EER, though 58.4 per cent of rental listings had their EER assessed (Lee & Wang, 2010). The price implications for sold and rented properties were investigated by Fuerst and Warren-Myers (2018) with a comprehensive dataset of property transactions from 2011 to 2016. The data proved that energy efficiency disclosure corrected the price distortions from information asymmetry between buyers and sellers, but supply issues (a tendency for greater demand than supply) may inhibit the impact of disclosure. Overall, the benefits of EER disclosure may not be sufficient to address all market barriers for the rental market, and under the current commercial processes may not always be available or communicated to renters (Fuerst & Warren-Myers, 2018).

Disclosure of energy ratings or predicted performance has been used successfully as a policy tool to enhance the energy efficiency of household appliances and household equipment (Equipment Energy Efficiency E3, 2022). This policy instrument called *energy labelling* has proven effective in encouraging the purchase of energy efficient appliances and decreasing related home energy use in Australia, North America, Asia, and Europe (Energy Efficient Strategies, 2016; Fuerst & Warren-Myers, 2018; Mills & Schleich, 2010; Wiel et al., 2006). Future energy savings from improved performance of appliances can be factored into purchase decisions by making energy performance transparent to consumers. Policy instruments like Minimum Energy Performance Standards (MEPS) and mandatory energy disclosure (which act as complementary regulations) are intended to address multiple market failures. Although there is some evidence that the combination of the two may provide more benefits than any single policy approach (Berry et al., 2022), other researchers have suggested the need for a more comprehensive examination of the issue (Doyon & Moore, 2020; Wiese et al., 2018).

The National Framework for Disclosure of Residential Energy Efficiency Information (DCCEEW, 2021), now managed under the Energy and Climate Change Ministerial Council, outlines the structures necessary to successfully implement nationally harmonised schemes that will enable disclosure of energy efficiency information of existing residential buildings across Australia. The Framework, and the associated research program, is expected to provide a pathway to enable implementation of jurisdictions' disclosure schemes, although the Framework is careful to avoid committing individual jurisdictions to voluntary or mandatory schemes. The evidence, both in Australia and internationally, has consistently found for several decades that mandated energy performance disclosure schemes are significantly better at addressing market failures than voluntary schemes (Berry et al., 2022).

4.3.4 Rental properties

Minimum energy performance standards for rental homes, either as part of a larger housing quality initiative or specific to energy performance alone, is applied in numerous countries (Hinge, 2020). Proposing the introduction of minimum energy efficiency standards for rental buildings in Germany, Steuer et al. (2019) noted that policies for introducing minimum standards for rental buildings should be designed with a financial mechanism and flanking instruments to ensure there is no displacement of existing tenants, and that deep redevelopment of climate policy sector objectives is achieved. Section 6.2.3 of this report discusses the latest international research and policy instruments relevant to rental properties. The investigation of Minimum Energy Performance Standards for rental properties is part of the *Trajectory for Low Energy Buildings* (DISER, 2020b) work for which international regulatory policies relating to energy efficiency standards are reviewed. Minimum standards have proven valuable in addressing high energy costs and affordability challenges, particularly for vulnerable low-income renters. In Victoria, under mandatory housing quality regulations, a fixed heater in good working condition must be present in the main living area of a rented property and that heater must meet a minimum 2-Star energy rating (Consumer Affairs Victoria, 2022). Victoria is the first state to set basic standards for rental homes that include insulation, draught sealing, and efficiency standards for appliances (Renew, 2020), even though the standards need to be higher to make better impact. This minimum standard aims to ensure renters are not impacted by high energy costs or health impacts resulting from living in cold homes. The outcomes of these regulations, and similar minimum energy standards for rental property instruments applied internationally (see Section 4.4), should be evaluated.

4.3.5 Assessor accreditation

Issues regarding non-accredited energy efficiency assessors (NAAs) completing energy assessments affect industry performance and confidence. NAAs may not have completed a recognised software training course, or undergone quality assurance checks and ongoing training conducted through NatHERS processes. Design Matters National (DMN) is a professional body approved in accordance with the NatHERS Protocol for Assessor Accrediting Organisations. DMN was a participant in the IRG for the Opportunity Assessment project reported here. In August 2021, DMN facilitated a focus group to ascertain the industry views on the impact of thermal performance assessments carried out by NAAs. Industry participants from states and territories from across Australia (excluding ACT) were represented in the focus group, including NSW where BASIX is used. The purpose of the focus group was to specify the implications of NAAs completing energy assessments, and to recommend mandating accredited assessments for building approval processes. The focus group concluded that *NAAs had significant negative impact on the industry, as they were not subject to audit procedures and moreover, used protocols with no accountability.*

DMN also stated that a *Sustainability Victoria peer review project on energy assessments* also revealed that the energy assessments that were conducted by NAAs contained many errors, resulting in non-compliant, underperforming as-built housing. Such inaccuracies in modelling also affects the data that feeds into NatHERS and the CSIRO database. The percentages of NAAs varied between states, but the impact on energy performance is significant. The key reason for the increase in NAAs is the lack of strong legislation. NCC (2019d) provisions only indicate the need for 6 Stars as a compliant solution with NatHERS-accredited energy rating software. With a focus on the NatHERS rating tool via initiatives such as NatHERS Whole-of-Home, NatHERS In-Home, Green Home Loans in the finance sector, and the Green Building Council of Australia's Green Star Homes in the volume building sector, stronger legislation is required to strengthen the efficacy and credibility of accredited NatHERS assessors and assessment certificates.

4.3.6 State-based energy efficiency schemes

A number of states and territories have introduced energy saving schemes for users to implement initiatives into their homes and businesses. The NSW Energy Savings Scheme (ESS) provides financial incentives to install energy efficient equipment and appliances in NSW households and businesses. The Peak Demand Reduction Scheme (PDRS) in NSW provides financial incentives for households and businesses to implement activities that reduce demand for electricity during peak times. In Victoria, through the Victorian Energy Upgrades program (VEU), households and businesses can receive rebates or discounts on energy-saving products which helps cut power bills and reduce greenhouse gas emissions. The South Australian Government's Retailer Energy Productivity Scheme (REPS) provides incentives for households and businesses to save energy by giving access through participating energy retailers to low-cost energy efficiency products (such as efficient electric hot water heat pumps). The ACT's Energy Efficiency Improvement Scheme (EEIS) sets a Territory-wide energy savings target and includes obligations for ACT electricity retailers to meet an individual Retailer Energy Savings Obligation. Most of these schemes have been extended until 2030. A systematic evaluation and comparison of these schemes should be carried out to understand market failures and opportunities.

4.3.7 Closing the performance gaps

Several studies (Ambrose & Syme, 2017; Gram-Hanssen et al., 2018; Miller et al., 2021; Zou et al., 2018b) have indicated a significant gap between design energy targets and actual energy consumption. The performance gap appears to be a global systematic problem unrelated to the codes or regulations in any single jurisdiction (IPECC, 2019). This issue is exacerbated when we consider that, with climate change, all building energy rating methods based on historical climate data fail to drive design to suit future climates which would impact new buildings that have an effective life over the next 40-50 years.

Lack of as-built verification was highlighted as the key barrier by the IRG members who recommended that thermal assessors should be involved in early stages in the design process. An evaluation study (Miller et al., 2021) designed to understand the extent of the gap between as-designed energy performance and as-occupied energy use found heating variations ranged from 19 to 172 per cent, and cooling loads were up to 4.8 times higher than the simulated values used for regulatory approvals in the NatHERS rating scheme. Such energy performance gap and variation in domestic energy use appears to be caused partially by occupant behaviour and technical issues (Salvia et al., 2020; Zou et al., 2018a). This highlights the need to review a suite of human behavioural assumptions, and assumptions about construction within NatHERS and other thermal performance rating software. For example, the NatHERS calculation engine assumes particular behaviour in operating internal and external shade devices which may not reflect common usage.

Important contributing factors to the performance gap between design and performance include the lack of sufficient knowledge and skills from the design and construction team (Breadsell et al., 2020), communication gaps between key stakeholders (Zou et al., 2018a), and lack of accountability post-construction, often without any measure for verification (Pitt & Sherry, 2014). The Passivhaus performance-based standard attempts to address the performance gap in energy efficiency in buildings with the ‘fabric-first’ design approach, verifying airtightness (passing blower door tests) with certification (Clarke & Marlow, 2019; Marlow, 2020; Parry, 2014). Similar checks to verify actual performance are generally not required by the NCC or BASIX. The UK Building Services Research and Information Association (BSRIA) considers Australia a market leader in pioneering the concept of ‘design for performance’ and is developing a prototype for the UK to deliver the energy performance assessed during the design stage (Better Buildings Partnership, 2021; Verco, 2018). The National Australian Built Environment Rating System (NABERS), mostly used in commercial buildings but also applied to common areas in apartment buildings, can be considered a viable solution to closing the design versus performance gap (NABERS, 2019), although with limited residential application. In the commercial building sector, NABERS uses actual performance data normalised for existing buildings, and a ‘commitment agreement’ that requires the building, once occupied, to demonstrate that it meets performance expectations (Precious et al., 2022). A similar system of ‘commitment agreement’ may be challenging to achieve in the residential sector because of the more significant influence of user behaviour on energy usage.

4.4 International policy review and best practice

Reviewing policy targets and performance values is essential to assess a country’s energy efficiency improvement. A comparative criterion-based policy and best practice analysis based on comprehensive examination of home energy performance was conducted (Table 7), focussing on jurisdictions around the world that are forerunners in the race to reducing emissions. Key elements for analysis were based on emerging housing transitions and policy development research by Li et al. (2022), Moore et al. (2014), and Tambach et al. (2010). The criteria for inclusion of programs and policies were residential focus, thermal fabric improvements, home technologies to improve thermal comfort, smart technology integration, and a focus on renters and vulnerable households.

The most effective method for increasing energy security and improving the health and wellbeing of building occupants is the establishment of minimum building performance rules combined with cost-efficient government policy initiatives (IEA, 2017). Setting mandatory provisions in building codes is a conditional requirement of all countries for setting their path to net zero emissions. In addition to requiring new buildings to meet these standards, IEA (2022) contends that to achieve the sector’s decarbonisation targets for 2030 and 2050, it is necessary for at least 20 per cent of existing building stock globally to be renovated and brought up to code by 2030. Retrofitting 20 per cent of existing building stock to a zero-carbon-ready level by 2030 is an ambitious but necessary milestone toward the Net Zero Emissions by 2050 Scenario (IEA, 2022).

This Opportunity Assessment reviewed and investigated international policies and best practices relating to home thermal efficiency to consider as opportunities in Australia’s residential sector. The European Union (EU) and California (USA) are the two most prominent models of policy innovation. Both have set policies that increased performance standards over a period of time in a stage-wise process and currently demand zero, or near zero, energy performance results (IEA, 2021; Li et al., 2022). From 2021, all new structures in EU member states should be nearly zero energy buildings, according to the EU Energy Performance of Buildings Directive (EPBD), which has been applied to public buildings since 2019. The majority of EU member states have

amended legislation to comply with this criterion (Council of the European Union, 2018). In the USA, local governments have significant opportunity to implement energy standards that are more stringent than national codes, as has been done in California (CEC, 2022). As a market leader, California introduced in 2022 zero carbon standards for compliance (CEC, 2022).

The UK 2025 codes require all new houses to have low-carbon heating and be zero-carbon ready (CEC, 2022; MHCLG, 2019). Including both energy efficiency and renewable energy regulations, recognising energy savings as economic value, and creating low or zero carbon/energy performance objectives, are three critical aspects for implementing the policies (Annunziata et al., 2013). The necessity of integrating technological systems of zero-carbon building regulations into legislative, social, and geographic settings has been observed by Pan and Ning (2015). Zero-carbon building policy tools can be categorised as required administration instruments, economic incentive instruments, or voluntary scheme instruments (Shen et al., 2016). Governments are increasingly using economic incentives to address concerns arising from economic effects of encouraging sustainable housing and associated infrastructure (Pan & Ning, 2015).

Research conducted (Pears & Bustamante, 2022) on EU and Australian policies for building and appliance energy efficiency showed significant similarities and contrasts between Australian and European Union (EU) institutional structures, past and present policy approaches connected to building and appliance energy and climate adaptation, as well as historical and present policy initiatives. Future scientific collaboration could grow resulting from both the parallels and differences. The report also summarises major themes in buildings and appliances areas, highlighting the potential for productive collaboration between the EU and Australia. A preliminary list of priority topics for potential EU-Australian collaboration is also proposed (Pears & Bustamante, 2022, p. 15). This report by Pears and Bustamante (2022) states that the EU and Australia both confront difficulties in drastically increasing efforts to reduce carbon emissions from homes and appliances, as well as in adjusting to harsher weather patterns and managing equitable transitions. Both contain substantial inventories of ageing structures that, without operating efficiency optimisation, renovation, or replacement, will continue to produce high emissions. Both regions have a wide range of climates and renewable energy options. The main variations are approach and implementation. The EU develops policies and emission reduction strategies thorough Directives with explicit expectations of results from Member States and sets them ambitious climate goals. In 2022 September, Australia's parliament passed legislation to cut carbon emissions by 43 per cent by 2030 and to achieve net zero by 2050. Victoria and New South Wales have set an interim target of 50 per cent reduction on 2005 levels by 2030, whereas Queensland has set an interim target of at least 30 per cent reduction on 2005 levels by 2030. The interim targets set by South Australia and ACT are at least 50 per cent reduction on 2005 levels by 2030, and 50-75 per cent reduction on 1990 levels by 2030 respectively. The EU has a 'top down' approach with varying implementation processes across member states, whereas Australia's current approach is bottom-up and fragmented (Pears & Bustamante, 2022).

Key international thermal performance policies are summarised in Table 7. The Netherlands has adopted best practice in residential energy codes, whereby new buildings must meet 'almost energy neutral' criteria. It performs well on policy metrics with excellent building energy codes and retrofit categories (Bodelier & Herfkens, 2021). Building performance certificates are mandatory with an energy efficiency score of A-G (with 'A' indicating a high-efficiency rating and 'G' indicating a low-efficiency rating) (European Commission, 2018). Similar to the Netherlands, the USA is a world leader on energy efficiency policies. Federal income tax credits are available providing up to USD3,200 annually to lower the cost of energy efficient home upgrades by

30 per cent. Improvement includes installing heat pumps, heat pump water heaters, insulation, doors and windows, electrical panel upgrades, and home energy audits (Energy Star, 2022b).

France, Spain and Germany performed similarly to the Netherlands, mainly because these jurisdictions meet the compliance requirements of EU's Energy Performance Building Directive. France has mandatory comprehensive residential building codes, with a requirement for energy rating systems and disclosures (Nadel & Hinge, 2020). In July 2021, the French parliament reached agreement on the *Climate and Resilience Law*, which should make it possible to achieve a 40 per cent reduction in greenhouse gas emissions by 2030 compared to 1990 levels (Jousseume, 2022). Under this Law, from August 2022 landlords can no longer increase rent on properties with poor energy efficiency ratings (ranked F or G) (Coulaud, 2022). From January 2023, it will be illegal to rent the absolute least energy efficient properties in France – those that consume more than 450kWh per square metre and per year (La Prensa Latina, 2022).

The International Energy Efficiency Scorecard developed by ACEEE presents basic comparison of energy use and efficiency policy efforts in the top energy-consuming countries. Australia ranks 13th in the Scorecard for its national efforts of setting goals to reduce greenhouse gas emissions by 26-28 per cent by 2030, based on 2005 emission values; and also for committing to increase energy productivity (Subramanian et al., 2022). Subramanian et al. (2022) suggested Australia could exhibit further improvements if governments provide fiscal support for energy efficiency programs and research designed to deliver on these commitments. The key reason for the recommendation is Australia's reduced investments in efficiency and incentive programs (ACEEE, 2022).

Financing mechanisms must be investigated to support upgrading low-income housing and reducing the burden and disincentive of upfront capital costs. One such successful finance model initially applied to social housing retrofits in Europe, the Energiesprong model, provides the capital cost of a retrofit which is then repaid to the loan provider using money saved from lower energy bills (Energiesprong Foundation, 2022). Accelerating uptake of energy efficiency improvements is a key challenge for policy makers, with Australian residential energy use intensity improving only by 5 per cent over the decade from 2005 to 2016 (ASBEC, 2016). The latest report of Energy Consumers Australia (2022) observes that Australian consumers are concerned about the state of the energy market, with increased costs a sign of a struggling system.

Table 7. Summary of selected international programs

Institute	Region	Title	Notes
USA Environmental Protection Agency (EPA) (Bloom et al., 2011)	USA	EPA Energy Star®	Voluntary energy efficiency program. These savings are based on space heating and cooling, and hot water energy use.
USA Department of Energy (Glickman, 2014)	USA	Home Energy Score	Standard rating system that estimates a home's energy use based on its 'envelope,' and is an asset rating.
California Energy Commission (CEC) (2022)	USA	California Residential Building Energy Standards Code	Net-zero energy requirements for all new residential buildings from 2020. Standard in 2022 encourages electric heat pumps, new homes to be electric ready, solar PV expansion and battery storage standards, and improved ventilation systems.
European Parliament and Council (2018)	EU	Directive (EU) 2018/844 on energy performance of buildings	Requires all new buildings across the EU from 2020 to be nearly zero energy.
Energy Efficiency Directive (EED) (2018)	EU	Long-term Strategies for Deep Energy Retrofitting	Aims to support renovation of existing buildings to be energy efficient and decarbonised by 2050.
Canadian Home Builders' Association (CHBA, 2017; Government of Canada, 2018)	CA	Net Zero Home Labelling Program, R-2000 Program	Net Zero Home Labelling Program provides a voluntary and affordable choice for consumers.
Natural Resources Canada (2015)	CA	EnerGuide Rating System Technical Procedures, Version 15.1	Primarily targets existing housing and now includes new housing. Evaluates energy efficiency of homes on a scale out of 100, where 100 represents an airtight and well-insulated house, achieving net-zero energy.
Ministry of Housing, Communities and Local Government (MHCLG, 2019)	UK	Future Homes Standard	Separate Fabric Energy Efficiency Standard (FEES) with thermal bridging, air tightness testing. Tighter transitional arrangements.
European Energy Performance of Buildings Directive (EPBD) (Bodelier & Herfkens, 2021)	Netherlands	Energy Performance of Buildings Decree (BEG), and Energy Performance of Buildings Regulation (REG)	New buildings must be nearly zero energy buildings (NZEB), accounting for the environmental impact of materials used.
Parliament of France (Joussemaue, 2022).	France	Climate and Resilience Law	Achieve 40 per cent reduction in greenhouse gas emissions by 2030 compared to 1990 levels.

5 Technology and Market Potential Assessment

As an end-use sector, the buildings sector still represents a large share of emissions due to electricity use in the residential sector (DISER, 2021), and a high proportion of peak demand at times when variable renewable energy production is low. Energy efficiency and building performance are key to decarbonising and reducing energy bills of homes. But in Australia, the focus is on rooftop solar and storage, not making buildings and appliances work well. While there is a decline in the long-term, efficiency-driven trend of consumption per household (DISER, 2020a), energy consumption in the residential sector grew 3 per cent in 2018-19 and 2019-20,, partially due to COVID-19 lockdown restrictions for most of Australia in 2020 (DISER, 2021). For the period 2019-20, residential electricity use was 22.8 per cent of total national consumption.

Many technologies are readily available which improve energy efficiency, thermal performance, and decarbonisation in the building sector. However, deployment and integration are identified as the main challenges (ClimateWorks Australia, 2020a). In the residential building sector, improved energy efficiency throughout the building system combined with electrification and use of renewable energy for power, heating and water services, is an available, mature and commercially competitive pathway (ClimateWorks Australia, 2020a) that has been demonstrated at scale (COAG Energy Council, 2018a, 2019a).

New homes have improved and increasingly become more energy efficient with insulation standards and required energy ratings (COAG Energy Council, 2018a). However, many of Australia's ten million homes are characterised by poor thermal and energy efficiency performance (Fox-Reynolds et al., 2021). Building energy performance solutions were identified early on as 'negative-cost' opportunities in the McKinsey (2008) 2030 carbon abatement cost curve. Solutions such as better insulation in new buildings are at the lower end of the curve compared to technologies (such as wind power and carbon capture and storage, which are higher up the cost curve). Widespread thermal improvement measures are available and commercially competitive, such as insulation (Hampton, 2010), draught sealing (Sustainability Victoria, 2020), windows (Turner, 2018), and passive house standards (Australian Passive House Association, 2018). Passive House standard buildings have gained momentum in recent years. Globally, some 60,000 passive houses (Clarke & Marlow, 2019) illustrate how using careful design and insulation can substantially reduce heating requirements in homes. In 2019 there were 25 certified passive houses in Australia and a reported 240 projects underway for a total of nearly 1200 dwellings across the country (Marlow, 2020). Although Passive House principles are often used in new homes, existing buildings can be retrofitted to a Passive House standard using the EnerPHit certification system. This system uses the same principles and processes as Passive House with slightly less stringent metrics because of the practical challenges of achieving high performance in existing buildings.

End-use technologies in the residential building sector associated with thermal efficiency are used for space heating and cooling, cooking, water heating, appliances, and lighting. Energy-efficient technologies continue to become cheaper and more effective. For example, LED lighting costs have declined (Energy Rating, 2021b) while efficiency has continued to improve over time.

5.1 Summary of strategies, technologies, and solutions for residential sector

Technological solutions to improve thermal integrity in the residential sector can be categorised according to strategies ranging from simple solutions to deep energy retrofits.

Technologies are classified as follows (ClimateWorks Australia, 2020b):

- Mature – can be deployed immediately
- Demonstrated – can benefit from accelerated deployment, or
- Emerging – following investment in research development and demonstration (RD&D), may be ripe for accelerated development

The following Sections 5.2 to 5.5 discuss the various technologies, including building fabric and equipment and appliances, their status and applications.

Table 8. Summary of strategies, technologies, and solutions for residential buildings sector. Adapted from: (ClimateWorks Australia, 2020b).

Technologies, practices, and solutions	Status	Exemplars and applications
Building fabric – construction with lower possible energy requirements for lighting, heating and cooling by ventilation		
Insulation and draught sealing; air leakage	Mature	Building insulation is well-established and a cost-effective solution in reducing energy consumption via building envelope performance (Johnston, 2022).
Air leakage; wall assembly; floor construction; thermal bridging and thermal breaks	Mature	General requirements on thermal construction are outlined in energy efficiency provisions of NCC-BCA Vol One, Part J (for multi-residential buildings), and Vol Two, Part 3.12 (for residential dwellings (ABCB, 2019a, 2019b)). Nevertheless, there is substantial potential to reduce thermal bridging more effectively; e.g., through concrete slabs that extend as balconies or walkways, retrofitting range from relatively easy or cheap to relatively difficult or expensive.
Airtightness, sealing, ventilation, and condensation management – trickle vent, vapour barriers, vapour retarder	Mature Adapt mechanical energy or heat recovery ventilation in Australia	Airtightness, sealing, and ventilation (Antretter et al., 2007; Reardon, 2013; Reardon & Marlow, 2020). Condensation management provisions are outlined in NCC-BCA Vol One, Part F6 (for multi-residential buildings), and Vol Two, Part 3.8.7 (for residential dwellings) (ABCB, 2019c, 2019d). Condensation design strategies to avoid condensation are well-established: vapour barriers, ventilation to reduce room humidity, and permeance control strategy (Australian Modern Building Alliance, 2021; Cement Concrete & Aggregates Australia, 2008; Edwards, 2019; Sustainability Victoria, 2020).
Window design – orientation, window-to-wall ratio (WWR); window type – frames and glazing, advanced coating	Mature Retrofitting needs cost reduction	Availability of Window Energy Rating Scheme ratings. Online tools (Australian Glass and Window Association, 2012).
Shading devices (shade sails, external blinds, changing roof colour)	Mature Cost reduction	Shading strategies and solutions to supplement window design (Cairns Regional Council, 2010; Hollo & Durie, 2012; Wrigley, 2012).

Technologies, practices, and solutions	Status	Exemplars and applications
Thermal mass – mud brick, reverse-brick veneer, trombe wall; internal masonry wall; concrete slab (ground floors); lightweight construction – mass-timber	Mature	Integration of thermal mass solutions with passive design (Hampton, 2010; Marlow et al., 2020): improvement in thermal performance through occupant behaviour. Mud-brick, reverse-brick veneer construction, internal masonry wall, concrete slab – ground floors (Baggs & Mortensen, 2006; Hollo & Durie, 2012). Light-weight construction – mass-timber (Dewsbury, 2016); PCMs (Reardon et al., 2017).
Cooling by ventilation – stack effect, cross-ventilation, ceiling fans, roof ventilators/whirly birds/automated windows	Mature	Passive cooling for heat gain reduction and increase heat loss (Aynsley, 2014; Cole, 2011; Hollo & Durie, 2012; Szokolay, 2006).
Cool roofs	Mature/Emerging	Range of options available for application of cool roofs (reflect more sunlight than a conventional roof, absorbing less solar energy) (Green et al., 2018; Jewell, 2014; Osmond & Sharifi, 2017; Thorpe, 2019; University of Melbourne, 2011).
Passive House standards	Demonstrated	The number of Passive House certified dwellings expected to increase in line with global trends where design and construction professionals are adopting physics-based approach to building design solutions (Clarke & Marlow, 2019).
Mechanical heat recovery ventilation (HRV) and energy recovery ventilation⁶ (ERV)	Emerging	With tight building envelopes, use of HRV or ERV ventilation systems as solutions to indoor air quality, where fresh air can be introduced with lower heat loss yet not create excessive demand on heating and cooling systems (Marlow, 2020; Parry, 2014; Stiebel Eltron, 2022; Sustainability Victoria, 2020).
Smart glass (light control) or dynamic glazing for windows – electrochromic (EC), PDLC⁷ and SPD⁸ films	Emerging	Smart glazing products for residential applications are available.
Energy efficient equipment		
Solar hot water (SHW)	Mature but heat pumps outperforming	SHWs can potentially provide 50-90% of home hot water requirements (depending on climatic zone). SHW with booster system is more cost-efficient to run than a standard gas or electric system (Clean Energy Council, 2021). The industry is well-established with SWH making around 13% of all hot water systems used across Australia (Energy Rating, 2020b). Total SWH systems installed more than 1.3M units with almost 73K systems installed in 2020 (Clean Energy Council, 2021). Poor winter performance and competition with PV for roof space means they are losing favour to heat pump HWS.
Reverse-cycle air-conditioning	Mature but scope for improvement	Offer all-year round comfort, and energy and cost efficiency. Air-conditioner energy efficiency has improved by 50% over the last ten years (Energy Rating, 2021a).

⁶ HRV systems recovers heat energy from air being removed to either heat or cool incoming air. ERV systems also transfer humidity along with heat from outgoing exhaust air to the incoming fresh air.

⁷ Polymer dispersed liquid crystal (PDLC) smart glass has high light transmittance (80%), ideal for privacy or project when opaque, and not for tinting. Gauzy. (2019, 3 December 2019). *What's The Difference Between PDLC And SPD Smart Glass*. Gauzy HQ. Retrieved 15 July 2022 from <https://www.gauzy.com/liquid-crystal-spd-smart-glass-whats-the-difference/>

⁸ Suspended Particle Device (SPD) smart glass blocks up to 99% of light, ideal for custom shading in outdoor window but does not offer solid privacy solution *ibid*.

Technologies, practices, and solutions	Status	Exemplars and applications
Heat pumps – hot water system	Mature	Air-source heat pumps (ASHP).
Ground-source heat pumps – space heating	Emerging and expensive	Ground-source heat pumps (GSHP) operate efficiently in extremely hot or cold conditions.
Air-conditioning – split system	Mature but scope for improvement	Air-conditioner energy efficiency has improved by 50% over the last ten years (Energy Rating, 2021a).
Mechanical heat recovery ventilation (HRV) and energy recovery ventilation (ERV)		Emerging Need to adapt to Australian conditions
Optimisation of equipment use		
Lighting controls	Mature	
Smart home system – energy management, comfort and lighting, home entertainment, control and connectivity, security, smart appliances	Mature/ Demonstrated	Need for retrofit user interfaces that provide user-friendly feedback on energy use and efficiency indicators such as appliance and equipment efficiency, emerging faults, etc. Devices that can be fitted to ‘dumb’ electricity and gas meters are needed.
Electrification – powered by renewables		
Rooftop solar PV	Mature but add storage	Almost 390K rooftop solar systems were installed in 2021 with over 3M solar homes in 2022 (DISER, 2022b).
Building integrated PV	Emerging	Practical applications have been slow in comparison to conventional rack-mounted solar PV (Yang, 2015).

5.2 Building fabric

The building fabric has the longest life span in comparison with technological-based installations, and typical savings for building fabric technologies fall in the range of 9-27 per cent per doubling of cumulative production, with 18 per cent being the average (Berry & Davidson, 2015). Studies show that existing NatHERS 5 or 6 Star building designs can be modified to achieve higher energy performance (thermal comfort) with a net reduction or slight increase in construction costs (AUD0-500) through simple changes to glazing, insulation, and shading specifications (Sustainability House, 2012a, 2012b).

Building insulation is a mature, well-established technology and a cost-effective solution in reducing energy consumption via building envelope (Johnston, 2022). While insulation is not the only design strategy for building thermal performance, it is considered the cornerstone to all energy efficient building design (Clarke et al., 2020). Technological advances and development of insulating materials continue to improve performance. Although still a niche market (Keech, 2018), the use of phase change material (PCM) is gaining popularity. PCMs are a capacitive type of insulation materials that release thermal energy during the process of melting and freezing (changing from one phase to another). The advantage of using PCMs for insulation is that they can store large amounts of heat within small ranges of temperature, encapsulated as they undergo a change of phase between liquid and solid (Kishore et al., 2021). Properly installed in a building structure, PCMs are reported to improve thermal performance of a lightweight building by at least 1 Star (Keech, 2018).

The influence of PCMs on building thermal performance has been widely investigated (Ahmadvand et al., 2017; Cao et al., 2017; Gerislioglu et al., 2020; Kalnæs & Jelle, 2015; Konuklu et al., 2015; Souayfane et al., 2016), as with the effects on improving indoor thermal comfort and reducing heating and cooling loads (Alam et al., 2014; Karim et al., 2014; Lei et al., 2016; Xu et al., 2005). This emerging technology is promising because the materials are easy to apply, lightweight, and compatible with conventional construction methods (CGS Facade Engineering, 2020). Lee et al. (2015) assessed the integration of a thin PCM layer in a residential building and evaluated the thermal performance with heat flux reduction and heat transfer time delay. The evaluation was done with experimental test houses. Lower heat fluxes were produced through residential walls with a time delay in heat transfer, and optimal location for the PCM in the wall cavities were found. Application of PCMs, in rooves for example, can reduce building energy loads and the results of a numerical investigation show temperature delay time of more than three hours in comparison with a common roof (Li et al., 2015). Experiments on passive solar buildings demonstrated that using phase change heat storage materials: reduces the variation in air temperature in rooms; shifts the peak of energy consumption for heating and cooling of lightweight buildings by several hours; and reduces energy consumption for maintaining comfort temperature levels in buildings (Kenisarin & Mahkamov, 2016). The experimental study on PCM bricks for walls in Spain by Castell et al. (2010) found that the indoor peak temperature can be reduced by around 1°C with no daily fluctuations. It also found that the cooling load in summer of 2018 could be reduced by 15 per cent. Another study by Alam et al. (2014) involved a numerical investigation on PCM integrated residential buildings in major Australian cities and it was demonstrated to save annual heating/cooling load by 17-23 per cent. Despite substantial research and development in PCM technology and application, key issues remain in the appropriate PCM selection for each climatic zone. The lack of systematic and comprehensive studies in these areas limits their widespread applicability in the residential construction industry, and future research endeavours on this topic are recommended.

Building fabric material choice affects vapour diffusion with some materials able to store moisture, and some materials able to stop moisture and vapour from migrating through the built fabric. Hence, it was suggested that successful condensation mitigation must be part of the building fabric as a complete system (Ambrose & Syme, 2015). Dewsbury and Law (2017) found that up to 40 per cent of all Australian homes constructed in the last 15 years have a visible internal formation of condensation. Condensation and associated problems (like mould, damage to materials) are also linked to the production of water vapour in homes due to clothes drying, bathing, and even indoor plants and aquariums. Heat pump clothes dryers, automated management of ventilation, and other measures including occupant education are key elements in addressing the problems.

Vapour diffusion and vapour management is a big issue in the building fabric envelope in Australia. A report published by Dewsbury et al. (2016a), *Condensation risk management for Tasmanian housing*, estimated that about 10 litres of water vapour is generated per person per day due to various human activities in a residential building (Dewsbury et al., 2016b). If the moisture is not released, the building fabric elements will continually absorb and accumulate moisture, leading to structural risk and decay (USA EPA, 2013). To calculate and simulate the diffusion of water vapour through a wall system, the vapour diffusion properties of all building materials are required. By understanding the vapour diffusion properties of materials in terms of temperature and relative humidity, architectural and engineering designers are informed on the proper construction assembly and material use to create an enclosure that can manage water vapour. In Australia, vapour resistivity values of common building materials are unavailable (Olaoye & Dewsbury, 2019). Several local and international researchers (Dewsbury et al., 2016b; Viitanen et al., 2010) have identified that it may take up to ten years for building fabric decay to become visible. Therefore, vapour resistance data is needed for all Australian climates to simulate hygrothermal analysis within floors, walls, and roof spaces. Olaoye et al. (2021) conducted research on vapour sensitivity of common building materials which assists in creating a database to be integrated into the material libraries of hygrothermal simulation software in Australia. This data can inform industry and government, and influence development of climate-friendly construction and construction systems that passively manage water vapour transport in new buildings.

5.2.1 Window technologies

As substantial sources of heat gains and losses, windows have a significant effect on thermal performance. Window technologies are generally mature but retrofitting with high performing windows tends to be a costly exercise. Online tools (Australian Glass and Window Association, 2012) such as efficient glazing tools, glass thickness calculator – AS 1288 tool (AGWA, 2022a) – and wind classification tools for housing – AS 4055 tool (AGWA, 2022b) – have been developed by the Australian Glass and Window Association to inform selection of efficient windows and doors, and to simplify compliance with NCC-BCA and Australian standards. Window Energy Rating Scheme data are also available for comparison of performances of windows, doors, and skylights, and glazing types (AGWA, 2021). The Commonwealth Scientific and Industrial Research Organisation (CSIRO) collects and publishes information about Australian houses (CSIRO, 2022c) based on data from NatHERS (Department of the Environment and Energy, 2022). The thermal performance of a window can be measured by its thermal transmittance or U-value, which is a measure of how much heat is transferred through the window via conduction, and its solar heat gain coefficient (SHGC), which is a measure of how much solar radiation passes through the window. Lower numbers indicate better thermal performance. The percentages of Australian houses constructed with windows of low U-value ($< 4 \text{ W/m}^2\text{K}$) and low SHGC (< 0.5) are summarised in Table 9. While a U-value of $4 \text{ W/m}^2\text{K}$ is higher than that for typical windows in North America and Europe, it is considered high performing in the Australian context. Double-glazed Australian

windows with highly insulating frames have much lower thermal values: 2 W/m²K for timber or unplasticised polyvinyl chloride (uPVC or vinyl) frames, and 3 W/m²K for thermally broken aluminium. However, most windows installed in new and renovated homes are aluminium-framed, the majority of which have U-values above 4 W/m²K. While advanced framing is commonplace elsewhere, there are relatively few high-performance windows in new and existing Australian housing, as shown in Table 9.

Table 9. Percentages of Australian house project types with high performance windows over the period 2016-21 (CSIRO, 2022c)

House project type	Low U (<4 W/m ² K)	Low SHGC <0.50)
	(%)	(%)
All	8.0	7.6
Existing	1.5	0.80
New build	7.5	7.7
Renovation	21.2	10.4

Statistics on the prevalence of different types of window frames in Australia could not be found. However, it is known that the most popular frames are all-aluminium frames (Renew Magazine, 2018), with high U- values, followed by timber frames. Frames made of uPVC with low U-values represent about 4-5 per cent of window sales, compared to 70 per cent in the USA and 55 per cent in Europe (Vinyl Council Australia, 2022).

Spectrally selective low emissivity coatings can be applied to single- and double-glazed windows to improve performance in both summer and winter. Existing glazing can also be retrofitted by applying such coatings and the glazing systems can be rated with Window Energy Rating System (WERS) (Turner, 2018; WERS, 2022b). Retrofitting with high performance glazing is typically expensive in Australia, whereas lower cost solutions are emerging overseas (US DOE, 2022). Smart glazing products for residential applications, such as electrochromic (EC), polymer dispersed liquid crystal (PDLC), and suspended particle device (SPD) films, are available and being specified in homes for temperature and lighting control (Ecosave Australia, 2022; Gauzy, 2022). The global market for smart glass is expanding with forecast annual growth of more than 10.3 per cent from 2022 to 2030 attributed to growing trends in deploying innovative technologies in new buildings and the architectural sector (Grand View Research, 2022).

As an example of what may be possible, significant research on an innovative Anti-Reflective Coating has been undertaken by Burning Palm Corporation PL, Melbourne, in collaboration with CSIRO, Division of Manufacturing Technology, and the Australian Institute for Bioengineering and Nanotechnology, University of Queensland. The coating – starting from the air interface – comprises of a 3 level GRIN structure. The principal novelty is the presence of never previously synthesised air-filled hollow, colloidal and transparent nanospheres at the air-surface boundary. Overall coating thickness is ~150nm and the expected RI (glass + coating) will be less than 1.23. The coating is totally transparent, thermally insulating, water-resistant, self-cleaning, anti-fogging and anti-condensation, and chemically resistant to acid, base, and solvent attack. The coating is also UV-resistant and has extremely low dielectric constant (poor conductor of electricity, heat, and external sound). The coating can be ultrasonically sprayed onto glass or plastic during manufacture but can also be similarly sprayed onto existing glass windows or plastic panels. Addition of a nano-powder, CWO, from Sumitomo Metal Mining Co, into the coating mix provides further infrared repellent and heat dispersing functions once the coating is applied on external and internal windows surfaces. The coating is expected to substantially

reduce heating and air-conditioning energy costs, as well as virtually eliminate the ‘visual pollution’ of glass reflections for display, lens, and other purposes. Increased power output from new and existing solar panels is another major application. Solutions like this provide the possibility of avoiding expensive replacement of windows and improving performance of new glazing. Further research, development, and innovation practice are recommended for these window solutions.

5.2.2 Envelope installation

A fundamental issue is the installation of building fabric and its integration with other elements during construction. Buildings are typically less energy efficient than predicted due to factors like: absence of (or gaps in) insulation; poor installation practices; tradespeople disturbing insulation when installing wiring and lighting, for example; and complex thermal bridging issues. Poor installation of insulation and weather sealing reduce energy performance of houses (Ambrose & Syme, 2015). Resistance to inward (infiltration) or outward air leakage (exfiltration) through unintentional leakage points or areas in the building envelope is known as air tightness. Air leakage is normally driven by differential pressures across the building envelope due to external wind and temperature conditions and existing mechanical ventilation systems that are in operation. Airtight buildings are buildings designed and constructed to minimise uncontrolled movement of air through building components such as walls, roofs, floors, and woodwork. Air tightness is essential to improving energy efficiency, it prevents structural damage, and maintains healthy indoor air (Pro Clima Australia, 2020).

Lack of specific quantification of air leakage rates until NCC 2015 was a key reason for leaky homes. NCC 2015 Volume 2 (ABCB, 2015) only had a performance requirement Section P2.6.1 which stated, ‘A building must have, to the degree necessary, a level of thermal performance to facilitate the efficient use of energy for artificial heating and cooling appropriate to the sealing of the building envelope against air leakage.’ The NatHERS software does not define a specific level of airtightness to be achieved and the air change rates are roughly estimated with the stack, infiltration factors, and wind speed (Ren & Chen, 2015). An average rate of 15 ACH at 50 Pa could result from the use of the NatHERS methodology (Ambrose & Syme, 2017). NatHERS methodology underestimates annual heating energy consumption by assuming better airtightness than the industry can typically provide. NatHERS airtightness assumptions should be set to an average level that the industry can achieve, and with options of higher air tightness levels to be included in the software (IBPSA Australasia, 2021). NatHERS could enable high-performance homes to have higher Star ratings by incorporating certified air pressure results into the NatHERS calculations (Ambrose & Syme, 2017). To increase the reliability of NatHERS Star rating, provisions to include air tightness levels are essential as they will encourage builders to build well-sealed houses. However, well-sealed and tighter buildings without adequate mechanical ventilation seem to experience increased condensation and mould problems. Automatic mechanical heat or energy recovery ventilation systems are key in airtight enclosures. Lack of mechanical ventilation or extractor systems, compounded by occupants’ limited knowledge of the increased importance of active management of ventilation, would affect indoor humidity conditions. Water leaks, moisture ingress, and thermal bridging due to low quality construction have amplified the problems. A study by Ambrose and Syme (2017) recommends issuing ‘as designed’ and ‘as built’ NatHERS certificates, with ‘as built’ issued after performance verification by testing. This could increase the requirement for air tightness testing, improve performance, and further reduce energy requirements. As testing becomes more widespread, the housing industry may gain a better understanding of how to improve airtightness of homes, and the simple measures that can be applied during construction that can lead to tighter homes.

Certain jurisdictions in the USA, like Washington state, and programs such as ENERGY STAR for Homes implemented by the USA's Environmental Protection Agency (EPA), have included air tightness as a requirement without any hard targets (Bloom et al., 2011; US DOE, 2014). Building air tightness testing is not a mandatory test prescribed in building codes, but a performance-based option that many designers are requiring (Air Barrier Association of America, 2020). The objectives were to increase the supply of trained testers, create an accreditation framework similar to Residential Energy Services Network (RESNET) in the USA, improve the supply chain of materials, help the industry make early improvements by learning from mistakes, and establish a stable path before introducing mandatory targets.

In 2019, ABCB released the Air Tightness Test requirements for updates of Building Regulations in Australia (ABCB, 2019c). Air Tightness Testing has been added as an optional requirement to demonstrate compliance, rather than the more arduous methods of demonstrating the detailing used throughout the building process. NCC 2019 Volume 2 Section V2.6.2.3, Compliance with P2.6.1 (f), is verified when a building envelope is sealed at an air permeability of not more than $10\text{m}^3/\text{hr}\cdot\text{m}^2$ at 50 Pa of pressure, when tested in accordance with AS/NZS ISO 9972 Method 1 for residential house (2015), with an option for verification, which is not mandatory in NCC 2019 Volume 2 Part 3.12.3 (ABCB, 2019d).

Occupant behaviour becomes increasingly important as buildings become tighter and sealed. For example, drying clothes on a clothes rack inside dumps substantial water vapour into the building, as does cooking or showering without exhaust or extractor fans. Furthermore, 'accidental' outdoor air leakage reduces the efficacy of appropriate vapour barriers designed to limit increased condensation inside wall cavities.

5.3 Equipment and appliances

5.3.1 Space heating and cooling

Space heating and/or cooling accounts for an average of 40 per cent of household energy use in Australia (Energy Rating, 2020a), and depending on the climate zone and building performance, this can range from 20 per cent to 50 per cent (DCCEEW, 2022b). Technologies installed at any location depend on the type of climate (heating or cooling dominated), humidity conditions, and available energy sources (notably gas). Below is a list of most used heating systems in Australia:

- electric reverse-cycle air-conditioners (medium to high capital cost)
- electric or gas portable or installed heaters (low to medium cost)
- ducted gas heating (high cost)
- hydronic radiant heating (medium to high cost)
- wood fireplaces (medium to high cost).

Gas appliances have lower efficiencies, ranging from 60 per cent to 90 per cent. Electric appliances can have varying efficiencies; for example, 100 per cent for an electric fan heater, and 300 per cent to 600 per cent for a reverse-cycle air-conditioner (heat pump) (Ryan & Pears, 2019). Reverse-cycle air-conditioners can be very economical in operation, with coefficients of performance of around three to six (Energy Rating, 2022). Ducted heating is found in newer homes and is expensive to operate due to significant gas consumption and electricity use for running fans, and heat losses through ductwork and pressurisation effects. It can be zoned to optimise energy to some extent. For hydronic heating, initial cost can be high but running cost could be reduced by using solar or electric heat pumps. Portable gas heaters can cause health, safety, condensation, and

mould issues. In New Zealand, almost a third of the households that relied on portable gas appliances for home heating reported problems with mould (BRANZ, 2022).

Ductless (or split) systems are common retrofit options as installation does not involve extensive ductwork. These systems are also good options for room additions in detached dwellings and multifamily residential units, where ductwork installation for a central air-conditioner is not feasible. Multisplit units, where several indoor units are linked to a single outdoor compressor unit, are also becoming more common.

The most common cooling choices in Australia are (DCCEEW, 2022b):

- ceiling, pedestal, and personal fans (low to medium capital cost)
- electric reverse-cycle air-conditioners (medium to high cost)
- electric evaporative cooling (medium to high cost)

Air-conditioner energy efficiency has improved by 50 per cent over the last ten years (Energy Rating, 2021a). Residential air-conditioners in Australia have been subject to MEPS since 2004 and sizes up to 65 kW have been regulated since April 2020. From October 2022, air-conditioners above 65 kW will need to meet MEPS standard (Energy Rating, 2022). Evaporative coolers, though costly to purchase, use only 50 per cent of the energy used by air-conditioners. However, these work better with low humidity. Effectiveness diminishes with high humidity and extreme temperatures. Evaporative cooling systems require air outlets or open windows, which potentially add to air leakage sources.

The estimated and projected trends for categories of household energy use are presented in Figure 6, adapted from Ryan and Pears (2019). Space conditioning trended down with better housing standards, and the shift from natural gas use for heating and cooling to reverse-cycle air-conditioners saw rapid improvements to MEPS up to 2011 (Ryan & Pears, 2019).

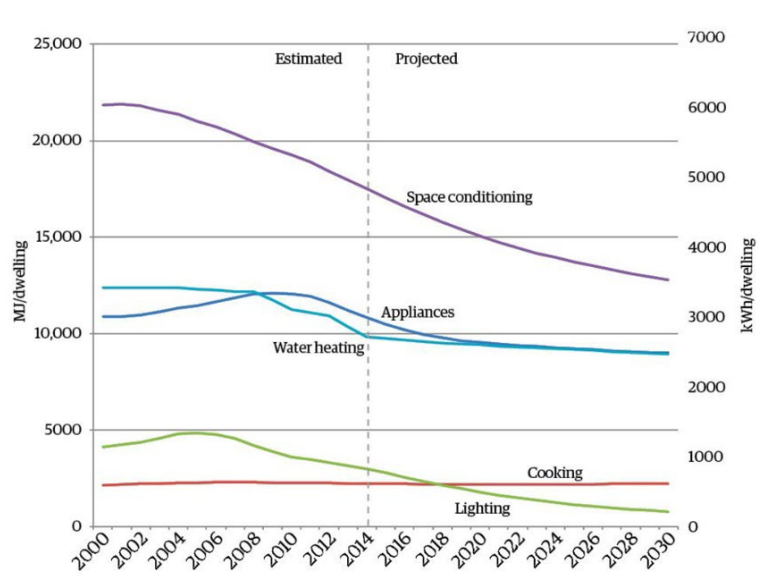


Figure 6. Trends in categories of the total energy per dwelling by end-use (Ryan & Pears, 2019)

With the proposed increase in the minimum Star rating, space conditioning loads for new housing are anticipated to drop even further. Trends in household air-conditioning systems will be influenced by policies concerning climate change abatement, reduced reliance on fossil fuels, and promoting further adoption of

rooftop solar PV systems (for example, through financial incentives). Policies in these areas can intersect to support greater reliance on electricity rather than natural gas for heating, leading to heat pumps as the logical choice. Furthermore, reverse-cycle heat pumps can be used for both heating and cooling, with the latter powered in part or fully by rooftop solar systems. Higher gas prices could accelerate this transition to electrification.

Figure 7 shows the average energy per household in 2014 for space conditioning for different types of heating and cooling systems in various states. In cooling dominated states, energy use is mainly for heating. In Tasmania, 31 per cent of households use wood heaters and gas ducted heating, whereas in Victoria and ACT 46 per cent of households use these modes. Tasmania, though colder than Victoria, uses lower heating energy due to high use of electric heating with higher efficiency in comparison to gas heating in most Victorian homes. The ACT government is proposing legislation (ACT Legislative Assembly, 2022) that would make heat pump electrification a requirement in all new dwelling developments. The Victorian government is refocusing its incentive programs towards heat pumps and has recently unveiled a Gas Substitution Roadmap (DELWP, 2022). Other states and territories are also reviewing their policies. It is estimated that heat pumps can save 60-85% of energy costs (Pears, 2022b), relative to electric fan heaters or traditional electric hot water services, which are similar to ACT Government (2021) estimates. Comparisons with gas are tricky as efficiencies and energy prices vary considerably. If excess solar output from the rooftop is used to run heat pumps, the energy cost will be up to 90 per cent cheaper than gas. Where 100 per cent electrification is not viable, such as in very cold climates, a majority of the heating load requirement can be met with electricity, and the rest can use fuel backup, resulting in big savings (Commonwealth of Australia, 2022b).

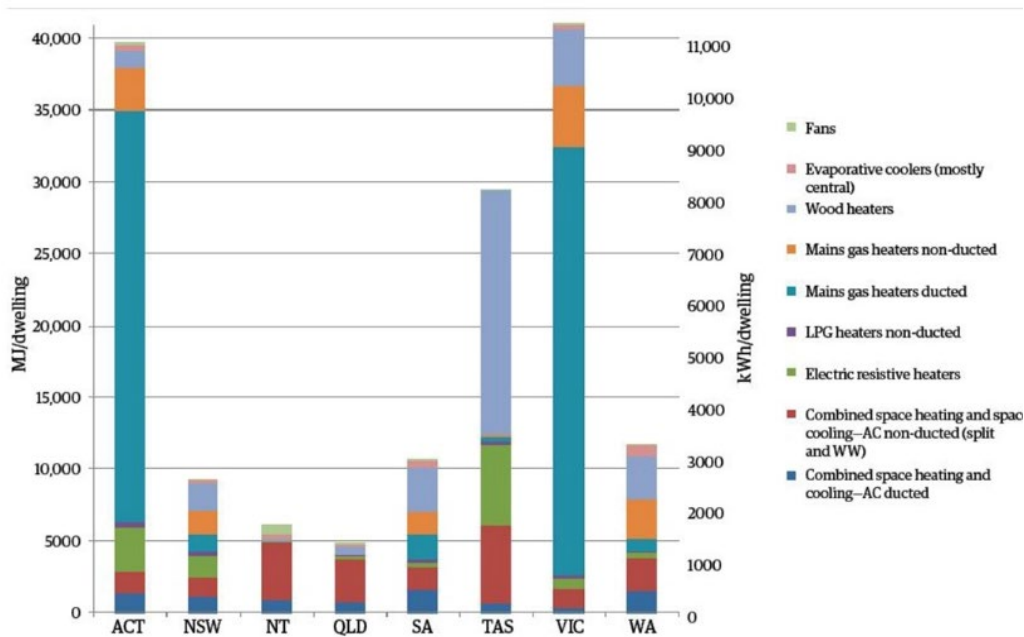


Figure 7. Space conditioning average energy use per household in 2014 (Ryan & Pears, 2019)

5.3.2 Exhaust fans and extractor fans

Exhaust fans remove moisture and help to control and eliminate odours. Good exhaust fans will use high performance motors and improved blade designs, operate quietly producing less noise, and seal shut automatically when not in use. For removing excess moisture and pollutants produced in kitchens and bathrooms, exhaust fans or extractor fans (in range hoods) should be ducted effectively to the exterior instead

of into the attic or cavity space. In contrast to other balanced systems (for example, energy recovery systems), exhaust fans only remove air from inside; they do not bring in fresh air from outside. NCC Vol.2 (2019d), Clauses 10.8.2 and 10.8.3, state that an exhaust system installed in a kitchen, bathroom, sanitary compartment, or laundry must have a minimum flowrate of: (i) 25 L/s for a bathroom or sanitary compartment; and (ii) 40 L/s for a kitchen or laundry. Victorian Building Authority has reported an increase in the number of complaints received about non-compliant discharge of exhaust fans (VBA, 2022), where incorrect discharge can cause condensation, and lead to mould growth and degradation of structural members. When the fan is not self-closing, heated air can escape, even when the fan is not in use. This is problematic in winter when heat needs to be retained (Sustainability Victoria, 2022a). In Victoria, under the Victorian Energy Upgrades program (Sustainability Victoria, 2015), households can have exhaust fans covered and sealed with draft stoppers for free, to maintain specific humidity and temperature levels inside their homes. However, exhaust fans can contribute to higher heating and cooling costs compared with mechanical heat/energy recovery ventilation systems (HRV/ERV) because exhaust or extractor fans do not remove moisture from the make-up air before it enters the house or recover heat (or coolth) from exhaust air. There are two main things to consider in selecting exhaust fans: noise, and the rate of airflow. The greater the rate of airflow, the noisier the fan would typically be, though improved fan design can reduce noise.

However, these systems can depressurise spaces in the home, which pulls unconditioned outdoor air in through cracks around doors and windows. Noise is an important consideration for selecting and using exhaust fans. Fans that are rated for quiet and continuous operation are available, running at low levels all the time, and when needed run at higher levels. The ENERGY STAR label in the USA measures fan performance in terms of flow rate and noise level in controlled conditions (Energy Star, 2022a). ENERGY STAR labelled exhaust fans are available in Australia. For Australian products, similar testing capacity is required.

5.3.3 Heat/energy recovery ventilation

Mechanical ventilation with heat recovery (HRV) supplies fresh filtered air into the building and simultaneously extracts damp, stale, or contaminated air without losing energy. There are two types of HRV systems: centralised, which uses a single large HRV unit with a duct network, and decentralised, which uses multiples of small through-wall HRV units without ductwork (Seagren, 2019). Centralised HRV systems are generally better performing than decentralised systems due to the ability to locate grilles for the best ventilation outcome. Well-designed, installed, maintained, and used HRV systems can make useful contributions to energy reduction and good ventilation. In the UK, a significant number of buildings use HRV systems though these are not widely used in Australia. Sharpe et al. (2016) undertook an assessment of HRV systems in the UK and found that many of the projects using these systems had several problems that would undermine the intended benefits. Common problems included: insufficient system air flow and system imbalance; lack of appropriate airtightness; poorly designed and installed ductwork; lack of occupant handover and understanding; and inadequate maintenance, in particular filter cleaning or replacement. There was clear dissatisfaction with the installers' procedures and competence, and quality of ductwork installed. Training and guidance are required during the handover stage to induct residents in how to use, operate and control the system. The most common problems at installation or commissioning stages include poor installation, and imbalance between supply and extract airflows (Sharpe et al., 2016). Other problems included airflow blockages, difficulty in commissioning the systems, and too high fan speeds. In addition, occupants concerned about the operating cost of the HRV systems tended to disable the units. High cost of running the system was a common perception among occupants. Occupants were also concerned about system service discontinuity and high

noise level. High temperatures and overheating were also experienced in several projects. In summary, HRV systems offer improved air quality, condensation management, and energy savings. But product quality, competent installation, effective user management, and user-friendly monitoring/feedback systems are critically important.

5.4 Electrification using renewable technologies

Electrification means shifting to use electricity rather than fossil fuels for heating and cooking. Such transition leads to all-electric buildings powered by solar, wind, and other sources of electricity. Electrifying an average household typically involves installing solar panels on the roof and replacing gas appliances with efficient electric models. As buildings that consume low energy are easier to electrify, energy efficiency is an important step toward fully electrified buildings (Cui et al., 2021). However, full electrification is easier and cheaper in new buildings compared to old buildings. Whenever gas appliances break down, they could be replaced with electric alternatives.

Heat pumps (hot water systems and reverse-cycle air-conditioning units) are the enabling technology of widespread building electrification, and paired with solar are a popular way to reduce grid reliance. Rooftop solar is a mature technology if storage is not a factor. Almost 390,000 rooftop solar systems were installed in 2021, and there are now more than 3 million solar homes in Australia – one in three Australian households (Clean Energy Council, 2022).

Ground-source heat pumps (GSHP), also called Geothermal Heat Pumps, use the ground as the heat source or heat sink via pipes placed either vertically or horizontally into the ground. These pipes are known as Geo-loops and they usually circulate water or refrigerant around the loop. Australia's uptake of ground source heat pumps is slow, due to a lack of government policy and the lack of standards for this technology in Australia (meaning it cannot be part of the technologies considered for certificates under the Renewable Energy Target or state mandatory energy efficiency schemes). GSHP installation remains expensive for most residential applications in Australia and uptake is still limited (Wyndham et al., 2020). Although both GSHP and Air Source HP technologies have similar performance in many Australian climates, the disparity in installation cost of GSHPs in Australia is four to seven times as much as Air Source HPs, which do qualify for government rebates (Radiant and Heating Cooling Solutions, 2020). As GSHPs are a mature technology used in other countries to efficiently heat and cool homes, it is recommended that work is undertaken to develop Australian standards, or to adopt suitable standards from overseas (for example, EU, USA or Canada).

Solar hot water and heat pumps are two renewable options for heating water. A solar hot water system uses heat directly from the sun. There are many things that determine household preference for either option. When deciding between a solar hot water system and an electric heat pump, the important factors to consider include initial and running costs, environmental benefits, how it works with existing power supply, and reliability. Solar hot water systems may be completely solar-powered during warmer months, but usually cannot collect enough solar energy to heat water during winter and will therefore need a booster powered by either gas or electricity. Households with a photovoltaic (PV) system installed on roof can use any excess solar electricity generated throughout the day to run a hot water system.

There are many challenges to full electrification. The biggest barrier for most households is the upfront cost of replacing gas appliances, which requires access to affordable capital or grants. A recent report by the Climate Council (Tidemann, Rayner, et al., 2022) noted that disconnecting from gas network can also be expensive and

time consuming, and governments should consider regulations for ending gas connections in homes.

Tidemann, Rayner, et al. (2022) suggested undertaking community-level pilots, and collaborative planning involving different levels of government, will give residents more control over their energy future. Indeed, this is one of the pilots being considered by the RACE project, Energy Upgrades for Australian Homes, to quantify the metrics around costs to electrify homes currently reliant on gas for heating and hot water in particular. Furthermore, it is possible to make sure many will benefit from such a scheme by investing in large-scale Australian manufacturing of heat pumps and other all-electric equipment, supplemented by upskilling the workforce to work with the latest all-electric appliances, including construction workers, electricians, and plumbers.

5.5 Smart home systems

A smart home automation system (also known as a Home Energy Management System, or HEMS), allows Wi-Fi enabled devices to work together to reduce energy consumption, lower energy bills, and increase occupants' thermal comfort. HEMS allows occupants to experience improved services within the home, such as comfort in the form of remote operation of systems and appliances (for instance, turn on heating or cooling device/s either to pre-cool or heat outside peak times, or to cool or warm the home before returning). HEMS also provide convenience (for example, automatic maintenance, turn on devices remotely), and home security and safety (such as light sensors and alarms) (Pears & Moore, 2019). In addition, HEMS has facilitated the emergence of sophisticated data analytics and artificial intelligence, resulting in increased use of smart home technologies to further simplify home operation. Home automation in Australia is rapidly expanding. The average Australian household had nine Wi-Fi connected devices in 2015, expanded to 17 in 2018. By 2022 the number was expected to reach 37 (Zaluzny, 2020). The number of active Australian households in the smart home market is expected to be 7.8m users by 2026. Household penetration is expected to hit 69.3 per cent by 2026, up from 38.1 per cent in 2022 (Statista, 2022). Connected devices can control almost any type of internet-enabled equipment. Most relevant for energy are for heating and cooling, hot water, lighting, and appliances (Dwyer, Wilmot, et al., 2020). Though smart homes offer potential to save energy, many studies have found no evidence for energy saving (Hargreaves et al., 2018; Nicholls et al. (2017)), possibly due to lack of education around energy intensity and or peak tariff times. Indeed, there is a risk they may generate forms of energy intensification (Nicholls et al., 2017).

Nicholls et al. (2017) conducted personal interviews with 40 households in Victoria and South Australia, finding that participants who had smart home devices made either limited or no use of the devices to manage energy use. The study also found participants were often confused about time-of-use tariffs, but even those with an understanding of peak vs off-peak rates generally did not use the devices to shift energy use to cheaper times, mostly due to smart home marketing promoted as a lifestyle benefit rather than for energy management. They also found that the more devices available, the tendency was to use these more often. Although these devices may be super-efficient, new additions for more homes may add up to more energy demand overall, unless information at point of sale includes energy usage education and peak tariff times. Therefore, the hidden impacts of these devices should be carefully researched as governments and households embrace these technologies which are promoted for their energy-saving benefits (Strengers et al., 2016). The HEMS industry needs assistance to include energy usage and electricity peak time information at point of sale, so that owners can benefit from reduced energy bills as well as increased thermal comfort.

6 State of Current Research

This section reports on the systematic review of current research on home thermal efficiency, thermal comfort, heat-related vulnerability, and health impacts. Standardised house energy retrofitting policies which have minimal consideration for occupant profiles can widen the performance gap between actual and estimated energy consumption. Consequently, it is necessary to understand specific occupant profiles to provide more user-centric energy retrofitting policies. Australia has an ageing population and many of this cohort have health issues and disabilities. Over time, these factors combined with climate change impacts and other life changes, may affect health requirements relative to a home's ability to provide appropriate conditions.

In this section, the term *vulnerability* will be used to provide clear scope for the review. An overview will be presented of recent field research on two vulnerable groups in the built environment: the elderly, and those in social housing and rented accommodation. The section will also explore thermal comfort, one of the most frequently researched home thermal efficiency topics, considering adaptive comfort for energy-saving, winter underheating, and summer overheating. The interventions for heat management will be examined and health impacts reviewed in detail. Finally, the section presents emerging research about cost-benefit analysis of improved thermal performance.

6.1 Good home thermal performance

Thermal performance is the amount of heating or cooling required to make a home a 'comfortable' space to live in. Good thermal performance of a home involves maintaining appropriate, healthy, and comfortable conditions for occupants under the range of environmental conditions which the building is exposed to. Health, as defined by the World Health Organization, is 'a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity.' Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ASHRAE, 2020). Health, as defined by the World Health Organization, is 'a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity.' In many cases, occupants may prefer higher levels of thermal comfort throughout larger areas within their homes than those necessary to maintain health. Recent research has focused on the concept of 'refuge rooms' that allow occupants to access a limited area of the home that is capable of reliably maintaining, at affordable cost, safe thermal conditions during extreme weather conditions. This is an extremely important concept for financially vulnerable households living in thermally inefficient housing.

The building shell is not the only factor impacting on thermal health and comfort. Other factors impacting internal thermal temperature include layers of clothing, level of physical activity (that generate heat internally), age, some medical conditions (for example, multiple sclerosis can affect ability to maintain a safe temperature), and user management of the building and space conditioning equipment. Key factors and parameters that affect thermal comfort as per Fanger's (PMV) model are described in Figure 8.

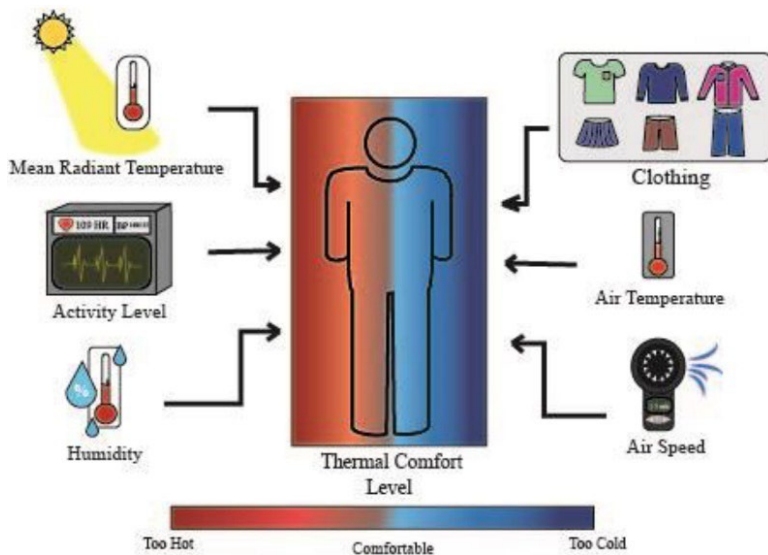


Figure 8. Six factors contributing to occupant thermal comfort in Fanger's (PMV) model (Ghahramani et al., 2020)

The assessment of 'comfortable conditions' is a substantial area of research and practice, with Australian thermal comfort researchers such as Professors Steven Szokolay (Szokolay, 2014), University of Queensland and Professor Richard De Dear, University of Sydney (De Dear & Brager, 2001) making major contributions some of which are discussed in Section 6.3.

6.2 Vulnerability

Vulnerability is broadly used in many disciplines, such as public health, energy policy, and disaster management. More recently, vulnerability has been reconceptualised as a complex and flexible phenomenon that occurs within a range of structural, individual, and market-based circumstances (ECA, 2022). Some population groups are especially vulnerable in certain conditions, including children, the elderly, people with disabilities, and those with chronic illnesses. From the energy market perspective, in broad terms consumer vulnerability refers to circumstances that make it difficult to use markets or receive adequate products and services, and create risks of harm, detriment, or disadvantage (O'Neill, 2019).

Energy poverty and income poverty are distinct but closely intertwined problems. For some households, poverty is exacerbated by energy costs, and for other households, energy costs are what pushes them into poverty (Burlinson et al., 2018). Ofgem (2019) defines vulnerability as when a consumer's personal circumstances and characteristics combine with aspects of the market to create situations where they are significantly less able than a typical domestic consumer to protect or represent their interests, significantly more likely than a typical domestic consumer to suffer detriment, or that detriment is likely to be more substantial. Consumers in a vulnerable situation are more likely to face multiple barriers compared to other customers. With regards to energy efficiency, many considerations can affect a person's ability to engage with the customer service function of an energy company, including mental health, age related vulnerabilities, disability, and low-income (Ofgem, 2019). The term 'vulnerability' however can cause shame or embarrassment when people seek assistance, such as contacting their energy provider, bank, and/or landlord to seek bill assistance. In the same vein, vulnerable people may consciously choose not to use appliances that maintain health and comfort because they fear being unable to pay the operating costs, leading to what is termed 'fuel poverty.' Fuel poverty is not usually associated with Australia, but more with countries where there are

extreme climatic conditions and thermally-poor housing stock. However, this situation has reversed since privatisation of Australia's energy assets in the 1990s, increased energy costs for electricity and gas use in homes in the 2000s and increasing thermal impacts of climate change. Across Australia, almost three million households receive financial assistance for their energy costs in the form of concessions or rebates on their electricity bills, with this assistance intended to ensure people on low incomes or experiencing financial hardship can pay their energy bills without forgoing other essential expenditure. Yet too many people in Australia cannot afford to pay for the energy they need, leading to one or more damaging outcomes (ACOSS, 2022). Recent research by Energy Consumers Australia (2022) showed that more than 28 per cent of people struggled to afford their energy bills in the past 12 months, and this number is likely to rise with 37 per cent of respondents anticipating difficulties in paying their bill during the next few years. The survey also revealed that some households are taking extreme action to decrease their energy use and minimise costs, including cutting back on heating and showering every second day. These extreme measures are very concerning and show many people lack access to affordable energy, so impacting their ability to live comfortably, safely, and securely. In addition, recent research has identified that Australia's housing stock has an average Star rating of 1.8 – particularly homes, strata developments, and apartments built before introduction of energy efficiency standards in the NCC.

The concept of resilience can provide an opportunity to avoid perceived implications of using the term 'vulnerability' (ECA, 2022). In this review, the term of vulnerability focuses on heat-related vulnerability due to lack of capacity to cope and adapt in housing, including homes occupied by the elderly and social housing. A particularly vulnerable group can be older people. People over 65 years of age are generally classified as 'older' by the Australian Bureau of Statistics.

January 2009 saw a record heatwave in Victoria. More than 100,000 homes were left without power as air-conditioning demand soared (Dobbin & Dowling, 2009). More than 370 people died from heat stress (Cooper, 2009), with the majority of deaths occurring among those aged 75 years or older, representing a 64 per cent increase in mortality (Department of Human Services, 2009). A year later, the Victorian branch of the Australian Medical Association recommended that the state government introduce cooling subsidies for domestic air-conditioners to mitigate heat stress among the elderly. In recent years, extensive public health campaigns have increased awareness of the risks of heat for elderly people in Australia (Bills, 2016), and international researchers have examined thermal conditions in homes where elderly people live that are usually considered to be old houses, or social housing with poor thermal performance and/or limited heating/cooling appliances (Ahrentzen et al., 2016; Miller et al., 2017).

In the global context, Lomas et al. (2021) assessed summertime overheating in 750 English homes and found that households with occupants over 75 years of age significantly under-reported the prevalence of overheating compared with monitored results. The prevalence of monitored overheating was greater in households living in social housing in which occupants are more likely to be people on low incomes or over state pension age. Serrano-Jiménez et al. (2020) evaluated indoor environmental quality in naturally ventilated multifamily social housing occupied by elderly people in Spain (Mediterranean climate). It was found that elderly occupants frequently suffer from unhealthy carbon dioxide concentrations, and from temperature values outside the established comfort range. Escandón et al. (2019) evaluated thermal comfort conditions and energy consumption in social housing in southern Spain during summer and found occupants were in discomfort conditions during a high percentage of occupied hours, mainly due to the severe climate and the unsuitable use of passive measures, including natural night-time ventilation.

In the Australian context, although the focus of thermal comfort studies is usually on winter conditions, the impact of extreme summer temperatures is becoming increasingly important, particularly in densely populated urban centres with the heat created from people, buildings, and transport trapped between buildings. However, it is not only these homes which are experiencing more extremes in internal temperatures; research suggests our average temperatures and sea levels will continue to rise, and Australia will experience more days of extreme heat in summer, and drought periods over southern Australia will be longer (CSIRO & BOM, 2020). Further research on how urban heat island impacts energy consumption and thermal comfort in various Australian climates is recommended.

Despite the difficulty of managing both underheating and overheating, it seems to be more difficult for older Australians to deal with the summer heat than the winter cold due to less capacity to cope with extreme hot days (Porto Valente et al., 2021). Bills (2016) examined the thermal practices of Australians over 65 years of age in Adelaide during extreme cold days in winter, and extreme hot days in summer; Bills reported that occupants find thermal comfort conditions comfortable at cooler temperatures in winter than predicted by comfort standards (ASHRAE, 2020; ISO, 2005), and they rarely reported comfort at warmer temperatures than predicted during hot summer. Another study examined the impact of energy poverty on older Australians who primarily rely on the government age pension for their income; the study drew on 23 in-depth, semi-structured interviews with older Australians in Sydney and Melbourne (Porto Valente et al., 2021). Baker et al. (2019) found many older Australians live in old, less energy efficient homes: 78 per cent of older Australians' homes were 25 years old or more (Australian Housing Conditions Dataset). Older homes are difficult to heat or cool adequately, and challenging for people less tolerant of extreme temperatures (van Hoof et al., 2017) and more likely to have health issues such as heart disease and high blood pressure.

Interestingly, the elderly who live in Mediterranean climates, where the focus of public health is much more on heat conditions than cold in mild winters, express more thermal discomfort, stressing the importance of heating in winter (Bills, 2016; Giamalaki & Kolokotsa, 2019). This is because houses in these climatic conditions are not designed for colder conditions, with few houses equipped with central heating systems and mainly relying on portable or local fixed heating appliances. Consequently, elderly people would consider heating in winter to be more important than cooling in summer as heating costs would be higher than cooling costs in Crete, Greece (Giamalaki & Kolokotsa, 2019). A summary of the research reviewed on vulnerable groups – elderly people and people living in social housing – is shown in Table 10.

Table 10. Vulnerable groups – social housing and the elderly

Authors	Year	Study	Location	Type	Sample
Lomas et al.	2021	Summertime overheating	England	Measurements and survey	Logs from 750 households
Serrano-Jiménez et al.	2020	IEQ in social housing with elderly occupants	Southern Spain	Measurements	3 multifamily apartments
Escandon et al.	2019	Thermal comfort and energy performance in summer	Southern Spain	Measurements and calculation	3 housing units (indoor conditions and energy consumption)

Giamalaki & Kolokotsa	2019	Seasonal thermal sensation of elderly people	Greece (Crete)	Survey, interview, and inspection	30 older adults (15 female and 15 male subjects)
Porto Valente et al.	2021	Energy poverty, housing, and health	Australia	Semi-structured interviews	23 low-income older Australians
Daly et al.	2021	Indoor temperatures and energy use	Australia	Energy ethnographies, home energy audits, and longitudinal monitoring	50 homes
Bills	2016	Cold comfort	Australia	Measurements and survey	10 households (4 men and 7 women)
Hansen et al.	2022	Thermal Environment impact on housing and health	Australia	Measurements, calculations, and survey	57 houses (71 participants)

6.2.1 Elderly people

Ageing populations are globally recognised as important due to increasing pressure on health and social services. In Australia, the proportion of the population aged 65 years and over increased from 12.3 per cent to 15.9 per cent over 20 years between 1999 and 2019. This group is projected to increase more rapidly over the next decade, as further cohorts of baby boomers turn 65 (ABS, 2019). Furthermore, the older population is itself aging. The oldest-old group (80 years of age or more) is growing even faster than older persons overall. The number of people aged 85 years and over increased by 117.1 per cent from 1999 to 2019, compared with a total population growth of 34.8 per cent over the same period (ABS, 2019). Globally, it is projected that in 2050 the oldest-old will triple compared to 2015, and the older population is more likely to live in urban than rural areas (UN, 2015).

Elderly people naturally prefer to age in their homes, not residential institutions. It is therefore necessary that the thermal environment in their homes provides comfort to maintain their health, as thermal discomfort is unpleasant and may cause health risks among vulnerable people (Soebarto et al., 2021). Although older people tend to own a house outright, these houses often fail to meet current standards; they report outdated heating systems, low or no insulation, single glazing, and draughty doors and windows (Hamza & Gilroy, 2011). As they increase in age, this cohort tends to spend most of the time at home due to their lower mobility, leading them to more sedentary lifestyles that generally require a higher winter indoor temperature (Hughes et al., 2019).

While thermal comfort is one of the most researched topics among age-related research in the built environment, there are inconsistencies in the results. Some studies reported that older people have different preferences and perceptions of thermal comfort than younger people, and others found no significant age differences. The current standards and guidelines on thermal comfort, such as ASHRAE Standard 55 (2020) and ISO 7730 (2005), consider occupant age; however, the neutral temperature is taken to be constant among different age groups with no specific guidance for the elderly. EN 16798-1:2019 (CEN 2019) specifies indoor environmental input parameters for design and assessment of energy performance of buildings, indicating the

high level of expectation for very sensitive and fragile persons, including the elderly. Given inconsistent results, an interesting question has been raised as to whether current thermal comfort standards and guidance are suitable for advising thermal comfort temperatures for elderly people. These may significantly overprescribe comfort temperatures (Hughes et al., 2019) and could represent an ethical dilemma: if healthy occupants are comfortable at low temperatures, should they be encouraged to increase internal temperatures up to current standards (Hughes & Natarajan, 2019)? Section 6.3.2 discusses acceptable indoor temperatures for elderly people during winter.

6.2.2 Social housing

The relationship between extreme weather conditions, low thermal efficiency of housing, and health risks are well-established in low-income households. There is a higher incidence of poor health (both physical and mental) among the energy poor populations of most countries, compared to non-energy poor households (Thomson et al., 2017). Australia is no different. A 2019 Australian study (Haddad et al., 2019) examined 106 low-income social housing in NSW and found that monitored indoor air temperature during summer exceeded comfort limits, reaching 39.8°C. The study also identified both house performance and occupant health issues; mould and condensation were reported for 42 per cent of dwellings and residents suffered from health symptoms such as allergies and psychological disorders. A recent paper reporting results from surveying residents of 94 apartment units in high-rise social housing in Melbourne (Jara-Baeza et al., 2023) found residents were least satisfied with indoor summer temperature.

Porto Valente et al. (2021) stated that although thermal discomfort has usually focused on winter temperatures, the impact of extreme summer temperatures is more pertinent in cities such as Sydney and Melbourne. Based on semi-structured interviews with older Australians in Sydney and Melbourne, the authors found it was more difficult for older Australians to deal with summer heat than winter cold. Daly et al. (2021) investigated indoor temperatures and energy use in NSW social housing and found that many homes operated outside World Health Organisation (WHO) (2007) healthy temperature recommendations for substantial periods during both winter and summer. This study also found that many participants made the choice between thermal comfort and manageable energy bills. It is noteworthy that many of the residents in social housing are elderly, thus most of the research reviewed concerns elderly people in social housing. Research needs to be structured so that findings across age groups can be compared and, where warranted, differentiated interventions can be proposed.

6.2.3 Private rentals

As discussed in section 4.3.4, the existing minimum energy performance standards for rental properties in Australia are insufficient. A study by Better Renting (Dignam & Barrett, 2022a) during winter months found temperatures were below the minimum threshold of 18°C for 75 per cent of the time. The study found ACT rentals had the country's coldest average minimum temperature at 7.4°C, with an average overall temperature of 14.2°C. A similar study in summer (Dignam & Barrett, 2022b) found that rental homes routinely exceed safe temperature limits, with indoor temperatures above 30°C for about an hour a day on average. Night-time temperatures were hot enough to impair sleep almost 50 per cent of the time. There are calls from bodies such as Australian Council for Social Service (ACOSS) to make air-conditioning mandatory in Australian rental properties. However, this can be detrimental because of unaffordability, heightened costs, and environmental impacts.

ACEEE's Energy Equity for Renters Toolkit ACEEE's Energy Equity for Renters Toolkit (Jarrah & Tanabe, 2022) offers guidance to local government and stakeholder groups on how to integrate energy efficiency and affordable housing policy. Showcasing multiple case studies, the Toolkit also discusses strategies for effectively engaging property owners, buildings staff, and renters on energy efficiency. Some of the initiative included financing of retrofitting with the inclusion of utilities. This assisted in extending the impact of local governments' limited energy efficiency funds. Utilities recover their investment under the tariff's terms via a fixed charge on the utility bill for each upgraded location. This model also avoids the landlord-renter split incentive because the utility covers all or most of the upfront cost, and the renters' energy savings support cost-recovery fees offers guidance to local government and stakeholder groups on how to integrate energy efficiency and affordable housing policy. The Rocky Mountain Institute (RMI, 2022) has created an action guide to equip policymakers with the resources needed to understand, design, implement, and administer efficiency standards for residential rental properties in their jurisdictions. Separated into three phases (Prepare, Implement, and Administer) this guide can build upon rental licensing policies. Extensive research is required to improve the thermal performance of rental properties in Australia.

6.3 Thermal comfort

6.3.1 Adaptive comfort for energy-saving

International research has aimed at reducing energy consumption for heating and cooling in the building sector with less sacrifice to occupant thermal comfort. Table 11 summarised recent research on adaptive comfort and energy-saving. One approach is to re-examine the ASHRAE adaptive model (ASHRAE, 2020) as it has been extensively tested in non-residential buildings, not homes. Bienvenido-Huertas et al. (2021) argued that the current adaptive thermal comfort model and standards cannot capture the particularities of certain cultures and climates due to the limitation of the database, and there is a necessity for soft approach-based policies to overcome the wide technological gap between countries in Europe. The authors concluded that standards for adaptive thermal comfort, ASHRAE 55- (2020) and EN 16798-1:2019 (CEN, 2019), can be applicable to guide a transnational policy towards reducing cooling and heating energy consumption. When compared with a static setpoint temperature of 15.5°C, heating energy savings from applying ASHRAE and EN standards to temperature settings are estimated to be around 35 per cent. For cooling, savings would be 13-55 per cent and 5-27 per cent, when compared with temperatures of 22°C and 18°C respectively.

A Japanese study demonstrated that the adaptive thermal comfort model is strongly supported by various adaptive mechanisms that enable residents to regulate the thermal environment (Rijal et al., 2013; Rijal et al., 2021). While the comfort temperature in free running mode in detached houses was 26.1°C in summer, and 15.6°C in winter, the mean comfort temperature is 25.6°C in summer and 19.8°C in winter in multiresidential buildings. The seasonal temperature difference was smaller in multiresidential buildings (5.8K) than in detached houses (10.5K), which could be related to differences in thermal design between the two building types. The authors stated changing temperature settings can reduce energy use for heating and cooling, and further adaptation such as passive building design and clothing adjustment can achieve energy savings (Rijal et al., 2021).

An Australian study on adaptive thermal comfort model for homes in temperate climates of Australia reported that occupants in temperature regions accept cooler temperature conditions than a traditional thermal sensation measure (Williamson & Daniel, 2020). The authors argued that currently specified 'acceptable'

indoor conditions in NatHERS are likely to give a misleading impression of how well the dwelling’s performance meets residents’ comfort preferences. Rajagopalan et al. (2020) predicted indoor heat stress and peak cooling energy for low-income housing in Australia using outdoor conditions. Indoor discomfort index (DI) values calculated inside living rooms and bedrooms were below heat stress limits ($DI < 28$) when Bureau of Meteorology (BoM) data was used. However, indoor DI exceeded the threshold when actual on-ground data was used. Peak cooling increased by 24 per cent when on-ground data was used. This is because microclimates around buildings are different from those recorded at BoM stations. It is recommended that along with energy performance, occupant thermal comfort also should be incorporated in current standards and guidelines.

Table 11. Adaptive comfort for energy-saving

Authors	Year	Study	Location	Type	Sample
Bienvenido-Huertas et al.	2021	Adaptive thermal comfort	EU (Mediterranean area)	Calculation	Climate data from 32,564 locations
Zeng et al.	2022	Pre-cooling during heatwaves	USA (California)	Building energy simulation	Building-scale and district-scale simulation
Rijal et al.	2021	Adaptive thermal comfort	Japan (Tokyo and Yokohama)	Measurements and survey	19,081 thermal comfort votes from 94 residents of 69 flats
Rijal et al.	2013	Adaptive thermal comfort	Japan (Gifu)	Measurements and survey	40 male and 38 female occupants from 30 houses
Williamson & Daniel	2020	Adaptive thermal comfort	Australia (temperate regions)	Measurements and calculation	37,490 votes from 245 houses
Rajagopalan et al.	2020	Indoor heat stress and peak cooling energy	Australia	Measurements, simulation, and calculation	81 field experiments across 26 precincts

6.3.2 Winter underheating

There is an increasing body of research that has investigated the association between indoor thermal conditions and elderly people in their homes. WHO provided one of the earliest guidelines on acceptable indoor temperature to protect elderly people (Hughes et al., 2019). It was recommended that an acceptable minimum indoor temperature can be 18°C in general, and 2-3°C warmer (that is, 20-21°C) for rooms occupied by sedentary elderly, young children, and people with disabilities (Collins, 1986). Hughes et al. (2019) examined 43 homes occupied by older people (65 years and over) in south-west UK to obtain evidence on actual and preferred indoor temperatures. Of homes in the area, 30 per cent are pre-1919 buildings, usually single-glazed,

solid walled dwellings, and it is less possible to make home improvements due to legal protection. Longitudinal indoor temperature monitoring found only 30 per cent of monitored homes met the WHO recommendation for elderly people of temperature between 20°C and 21°C, and 70 per cent met the minimum threshold of 18°C.

Furthermore, to investigate strategies for deal with the cold, Hughes and Natarajan (2019) interviewed elderly residents from seven homes in the UK where internal temperatures were below the WHO threshold of 18°C. Heating duration per day in the homes of the people interviewed was much shorter than the entire sample of 43 homes. Coping strategies used by older people in winter included heavy clothing, exercises, additional heat sources, physical alterations to the home, and alternative routines. Although most of the interviewees would be willing to incorporate retrofit measures or new technologies in their homes, there were barriers such as unaffordable cost and fear of lack of control. Interestingly, although none of the homes in which interviewees lived met the WHO recommended temperatures, some residents self-reported as thermally comfortable.

A field measurement study on thermal environment in urban and rural houses in China in which elderly people lived found that urban houses maintained warmer and steadier indoor temperatures (Zhang et al., 2019). The urban houses had centralised heating systems in all functional rooms, whereas rural houses had decentralised heating systems only in bedrooms and kitchens as a result of which elderly occupants frequently experienced large indoor and outdoor temperature differences (Zhang et al., 2019). The average temperatures of living rooms, bedrooms of elderly residents, and toilet in urban households were $22.77\pm 0.58^{\circ}\text{C}$, $21.88\pm 0.48^{\circ}\text{C}$ and $22.29\pm 0.25^{\circ}\text{C}$, respectively. In rural houses, average temperatures of living rooms, kitchens, and toilets were $15.06\pm 1.81^{\circ}\text{C}$, $9.93\pm 1.46^{\circ}\text{C}$ and $-16.43\pm 4.90^{\circ}\text{C}$, respectively. However, most elderly who lived in rural houses did not express thermal discomfort despite living in colder rooms as they relied on heavy clothing and had lower comfort expectations. It could be interpreted that older people show less thermal sensitivity to cold or warmth than young adults due to physiological changes (Anderson et al., 1996; Yochihara et al., 1993). Giamalaki & Kolokotsa (2019) further identified that a greater proportion of elderly people felt cold in winter than warm in summer, and reported greater dissatisfaction with the thermal environment in winter than summer. Elderly people consider that winter heating is more important than summer cooling; consequently, their heating expenditure is higher than expenditure on cooling in a mild climate. A summary of recent thermal comfort research on underheating is presented in Table 12.

Table 12. Thermal comfort research on underheating in homes

Authors	Year	Study	Location	Type	Sample
Hughes, et al.	2019	Elderly thermal comfort	Bath, UK	Longitudinal indoor temperature monitoring and occupant survey	43 homes (pre-1919)
Hughes & Natarajan	2019	Elderly thermal comfort	Bath, UK	Interview	7 homes
Zhang, et al.	2019	Elderly thermal comfort	North-west China	Measurements and survey	5 urban and 10 rural houses
Giamalaki & Kolokotsa	2019	Seasonal thermal sensation of the elderly	Crete, Greece	Survey	30 older adults
Bills	2016	Thermal sensation and indoor temperatures	Adelaide, Australia	Measurements and survey	10 households

6.3.3 Summer overheating

Research studies have also been conducted on summertime thermal discomfort (overheating) in temperate climates where heating is dominant. Many studies indicate improved winter envelope performance can potentially increase overheating risk during warmer seasons, particularly when building elements are exposed to direct solar radiation. Ade and Rehm (2021) reported a consistent trend in New Zealand for newer housing to be warmer than older housing stock. Summertime temperature in newly constructed 6-Homestar certified dwellings was above the WHO recommended healthy temperature threshold of 24°C for 75 per cent of the time in summer months, resulting in predicted occupant discomfort 16 per cent of the time.

It seems likely that measures such as insulation and draft-sealing exacerbate the impact of summer solar gain and indoor heat generation from people and appliances. Recently, significant research progress has been made on summertime overheating in the UK. Lomas et al. (2021) measured the prevalence of overheating in the living rooms and bedrooms of homes during England's hottest summer in 2018. Weighting the results to the national stock revealed that 19 per cent of bedrooms and 15 per cent of living room were overheated. Overheating was more prevalent in bedrooms at night than in living rooms during the day. The prevalence of living room overheating was significantly greater in flats or apartments (30 per cent) than other dwelling types. Escandón et al. (2019) evaluated thermal comfort conditions and energy consumption in multifamily social housing in southern Spain during summer conditions. Three case study buildings were built between the 1960s and 1980s, and local thermal conditioning systems (reversible heat pumps) were placed in the living room or in the main rooms. The authors found that the percentage of hours that the local cooling systems were operated was less than 10 per cent, despite occupant thermal discomfort during a high percentage of occupied hours, due to users' socioeconomic characteristics.

In the Australian context, a recent study confirmed that monitored indoor air temperature during summer exceeded comfort limits, reaching 39.8°C in social housing in humid, subtropical Sydney (Haddad et al., 2019). Residents expressed more dissatisfaction with their home thermal conditions during summer than winter, with

62 per cent of residents reporting they were dissatisfied. Furthermore, the authors stated that the group over 60 years old was slightly more dissatisfied with their thermal conditions, and more sensitive to higher indoor temperatures (Haddad et al., 2019). Willand et al. (2016) examined the relationship between thermal performance rating, summer indoor temperatures, and cooling energy use in 107 Melbourne homes. The authors reported that regulation compliant 6-Star rated homes tended to be warmer, not cooler, in summer than lower rated homes under natural ventilation. Furthermore, Moore et al. (2017) examined low-energy house performance in comparison to current code-compliant house performance. They found that code-compliant houses were warmer than low-energy houses during summer. Indoor air temperatures in both living areas and bedrooms tended to be higher in code-compliant houses, reporting a larger difference in the living areas. A summary of recent thermal comfort research on overheating is presented in Table 13. It is noteworthy that the results of these studies are not consistent and are less generalisable due to short monitoring periods or small sample sizes. Detailed research is required to investigate thermal comfort of Star rated houses, with a focus on different demographic profiles during extreme summer days. Also, pilot projects on building improvements are required to analyse and trial their performance.

Table 13. Thermal comfort research on overheating in homes

Authors	Year	Study	Location	Type	Sample
Ade & Rehm	2021	Adaptive thermal comfort	New Zealand	Measurements and calculation	29 houses
Lomas et al.	2021	Summertime overheating	England	Measurements and survey	Logs from 750 households
Escandon et al.	2019	Thermal comfort and energy performance in summer	Southern Spain	Measurements and calculation	3 housing units (indoor conditions and energy consumption)
Haddad et al.	2019	Energy use, thermal comfort, and health	Sydney, Australia	Measurements and survey	106 households, 109 residents
Moore et al.	2017	Summer comfort and house performance	Victoria, Australia	Measurements and interview	10 homes
Willand et al.	2016	Thermal performance ratings and summer indoor temperatures	Melbourne, Australia	Measurements	107 homes

6.4 Interventions for heat management

Energy use and thermal comfort of homes are strongly dependent on occupant behaviour, as well as building design and climate. Adjusting setpoint temperatures can lead to energy savings in mechanically conditioned homes. However, some occupants prefer more economical adaptive options over technology/energy-based ones. Giamalaki & Kolokotsa (2019) reported that window openings (57 per cent) are the most common adaptive behaviour for elderly people when they feel hot in summer. In winter seasons, clothing adjustment (73 per cent) is the most common behavioural action. This is consistent with previous research findings that the

elderly participants wore heavier clothing in winter and there was very little correlation between the level of clothing and thermal sensation in winter ($R^2=0.18$) (Bills, 2016). It seems that elderly people adopted low energy consumption strategies before using high energy-consuming methods such as portable heaters and fans. Furthermore, if rooms in the house were thermally unsatisfactory, these rooms were not used to avoid heating or cooling the space. This finding indicates that thermal conditions can influence use of spaces in homes (Bills, 2016).

6.4.1 Home design and services

It is still unclear whether homes that consume less energy are more comfortable than conventional homes in both winter and summer. Homes that incorporate passive solar design principles keep homes comfortable through different times of the year. For example, large north-facing windows (in the southern hemisphere) can allow winter sun to heat a home, but also allow overheating in summer unless effective shading is used. If designing the entire house for extreme heat is impractical due to budget constraints, transforming the naturally coolest room to a cool retreat provides a more affordable option. Also, planting deciduous trees next to windows will provide summer shade and allow winter sun.

While Ade and Rehm (2021) reported highly insulated dwellings can cause summertime thermal discomfort, Lomas et al. (2021) stated that improved fabric energy efficiency did not significantly increase overheating risk. A recent Australian study examined through simulation various residential housing construction scenarios in Sydney (Albayyaa et al., 2021). It found that a standard fibro house had the highest cooling and heating energy requirements (30,721kWh/year), and an improved reverse-brick veneer house had the lowest energy requirement at 9,628 kWh/year. The authors stated that passive solar and energy efficient strategies are more effective in reducing heating energy consumption, yet less effective in reducing cooling energy consumption (Albayyaa et al., 2021). Many Australian homes in temperate climates were not designed for cold conditions, particularly old housing stock. The current Australian building code (ABCB, 2019c, 2019d) on energy efficiency in home construction could improve thermal performance in cold conditions by adopting higher insulation levels and promoting passive design elements, but these may not be effective in hotter climates. Indeed, measures that improve winter performance could adversely affect summer performance, unless there is the ability for mechanical or human intervention (for example, opening windows to create cooling cross-flow ventilation).

Escandón et al. (2019) reported thermal discomfort conditions during a high percentage of occupied hours, mainly due to the severe climate and unsuitable use of passive measures including natural night-time ventilation and solar protection. The authors suggest that retrofitting proposals must include characterisation of the real user profile for the estimation of energy savings and return periods, instead of using standardised patterns. Bills (2016) reported that few houses have central heating; many have fixed heating only in the living area and rely on portable heating appliances for other rooms in Adelaide, Australia. Similarly, few houses, especially older ones, have whole house cooling, but may have individual reverse-cycle appliances (or similar) in living rooms and bedrooms. Serrano-Jiménez et al. (2020) found that elderly occupants in naturally ventilated social housing in Spain frequently suffer from unhealthy carbon dioxide concentrations, and from temperature values outside the comfort zone. The study promoted renovation plans focused on improving ventilation systems and incorporating elements that complement natural ventilation.

6.4.2 Pre-cooling

Increased use of air-conditioning in residential buildings can put a large load on electricity grids. During extreme heat weather events, the extra cooling load can cause high electricity demand that could lead to power outages. Pre-cooling is a strategy to control peak electricity demand by setting the indoor air temperature a few degrees lower for a period preceding the start of on-peak hours. The resulting lower indoor air temperature can, in principle, delay the start time of HVAC systems, reduce initial ‘cooling down’ demand, and reduce the running time during on-peak hours while maintaining occupant comfort as a result of thermal mass effect (Wang et al., 2020). It is an operational shift rather than a technological one requiring mechanical cooling (Arababadi & Parrish, 2015) to meet comfort demands.

This approach involves a trade-off. Pre-cooling utilises surplus power generated by renewables earlier in the day to lower ambient air temperature, shifting time of usage and reducing network load during the time of peak demand. The net outcome depends on the building’s thermal performance, and its thermal mass and the weather pattern on warm days. Over time, as the stored ‘coolth’ due to the thermal mass is dissipated, cooling energy demand trends towards the level it would have reached without pre-cooling.

The focus of the research has been on rule-based pre-cooling strategies to find out useful setback periods, setpoints, and setback temperatures. These studies examined the impact of building design and operating conditions such as building location, mass level, pre-cooling strategy, and time-of-use utility rate on the effectiveness of pre-cooling strategy (Arababadi & Parrish, 2015; Morgan & Krarti, 2007; Xu, 2009). It seems that, for the types of construction studied (which could potentially be high mass), 4 to 8 hour pre-cooling time was most effective in reducing peak cooling loads without a dramatic increase in overall energy use (Morgan & Krarti, 2007), and a minimum 5 hour pre-cooling period with a shallow pre-cooling setpoint temperature (23.3°C) showed the best pre-cooling results for most climates. In particular, high thermal mass can work effectively with pre-cooling strategy where the climate is characterised by large diurnal temperature swings (Morgan & Krarti, 2007). In a Californian study, it was found that although pre-cooling strategies were effective in both light and heavy mass commercial buildings, these can be more effective if the building mass is relatively heavy (Xu, 2009). Interestingly, in a simulation study, the highest mass level did not offer the most energy cost savings as the building mass absorbs some of the loads during the day and releases the heat at night. It was found that medium mass levels showed the best cost-saving performance, reporting a small difference between medium and high mass savings potential (Morgan & Krarti, 2007). Simulating the potential for mechanical pre-cooling of buildings with low thermal mass, such as timber-frame houses in 12 USA climate zones, Turner et al. (2015) found that the best pre-cooling results for most climates were obtained using a medium (5 hour) pre-cooling time window with a shallow (23.3 °C) pre-cooling setpoint temperature. The study found that all pre-cooling strategies caused annual cooling energy demand to increase. Additionally, all pre-cooling strategies in all climates shifted at least 50 per cent of on-peak cooling loads away from a peak period window of 4pm-8pm.

RACE for 2030 conducted an Opportunity Assessment as a scoping study (Wilmot et al., 2021) to discover what is currently known about home solar pre-cooling and pre-heating (SPC/H), and to indicate where RACE for 2030 should focus its research efforts. This Opportunity Assessment identified a number of social factors that influence consumer engagement and acceptance in solar pre-cooling programs, including benefits, motivations, housing quality, and thermal comfort preferences. The report recommended more research to assess the impact of SPC/H on thermal comfort, and additional data collection including thermal mass conditions of existing homes (Wilmot et al., 2021).

6.4.3 Ventilation strategies and air quality

Unwanted ventilation is often neglected in home heating and cooling, as are the benefits of cross-flow ventilation to cool the house once outdoor temperature is lower than inside. As ventilation rates increase (that is, in a 'leaky' house), energy consumption also increases because unconditioned outside air must be heated or cooled as it replaces conditioned, indoor air being exhausted. A tighter building envelope will reduce the rate of infiltration (and exfiltration) through cracks, gaps, and openings. Australian homes are generally considered leaky compared to homes in other countries, and older Australian homes are often much leakier than those built more recently (Ambrose, 2018). In a study of air tightness in new Australian homes (that is, less than 3 years old), the average ACH ranged between 7.9-28.5 @ 50 Pa, depending on state or territory. While older homes in Melbourne and Sydney had the least air-tight homes, older Canberra homes were found to have ACH slightly below the national average of 15.5 ACH @ 50 Pa (Ambrose, 2018). This is equivalent to a typical, naturally driven air infiltration rate of 0.78 ACH (1/h).

Good air quality in homes requires a fine balance of temperature, relative humidity, carbon dioxide (CO₂) concentration levels, particulate matter, and volatile organic compounds (VOCs). As the envelope becomes tighter, supplementary ventilation supply can be required to control indoor pollutants. ASHRAE Standard 62.2-2019 Ventilation and Acceptable Indoor Air Quality in Residential Buildings (ASHRAE, 2019) recommends 0.35 air changes per hour. ASHRAE also suggests intermittent exhausts for bathroom and kitchens to control pollutants and moisture. Reverse-cycle, split air-conditioning systems do not necessarily have provision for outdoor (fresh) air. Evaporative cooling systems ensure constant outdoor air supply. Balanced, or power-flue gas heaters, do not introduce outdoor air as the combustion air is isolated from the indoor air. Naturally flued gas heaters draw in outdoor air to replace the air that escapes via the flue – though negative pressure created by running exhaust fans can draw flue gases back down into the building. Unflued gas heaters use indoor air and are required to have outdoor air supplies to manage indoor air pollution from combustion (which can at times add to energy waste when the heater is not operating). Ducted heating and cooling systems can pressurise a house, significantly increasing its net rate of air leakage and energy waste. Air enters the rooms through open doors and windows. Prolonged window opening, especially in heating or cooling seasons, will impact on the building's thermal balance, particularly during winter and hot summer days.

Passive House (or Passivhaus) standards for buildings have strict guidelines for air tightness which must be demonstrated with a pressure test, and allowable net air change rate cannot exceed 0.6 per hour at 50 Pa (Marlow, 2020). This is to ensure that buildings are comfortable all year round, with temperatures above 20°C in winter and below 25°C in summer. Ventilation in Passivhaus homes is achieved through a mechanical heat recovery ventilation (HRV) system, a balanced system of extracting and supplying fresh air, aligned with heat recovery. However, studies have found issues with design, installation, commissioning, and occupant use that have led to mechanical HRV systems not operating as intended (Foster et al., 2016). This is due to occupants' lack of understanding about when to use the systems, as HRV also provides heat, in addition to recovered heat. In a study involving five Passive House-standard homes in Scotland, conducted by Foster et al. (2016), imbalanced HRV systems were identified in 80 per cent of the dwellings. The authors found that significant issues around sizing residential HRV units has been noted in current Passivhaus practices, as they typically deliver the same background ventilation regardless of occupancy levels.

Militello-Hourigan and Miller (2018) monitored the IAQ of tightly constructed homes and found that PM_{2.5} (particles with a diameter of 2.5 micrometres or less) concentrations are generally low indoors, but cooking drastically increases concentrations, which are slow to decay. Modelling of cooking activities showed that

installing and using a directly exhausting range hood reduced peak PM_{2.5} concentrations by 75 per cent or more. Moreno Rangel et al. (2020) reviewed studies on IAQ of Passive House dwellings and found that they are generally better than conventional houses. However, indoor pollutant concentrations depend very much on occupant behaviour and pollution from outdoor sources.

When ambient air becomes heavily polluted, such as during planned burns and bushfire events, concentrations of indoor pollutants, particularly fine particulate matter (e.g., PM_{2.5}), can increase substantially. In a study of Australian homes during controlled burning, Reisen et al. (2019) found that the PM_{2.5} infiltration was significantly influenced by the age of the house and ventilation behaviour (for example, windows open or closed). In a more recent study in Melbourne during the 2019-20 bushfire season, Munro and Seagren (2020) found that PM_{2.5} levels in a conventional leaky building were under 500 µg/m³ when outdoor levels were close to 600 µg/m³, while levels in airtight homes peaked at 320 to 380 µg/m³ which is 30 per cent lower. An airtight building alone is unlikely to keep particles within recommended concentrations during extreme events. Fine grade filters are required during such instances. Munro and Seagren (2020) also monitored two identical airtight homes that use mechanical ventilation, one with a standard F7 filter and the other with a HEPA filter, and found that the home with the HEPA filter achieved lower PM_{2.5} concentrations that are within recommended guidelines.

Most past studies used short-term IAQ monitoring periods of less than two weeks; therefore, it is difficult to determine how housing design impacts on IAQ and occupants' well-being during longer periods. Also, it was noted that there are few studies from non-European countries, and from hot and humid climates. If people perceive mechanical ventilation systems to be complicated or expensive to run, they will not engage with these technologies, potentially effecting comfort and air quality. Moreover, regular cleaning of filters is important for most heating, cooling, and ventilation systems. Clogged filters can reduce energy output and undermine energy efficiency.

6.5 Health impacts

The link between residential energy efficiency and health is dynamic and dependent on social, economic, and climatic contexts. Outcomes from improved energy efficiency leading to better health benefits for home occupants may also lead to reduced energy consumption and costs, warmer indoor temperatures and reduced mould during winter, and increased satisfaction with the home (Willand et al., 2015). For low-income populations, further physical and mental health benefits can be achieved through savings made on their energy bill which can be diverted to options such as buying more efficient appliances. If implemented on a larger scale, facilitating access to such options could help to ease strain on the public healthcare system. Health may be measured through subjective surveys; for example, SF-36 (which covers general, physiological, social, and mental health), subjective (self-reported) surveys, or objective biomedical measurements of cardiovascular and respiratory health (Willand et al., 2015).

There is inconclusive evidence for a causal influence between energy efficiency improvement and better health. This uncertainty is due to the heterogeneity, and often low quality, of published studies, geographical limitations to colder climates, and contextual influences such as target groups and delivery. Furthermore, the effects of indoor air quality are rarely considered. Some studies (eg. Ezratty et al., 2009; Tonn et al., 2021) rely on associations between residential energy efficiency and health via varied pathways, most of them via objective or subjective indicators of indoor temperatures. However, associations are not proof of causal relationships. With the completion of the Victorian Healthy Homes Program (Sustainability Victoria, 2022c),

evidence is emerging on the causal relationship between improved energy efficiency of dwellings and household health in Australia, as discussed in Section 6.5.2.

6.5.1 International evidence

The most reliable evidence for causality of health outcomes comes from systematic reviews followed by randomised trials and then observational studies (NHMRC, 2009). Two systematic reviews conducted in 2013 (Milner & Wilkinson, 2017; Hilary Thomson et al., 2013) looked for a causal relationship between residential energy efficiency and health impacts. These reviews agreed there was ‘suggestive, although not conclusive’ evidence ‘that interventions that improve home energy efficiency and/or home heating are generally beneficial for health’ (Milner & Wilkinson, 2017, p. 87).

Health impacts seemed most likely if they improved the thermal comfort among low-income households and people with respiratory illnesses (Hilary Thomson et al., 2013). A few years later, a systematic realist review confirmed that retrofits ‘improved winter warmth and lowered relative humidity with benefits for cardiovascular and respiratory health’ among common target groups most vulnerable to cold – low-income households, children, and older people – but that ‘comprehensive refurbishments were not necessarily more effective than thermal retrofits or upgrades’ (Willand et al., 2015, p. 191). The review highlighted the importance of contextual conditions in retrofit trials, such as target groups, householder expectations, heating and ventilation practices, workmanship, and technological handover (Willand et al., 2015). An ACEEE study (Hayes et al., 2020) reviewed the literature and interviewed experts to develop a simplified estimation equation to calculate a range of potential cost savings in terms of the dollar value of avoided health care costs and mortality. The report concluded that if existing weatherisation programs targeted four common health risks – asthma, falls, and exposure to extreme heat or cold – they could save more than USD228 million in avoided health harms. Those savings could reach USD2.9 billion over 10 years. The most recent systematic review on effectiveness of residential energy efficiency improvements (REEI) has reinforced the importance of the context. However, the same type of REEI installed in different studies caused different effects, indicating that effects are conditional on implementation and context (Berretta et al., 2021, pp. 2-3).

6.5.2 Australian studies

The co-benefits associated with energy efficiency were referred in the Low Income Energy Efficiency Program (LIEEP, 2016), a competitive merit-based grant program that trialled approaches for improving energy efficiency of low-income households and enabling them to better manage their energy use. A study investigating multiple impacts of household energy efficiency (Energy Consumers Australia, 2017) recommended that an established research protocol should be implemented to assess the impact of energy efficiency on physical health, mortality rate, mental health and well-being, family tensions, and social isolation. Another study conducted by the CRC for Low Carbon Living (Daly et al., 2018) found that uncertainty regarding direct causal pathways from an energy intervention to a health outcome means large scale experimental studies are necessary to explore this area. The report recommended further research to improve understanding of direct causal pathways between housing quality, internal environmental conditions, and health outcomes. Various quantitative studies on health impacts of improved energy efficiency, ranging from simulation, observational studies, and retrofit trials, are discussed below.

6.5.2.1 Simulation and observational studies

In 2009, a simulation study examined potential health impacts of moving from a 5-Star to 6-Star NatHERS standard for new houses. Average winter indoor temperatures in 6-Star rated houses in free-running mode, (that is, without any space-conditioning), were warmer by 0.4°C and 0.5°C depending on the climate zone (Williamson et al., 2009). Using health impact assessment data from a New Zealand study, the maximum annual health benefit costs were estimated to be AUD111.00 among low-income households and households with older people, which were considered the most vulnerable households (Williamson et al., 2009, p. 5).

In 2012-13, a study using empirical data from 414 homes in Brisbane, Melbourne and Adelaide (Ambrose et al., 2013) found that houses with 5 or more Stars were warmer and used less energy to achieve warmth than homes in all three cities with less than 5 Stars (Ambrose et al., 2013). However, a more nuanced investigation of the Melbourne cohort (Willand & Ridley, 2015) revealed that Star ratings did not predict indoor temperatures in winter. But continuous occupation and heater use, as well as higher energy costs, did predict better winter warmth (Willand & Ridley, 2015). As Star ratings do not linearly reflect heating energy use, a correlation between MJ/m² and temperatures in heated spaces might give a different result.

6.5.2.2 Retrofit trials

A one-dwelling before-and-after investigation in Tasmania revealed health improvements, particularly among children in the family (Alison Weaver, 2004; Anthony Weaver, 2004). The Brotherhood of St Laurence's Warm Home Cool Home (WHCH) energy efficiency program, which targeted low-income households, also showed improved thermal comfort and mixed health outcomes (Johnson et al., 2013).

In 2013-2016, the CSIRO conducted Australia's first evaluation of a larger retrofit and behaviour change trial. Participants were older and frail and used Home and Community Care services provided by local governments in the south-east of the greater Melbourne area. Retrofits included insulation, draught-proofing, lighting upgrades, and occasional heater exchanges. The quantitative study monitored indoor temperatures and energy consumption. The final report states that 'retrofit only' interventions achieved a statistically significant energy efficiency outcome of 7 per cent reduction in total energy use based on distributor data (compared to a control group), while simultaneously increasing winter indoor temperatures by an average of 1-1.9°C (SECCCA, 2016, p. 20). A complementary mixed methods evaluation of the retrofit trial (Willand, 2016; Willand & Horne, 2018b) involving a sub-group of 30 households confirmed some increase in winter warmth but could not find a statistically significant effect on health using SF-36 v2 scores. Importantly though, the study identified that the physiological capabilities of the householder, the modes of energy bill payment, and the social construction of the adequacy of indoor temperatures, were important contextual moderators of health outcomes (Willand, 2016; Willand & Horne, 2018b).

In 2022, the first substantive randomised trial into health impacts and health cost impacts of residential energy efficiency improvements was undertaken in Victoria. The Victorian Healthy Homes program (Campbell et al., 2022; Sustainability Victoria, 2018) involved free thermal retrofits and appliance upgrades in the homes of 1000 Victorian Home and Community Care recipients who suffered from a chronic respiratory condition. Outcome measures included average winter indoor temperatures, energy consumption and costs, as well as self-reported health outcomes using SF-36 and similar surveys (Campbell et al., 2022). The results showed that improving winter warmth through thermal shell and energy efficiency upgrades provided multiple important benefits, both for householders and the broader community (Campbell et al., 2022). Even with the most

conservative assumptions, cost-benefit analysis in this study indicated that the upgrade cost is paid back within three years. Having a warm-enough house resulted in increased social connectedness and better quality of life. Data on healthcare utilisation over winter revealed that people in upgraded homes used fewer services and had lower health costs, with AUD887 cost savings over the single three-month winter period. However, the potential to generalise findings from this study to the whole Australian population is limited due to the study's geographic scope, and with frail participants suffering ill health. It is therefore recommended that further research is undertaken in Australia to develop a standardised methodology and then roll this out across climatic zones and different housing stocks in Australia.

6.5.3 Key points for research related to health, welfare, and vulnerable households

1. The heterogeneity of studies makes it difficult to synthesise studies or make general statements about the impacts of residential energy efficiency improvements across time, place, population, and housing characteristics. Studies vary in data collection methods and analysis, are often limited in outcome measures and restricted to evaluating short term outcomes, and use different ways to assess and report energy efficiency of homes (if they do it at all) (Berretta et al., 2021; McAndrew et al., 2021; Milner & Wilkinson, 2017; Willand et al., 2015). Strategies to improve replicability and synthesis of energy efficiency studies have been proposed (Huebner et al., 2017).
2. Contextual factors are hardly considered. Most studies are quantitative studies that look for summative assessments. However, participant expectation, the quality of homes before the retrofit, workmanship, and handover or the placebo effect are hardly considered. Many studies also focus on low-income households, improve housing of particularly poor quality, and reveal little about program implementation (Berretta et al., 2021; Fisk et al., 2020; Hilary Thomson et al., 2013; Willand et al., 2020). Mixed methods studies that explore the contexts, and attempt to explain surprising findings, are rare.
3. The association between residential energy efficiency and better health outcomes via cleaner outdoor air is under-researched and not considered in published systematic reviews. There is a small body of literature that has used atmospheric models to simulate health benefits of residential energy efficiency improvements. The pathway considers lowering carbon emissions of fossil fuel fired electricity generation, and reduced direct pollutant emissions from residential combustion (for example, from wood and gas), and their mortality benefit on state-wide or nationwide scales. Such studies have been conducted for the USA (Abel et al., 2019; Levy et al., 2003; Levy et al., 2016). Cleaner outdoor air is also the aim of some residential energy efficiency improvements in New Zealand and Chile that include fuel switches where households rely on wood for heating (Free et al., 2010; Reyes et al., 2019; Schueftan & González, 2015). While heater exchange programs in New Zealand have been evaluated (Free et al., 2010; Telfar-Barnard et al., 2011), retrofit studies investigating health outcomes in South America are rare (Berretta et al., 2021).
4. There is limited understanding of the link between residential energy efficiency and health in warmer climates. Most retrofit intervention studies have been conducted in colder climates where health benefits are derived via better winter warmth (Fisk et al., 2020; Hilary Thomson et al., 2013; Willand et al., 2015). This narrow focus is particularly important for a country like Australia that presents a range of climates, where there is emerging evidence on overheating in well insulated buildings, and where future climates are likely to be warmer.

6.6 Estimating cost-effectiveness

There is an increasing focus by researchers and policy makers on the costs and benefits of improving housing sustainability for individual households and also wider society. As noted, with the economic analysis of increasing the stringency of the National Construction Code, there is much debate around estimating the economic benefits and cost-effectiveness of energy-related savings, and the impacts of building energy and thermal efficiency. Discount rates, duration of savings, energy price estimation, impacts on energy supply infrastructure, avoided carbon costs, and many other issues remain contentious.

The following is a summary of some of the emerging research on improved thermal performance of housing beyond just direct energy benefits. Some of these issues have already been discussed in previous sections in a different context. Wider benefits include improved householder health and comfort, improved living affordability, poverty alleviation, energy security, and equity (Berry et al., 2014a, 2014b; Boardman et al., 2005; Bouzarovski, 2018; Chapman et al., 2009; CSIRO, 2010; Daniel et al., 2019; DCLG, 2008; De Dear, 2004; Golubchikov & Deda, 2012; Gower, 2021; Huang C et al., 2013; IEA, 2014; Kearns, 2020; Kolokotsa et al., 2011; Moore et al., 2017; Osmani & O'Reilly, 2009; Ridley et al., 2014; Ridley et al., 2013; Szatow, 2011; Willand & Horne, 2018a; Willand et al., 2019; Williamson et al., 2009; Yudelson & Meyer, 2013; Zabaneh, 2011; Zhu et al., 2009).

A key focus of research into benefits of improved thermal performance of dwellings has also been in exploring any implications for resale or rent value. Research from around the world finds there could be a sale premium of 15 per cent or more resulting from improvements to design, quality, and performance, although this is not universal across all studies with some noting no influence on sale or rental value (Berry et al., 2008a; Bloom et al., 2011; CABE, 2002; DEWHA, 2008; Fuerst & Warren-Myers, 2018; Geller et al., 2006; Hoen et al., 2011; Kok & Kahn, 2012; Marmolejo-Duarte & Chen, 2019, 2022; Marmolejo-Duarte et al., 2020; Nevin & Watson, 1998; Yudelson, 2010). For example, in Australia mandatory disclosure legislation in the ACT has seen higher house energy ratings achieve a sale premium of approximately 3 per cent for every additional Star improvement in the rating (Berry et al., 2008a; Department of the Environment Water Heritage and the Arts, 2008; Fuerst & Warren-Myers, 2018).

House energy performance rating in other countries has involved the whole house compared to Australia where only the building envelope is rated. Therefore, direct comparison of the benefits is difficult. For example, in California voluntary labelling through programs such as Energy Star, LEED for Homes, and GreenPoint have been found to increase value by about 9 per cent (Kok & Kahn, 2012), while across the country the added resale value was found to be in the 3-5 per cent range (Argento et al., 2018). In Colorado, Bloom et al. (2011) found that Energy Star certified homes achieved an additional sale premium of USD8.66 per square foot compared to standard homes. In Atlanta researchers found that for dwellings with an energy certificate there was a premium of up to 11.7 per cent (up to USD47,000 at the time of research compared to the average home sales price of USD381,513) (Zhang et al., 2018).

There has been significant research exploring the creation of Energy Performance Certificates (EPCs) to drive energy efficiency upgrades across the EU. However, this research provides analysis for whole-of-dwelling energy performance without specifically attributing the role of thermal performance (Amecke, 2012; Copiello & Donati, 2021; Marmolejo-Duarte & Chen, 2019; Olaussen et al., 2017; Sejas-Portillo et al., 2020). Khazal and Sønstebø (2020) found that the sale premium rises as the EPC label improves in the Norwegian residential sector. The authors found that green labels (A, B, and C) have a 5.8 per cent premium over non-certified dwellings and achieve a similar outcome for increased rents. In the UK, Fuerst et al. (2015) found significant

positive price premiums for dwellings with EPC ratings of A/B (5 per cent) or C (1.8 per cent) compared to dwellings rated D. For dwellings rated E and F, discounts were estimated respectively at -0.7 per cent and -0.9 per cent. In the Welsh housing market, even higher premiums were found: 12.8 per cent for A/B EPCs compared to dwellings rated D (Fuerst et al., 2016). In Flanders, a higher resale value of 0.075 per cent for each 1 per cent increase in EPC score has been found (Taranu et al., 2020).

A positive relationship between EPC and house sale/rental value was not a universal finding. For example, research from Chile found that energy ratings negatively affected households' willingness to buy (Encinas et al., 2020). The researchers suggested that consumers were relating higher ratings of dwellings to what they saw in the appliance market, which was that higher ratings equalled higher prices and so this made it less attractive as they perceived it increased the dwelling price. In Belfast, researchers found no increased probability of an increase in sales price for dwellings with higher EPCs (McCord et al., 2020).

The financial value is not just at the point of sale or rent but also in reduced living costs achieved by improved thermal performance and other factors, such as resilience in power outages and status among peers. The label, and communication design and effectiveness of promotion, can also affect impacts. Research from Australia found that an 8-Star zero energy home could save more than AUD90,000 in energy bills over a 40-year period (Moore, 2012). Additionally, if energy savings were reinvested into the household's home loan it offset additional capital cost borrowing for sustainability elements, reduced home loan interest paid by more than AUD50,000, and resulted in paying off the house up to four years sooner.

Health benefits from improved design and performance include a reduction in respiratory disease, improved sleep, reduced severity of conditions like arthritis, and other milder ailments such as colds and coughs (Baker et al., 2017; Baker et al., 2020; CABE, 2002; Chapman et al., 2009; Kent et al., 2011; Moore et al., 2017; Pevalin et al., 2017; Pevalin et al., 2008; Willand et al., 2019). For example, in Australia, a 1-Star increase in dwelling performance was found to result in a financial health benefit of AUD9.50 per householder per annum (Williamson et al., 2009). These health benefits go beyond the individual household and can be scaled. In the UK, the additional cost to the health care system from poor quality housing is estimated to be GBP1.4 billion per year, with wider societal costs of poor housing estimated to be GBP18.5 billion (Garrett et al., 2021). Vulnerable people in households, such as children, the elderly or those who are low-income, are often disproportionately impacted by health implications from housing, but also gain most from significant design and performance improvements. Research from Boston, USA, found that a cohort of public housing tenants in sustainable housing experienced a reduction in self-reported health issues of 57 per cent compared to those in standard public housing (Colton et al., 2014). These health benefits link to wider community costs and benefits, such as cost implications for the health care system (Garrett et al., 2021).

There is increasing research emerging which looks at the health and wellbeing implications for occupants in various forms and types of housing. For example, research out of the UK and EU has looked at reduced real and potential health implications from improving the thermal performance of dwellings (Chapman et al., 2009; Ridley et al., 2013). It is argued that improving thermal performance of a dwelling results in better internal thermal temperatures. It has been demonstrated that exposure to extreme temperatures and weather conditions can exacerbate health issues and result in increased death rates (Huang C et al., 2013; Kosatsky, 2005). Other research on comfort and wellbeing is being undertaken in Australia (De Dear, 2004; De Dear & White, 2008; Maller & Strengers, 2011; Nicholls & Strengers, 2014).

While much research has focused on the direct benefits to individual households, increasingly research is looking at the wider social benefits of delivering at scale improved thermal performance of housing. Research at Cape Paterson ecovillage in Victoria estimated that if average energy savings for new housing in that development were replicated across all new houses built in Australia, household energy bills could reduce by AUD5-10 billion across a 10 year period (Moore et al., 2020). Analysis of the benefits of minimum regulations is not just limited to private benefits to house owners. Berry and Davidson (2015) looked at the potential impact of a net zero energy housing standard for South Australia and found a net present value of at least AUD1.31 billion over a 10-year policy life, resulting in a benefit/cost ratio of 2.42. This economic impact did not include health and other social benefits expected from higher performance housing. Research by ClimateWorks Australia (2018a) calculated that a delay of three years (that is, until 2022) for increasing the current minimum 6-Star standard to 7-Star would impact on almost 500,000 Australian houses and lead to AUD1.1 billion of unnecessary energy bills for households to 2050. The research also found that this delay would lock in AUD530 million of unnecessary energy network investment.

7 Scenario Modelling

The aim of this section is to understand performance of the existing housing stock, and to assess potential improvements in energy efficiency and overheating risks in current climate conditions, as well as in projected climate conditions in 2030 and 2050.

7.1 Methodology

7.1.1 Sample dwellings

A total of 208,204 residential building designs collected from the Australia Housing Data portal (CSIRO, 2022a) were selected for this study. These sample dwellings represent around 90 per cent of the total 229,142 dwellings approved for building during 2021 in Australia (ABS, 2022b). These buildings were built before 1991 and are assumed to have no insulation as thermal insulation as a contributor to energy efficient homes was introduced only after 1991. Table 14 shows the distributions of these dwellings in each state and territory. In Table 14, Class 1A buildings are detached houses or one of a group of attached dwellings (for example, a town house, terrace house, or the like). Class 2 buildings are apartments. These sample dwellings cover 68 climate zones (CZs) out of the 69 NatHERS CZs in Australia, with no new dwelling designed in 2021 for CZ 51, Forrest, Western Australia, since its population is zero according to the 2016 census (ABS, 2022a).

7.1.2 Existing old housing stock and improvement scenarios

The Star rating of a typical existing old Australian residential dwelling, built before mandated Star rating and insulation, is frequently cited to be approximately 2 Stars. In Victoria, this is supported by data from the Australian Housing Data portal (CSIRO, 2022a) with an average of 2.1 Stars for 14,901 existing old dwellings. The reason there is such a relatively good collection of Star ratings for existing old dwellings in Victoria is that for large renovation projects, Victoria has mandated since May 2008 energy efficiency assessment of existing old dwellings where the project represents more than 50 per cent of the building's original volume. However, this is not mandated in other states and territories and databases of energy Star ratings for existing old dwellings in other states and territories are not available. Consequently, it is believed that the cited average Star ratings of existing old dwellings in other states and territories is likely based on a small number of sample dwellings and the average 2-Star rating may be inaccurate.

For this study, a database of energy Star rating for existing old dwellings, or a pseudo-old building stock, covering all states and territories was developed by the CSIRO, based on 208,204 recent real dwelling designs submitted for NatHERS Star rating in 2021 (CSIRO, 2022a). As recent dwellings are generally around or above 5 Stars, the following modifications to the original designs were implemented to back-construct the pseudo-old building stock:

- a. All insulation in walls, floors, rooves are removed and insulation in ceiling to roof spaces is assumed to be R0.25, considering that ceiling insulation does exist in a small proportion of existing old dwellings.
- b. Infiltration at ambient conditions is assumed to be 1.0 ACH (air change rate per hour), which is consistent with the air change rate reported in Biggs et al. (1986).
- c. All windows are assumed to be clear 3mm single glazing with timber window frame.

Table 14 shows dwelling distributions and average Star ratings in different states and territories. The average Star rating of 2.15 in Victoria closely matches the average 2.1 Stars for the 14,901 existing old dwellings reported in the Australian Housing Data portal (CSIRO, 2022a). The national average Star rating of this pseudo-old building stock is calculated to be around 2.47. The highest average Star rating of existing old dwellings is found in Northern Territory at 4.46. Although dwelling designs and floor plans of the 2021 designs may be somewhat different from existing old dwellings, the average Star ratings from this pseudo-old building stock gives the depth of data on each house upgraded.

Table 14. Sample dwelling distributions and average Star ratings for base design in different states and territories

State/Territory	Building Class 1A		Building Class 2		All	
	Number	Stars	Number	Stars	Number	Stars
Australia	145,696	2.17	62,908	3.16	208,204	2.47
Australian Capital Territory (ACT)	1,334	1.95	406	3.52	1,740	2.32
New South Wales (NSW)	38,166	2.04	49,802	3.06	87,968	2.62
Northern Territory (NT)	704	4.47	3	2.70	707	4.46
Queensland (QLD)	12,313	3.47	2,759	4.55	15,072	3.67
South Australia (SA)	4,746	2.07	321	3.36	5,067	2.15
Tasmania (TAS)	4,435	1.87	126	3.03	4,561	1.90
Victoria (VIC)	7,6515	2.02	9,331	3.27	85,846	2.15
Western Australia (WA)	7,483	2.42	160	2.98	7,643	2.43

Improvements were then modelled for this pseudo-old building stock (Base) with the following three categories: rehabilitation (Rehab), refurbishment (Refurb), and renovation (Renov), as listed in detail in Table 15. From Base, Rehab, Refurb to Renov, improvements are from relatively easy or cheap to relatively difficult or expensive. The improvements listed as bold in Table 15 are improvements relative to immediate lower-level home improvements. For example, Floor R2.0 and addition of a glass insulation layer on existing windows in Refurb are improvements relative to Rehab.

Table 15. Three improvement categories to the pseudo-old building stock (Base)

Improvement Category	Items improved	Improvements
Base	Insulation	Ceiling R0.25
	Infiltration	1.0 ACH
Rehab	Insulation	Ceiling R3.0
	Infiltration	0.5 ACH
	Curtain	Heavy drapes
	Window shade	Roller shutters
Refurb	Insulation	Ceiling R3.0, Floor R2.0
	Infiltration	0.5 ACH
	Curtain	Heavy drapes
	Window shade	Roller shutters
	Window system	Addition of a glass insulation layer

Renovate	Insulation	Roof/Ceiling R3.0, Floor R2.0, Wall R2.0
	Infiltration	0.2 ACH
	Heat recover ventilation	0.4 ACH, 85% heat recovery efficiency
	Curtain	Heavy drapes
	Window shade	Roller shutters
	Window system	Energy efficient double glazing

7.1.3 Overheating criteria

With the NatHERS scheme, energy efficiency of houses is regulated under the assumption that the house is always heated or cooled whenever needed. However, thermal performance, and thus overheating risk under naturally ventilated (NV) operation, is currently not regulated in Australia. Overheating risks in residential buildings have had relatively extensive investigations in European countries (Chen, 2019). In this study, we adopted overheating criteria recommended by CIBSE TM59 (2017) for predominantly naturally-ventilated residential buildings. CIBSE TM59 (2017) specifies two overheating criteria:

- A. For living rooms, kitchens and bedrooms: the number of hours during which ΔT is greater than or equal to one degree (K) during the period May to September inclusive (equivalent to November to March in the southern hemisphere) shall not be more than 3 per cent of occupied hours.
- B. For bedrooms only: the operative temperature in the bedroom from 10pm to 7am shall not exceed 26°C for more than 1 per cent of annual hours.

Here ΔT is calculated based on Equations (1)-(3):

$$T_{max} = 0.33T_{pma(out)} + 21.8 + DT_{speed} \quad (1)$$

$$\Delta T = T_{op} - T_{max} \quad (2)$$

$$DT_{speed} = 6(v - 0.2) - (v - 0.2)^2 \quad (3)$$

Where,

T_{max} (°C) is the thermal comfort upper limit temperature for Category II buildings (new buildings and renovations) operating in NV mode defined in the European standard BS EN 15251(BSI, 2007)

T_{op} (°C) is the indoor operative temperature

$T_{pma(out)}$ (°C) is the prevailing mean ambient temperature

ΔT_{speed} (°C) is the cooling effect of air movement based on Aynsley and Szokolay (1998)

v (m/s) is the indoor air speed

If one living room or bedroom fails either criterion, then the dwelling fails the overheating assessment.

7.1.4 Weather files used in this study

AccuRate Sustainability V2.4.3.21 includes a total of 69 RMY (Refence Meteorological Year) weather files for the 69 NatHERS climate zones which cover Australia. The current 69 NatHERS climate zone weather files used in Star rating are based on historical weather data from the 1960s to 2004. In NCC 2022, this existing set of RMY

weather files will be obsolete and replaced by a new set of 69 NatHERS 2016 RMY weather files which were based on recent historical weather data from 1990 to 2015. Consequently, this study uses the new 69 NatHERS 2016 RMY weather files for energy efficiency and overheating risk assessment. For energy efficiency and overheating risk assessment in future climate conditions, the projected 2030 and 2050 weather files, under the RCP8.5 future climate scenario which CSIRO developed based on the new 69 NatHERS 2016 RMY weather files (CSIRO, 2022b), were adopted. With this approach, the energy efficiency and overheating risk assessment are consistent, considering that future weather files are generated based on the new NatHERS 2016 RMY weather files.

7.1.5 Simulations

Simulations were carried out for the sample dwellings using AccuRate Sustainability V2.4.3.21 SP1 under rating mode (using standard NatHERS assumptions) for the energy efficiency rating, and free-running mode for overheating risk assessment. The free-running mode used the same occupant behavioural settings, internal heat loads, and other factors as the NatHERS rating mode, except that the dwelling is not heated and cooled in the simulations.

It is noted that for the free-running mode simulations in this study, an internal thermal mass was added. The internal thermal mass was implemented as a within-zone internal wall and assumed to be a 50 mm thick, soft timber per m² of floor area for each room. This within-zone internal wall represents an approximation of the internal thermal mass relating to furniture and other household contents in residential dwellings as reviewed by Johra and Heiselberg (2017). It is understood that such an internal thermal mass implementation is rough; however, it is thought this contributes one step closer to the real dwelling and can be refined in the future once better information about thermal mass in Australian dwellings becomes available. Due to the large number of sample dwellings, simulations were carried out in parallel using a total of around 100 cores/200 treads over 11 workstations. One batch simulation of the 208,204 sample dwellings took approximately 12 hours to complete. A total of 25 batch simulations were carried out in this study, as listed in Table 16, for energy efficiency and overheating risk assessment with different dwelling improvement categories under different climate conditions.

Table 16. Simulation run specifications

Run No.	Improvement Category	Energy/Overheating	Weather files
1	Base	Energy efficiency	NatHERS 2004 RMY
2	Base	Energy efficiency	NatHERS 2016 RMY
3	Base	Energy efficiency	Future 2030 RMY
4	Base	Energy efficiency	Future 2050 RMY
5	Base	Overheat assessment	NatHERS 2016 RMY
6	Base	Overheat assessment	Future 2030 RMY
7	Base	Overheat assessment	Future 2050 RMY
8	Rehab	Energy efficiency	NatHERS 2016 RMY
9	Rehab	Energy efficiency	Future 2030 RMY
10	Rehab	Energy efficiency	Future 2050 RMY
11	Rehab	Overheat assessment	NatHERS 2016 RMY

12	Rehab	Overheat assessment	Future 2030 RMY
13	Rehab	Overheat assessment	Future 2050 RMY
14	Refurb	Energy efficiency	NatHERS 2016 RMY
15	Refurb	Energy efficiency	Future 2030 RMY
16	Refurb	Energy efficiency	Future 2050 RMY
17	Refurb	Overheat assessment	NatHERS 2016 RMY
18	Refurb	Overheat assessment	Future 2030 RMY
19	Refurb	Overheat assessment	Future 2050 RMY
20	Renov	Energy efficiency	NatHERS 2016 RMY
21	Renov	Energy efficiency	Future 2030 RMY
22	Renov	Energy efficiency	Future 2050 RMY
23	Renov	Overheat assessment	NatHERS 2016 RMY
24	Renov	Overheat assessment	Future 2030 RMY
25	Renov	Overheat assessment	Future 2050 RMY

7.1.6 Cost and CO₂ emission calculation

From the energy simulation results, the total energy cost for both cooling and heating are calculated. The Coefficient of Performance (COP) values assumed in this study for various heating and cooling appliances are listed in Table 17.

Table 17. Coefficient of Performance (COP) values assumed for various appliances

Appliance	COP
RC Cooling	3.0
RC Heating	3.5
Gas Heating	0.8

Considering the availability of natural gas in different regions, the average splits between gas and reverse-cycle heating as listed in Table 18 were assumed for each State/Territory.

Table 18. Average splits between gas and reverse-cycle heating for each state/territory

State	Gas Heating	RC Heating
ACT	0.7	0.3
NSW	0.5	0.5
NT	0	1
QLD	0	1
SA	0.2	0.8
TAS	0.5	0.5
VIC	0.7	0.3
WA	0.5	0.5

The energy tariffs for electricity were assumed to be AU\$0.322/kWh and the gas tariff was assumed to be AU\$0.025/MJ. For CO₂ emission calculation, emission coefficients of 0.96 kgCO₂e/kWh for electricity and 54 kgCO₂e/MJ for gas were assumed. The following cost and CO₂ calculations were then applied against each house:

RC Cooling:

$$\text{Cooling Cost} = \frac{\text{CoolingEnergy}(\text{MJ}/\text{m}^2) \times \text{ConditionedArea} \times \text{ElectricityTariff}(\text{AUD}/\text{kWh})}{3.6 \times \text{Cooling COP}} \quad (4)$$

$$\text{Cooling CO}_2 = \frac{\text{CoolingEnergy}(\text{MJ}/\text{m}^2) \times \text{ConditionedArea}}{3.6 \times \text{Cooling COP}} \% \times \text{ElectricityEmissionFactor} \quad (5)$$

RC Heating:

$$\text{RC Heating Cost} = \frac{\text{HeatingEnergy}(\text{MJ}/\text{m}^2) \times \text{ConditionedArea} \times \text{ElectricityTariff}(\text{AUD}/\text{kWh})}{3.6 \times \text{RC Heating COP}} \times \text{RC Heating \%} \quad (6)$$

$$\text{RC Heating CO}_2 = \frac{\text{HeatingEnergy}(\text{MJ}/\text{m}^2) \times \text{ConditionedArea}}{3.6 \times \text{RC Heating COP}} \times \text{RC Heating \%} \times \text{ElectricityEmissionFactor} \quad (7)$$

$$\text{Gas Heating Cost} = \frac{\text{HeatingEnergy}(\text{MJ}/\text{m}^2) \times \text{ConditionedArea} \times \text{GasTariff}(\text{AUD}/\text{MJ})}{\text{Gas Heating COP}} \times \text{Gas Heating \%} \quad (8)$$

$$\text{Gas Heating CO}_2 = \frac{\text{HeatingEnergy}(\text{MJ}/\text{m}^2) \times \text{ConditionedArea}}{\text{Gas Heating COP}} \times \text{Gas Heating \%} \times \text{GasEmissionFactor} \quad (9)$$

7.2 Results and discussion

7.2.1 Potential energy savings and CO₂ emission reduction

The average heating and cooling costs for different dwelling improvements in each state and territory for Class 1 and Class 2 dwellings are shown in Table 19 and Table 20 respectively.

Table 19. Average heating and cooling costs for different dwelling improvements for Class 1 dwellings in each state/territory (AUD written as \$)

State		Base	Rehab	Refurb	Renov
ACT	Avg. Cooling Cost	\$268.10	\$189.22	\$165.14	\$79.54
ACT	Avg. Heating (Gas) Cost	\$1,747.98	\$1,297.29	\$1,250.95	\$400.43

ACT	Avg. Heating (RC) Cost	\$610.19	\$452.86	\$436.68	\$139.78
NSW	Avg. Cooling Cost	\$269.78	\$202.11	\$186.32	\$100.26
NSW	Avg. Heating (Gas) Cost	\$566.62	\$423.44	\$397.02	\$100.27
NSW	Avg. Heating (RC) Cost	\$461.53	\$344.90	\$323.38	\$81.67
NT	Avg. Cooling Cost	\$1,479.06	\$1,153.74	\$1,103.81	\$718.50
NT	Avg. Heating (Gas) Cost	\$0.00	\$0.00	\$0.00	\$0.00
NT	Avg. Heating (RC) Cost	\$56.91	\$39.77	\$35.51	\$6.15
QLD	Avg. Cooling Cost	\$332.47	\$219.06	\$211.68	\$152.01
QLD	Avg. Heating (Gas) Cost	\$0.00	\$0.00	\$0.00	\$0.00
QLD	Avg. Heating (RC) Cost	\$184.13	\$96.97	\$87.12	\$21.34
SA	Avg. Cooling Cost	\$324.52	\$194.91	\$180.64	\$92.47
SA	Avg. Heating (Gas) Cost	\$279.44	\$189.69	\$179.97	\$62.79
SA	Avg. Heating (RC) Cost	\$910.44	\$618.02	\$586.36	\$204.57
TAS	Avg. Cooling Cost	\$40.40	\$26.92	\$25.85	\$14.73
TAS	Avg. Heating (Gas) Cost	\$998.85	\$740.91	\$678.87	\$222.93
TAS	Avg. Heating (RC) Cost	\$813.58	\$603.48	\$552.96	\$181.58
VIC	Avg. Cooling Cost	\$192.38	\$114.37	\$105.72	\$60.75
VIC	Avg. Heating (Gas) Cost	\$1,299.04	\$894.51	\$841.94	\$302.73
VIC	Avg. Heating (RC) Cost	\$453.47	\$312.26	\$293.90	\$105.68
WA	Avg. Cooling Cost	\$289.81	\$182.25	\$170.22	\$94.00
WA	Avg. Heating (Gas) Cost	\$330.98	\$186.84	\$170.73	\$45.09
WA	Avg. Heating (RC) Cost	\$269.59	\$152.19	\$139.06	\$36.72

Table 20. Average heating and cooling costs for different dwelling improvements for Class 2 dwellings in each state/territory (AUD written as \$)

State		Base	Rehab	Refurb	Renov
ACT	Avg. Cooling Cost	\$78.92	\$57.64	\$52.17	\$21.69
ACT	Avg. Heating (Gas) Cost	\$605.13	\$469.63	\$441.53	\$103.63
ACT	Avg. Heating (RC) Cost	\$211.24	\$163.94	\$154.13	\$36.18
NSW	Avg. Cooling Cost	\$77.28	\$66.80	\$59.36	\$35.37
NSW	Avg. Heating (Gas) Cost	\$173.36	\$143.03	\$128.61	\$25.40
NSW	Avg. Heating (RC) Cost	\$141.20	\$116.50	\$104.75	\$20.69
NT	Avg. Cooling Cost	\$1,607.47	\$1,214.62	\$1,170.04	\$750.74
NT	Avg. Heating (Gas) Cost	\$0.00	\$0.00	\$0.00	\$0.00
NT	Avg. Heating (RC) Cost	\$0.08	\$0.00	\$0.00	\$0.00
QLD	Avg. Cooling Cost	\$240.20	\$173.73	\$167.56	\$123.89
QLD	Avg. Heating (Gas) Cost	\$0.00	\$0.00	\$0.00	\$0.00
QLD	Avg. Heating (RC) Cost	\$73.90	\$51.28	\$41.91	\$7.30
SA	Avg. Cooling Cost	\$137.07	\$114.09	\$103.98	\$63.12

SA	Avg. Heating (Gas) Cost	\$69.01	\$50.04	\$46.04	\$11.23
SA	Avg. Heating (RC) Cost	\$224.84	\$163.02	\$149.99	\$36.57
TAS	Avg. Cooling Cost	\$25.86	\$22.31	\$18.57	\$18.81
TAS	Avg. Heating (Gas) Cost	\$578.58	\$436.80	\$396.78	\$107.90
TAS	Avg. Heating (RC) Cost	\$471.27	\$355.79	\$323.18	\$87.88
VIC	Avg. Cooling Cost	\$123.89	\$98.93	\$78.31	\$49.13
VIC	Avg. Heating (Gas) Cost	\$650.71	\$456.96	\$419.98	\$143.85
VIC	Avg. Heating (RC) Cost	\$227.15	\$159.52	\$146.61	\$50.21
WA	Avg. Cooling Cost	\$196.02	\$113.37	\$103.59	\$66.51
WA	Avg. Heating (Gas) Cost	\$234.78	\$122.42	\$110.10	\$32.13
WA	Avg. Heating (RC) Cost	\$191.23	\$99.72	\$89.68	\$26.17

Table 21 shows the cost savings. For Refurbishment, the savings are from the Rehabilitation costs. For Renovation the savings are from the Base case costs. As expected, savings were least from Rehab and maximum from Renov. For example, for a concrete slab on ground (CSOG) house in ACT, total savings are AUD646.31, AUD708.51, AUD1,862.18 for rehabilitation, refurbishment and renovation respectively. Although renovation can achieve much high energy cost savings, the cost for renovation is generally high.

Table 21. Average heating and cooling cost savings for different dwelling improvements for Class 1 and Class 2 dwellings in each state/territory

State	Scenario	House		Apartment	
		CSOG	Suspended	CSOG	Suspended
ACT	Rehabilitation	\$646.31	\$891.96	\$205.60	\$63.97
ACT	Refurbishment	\$62.20	\$212.44	\$42.28	\$143.73
ACT	Renovation	\$1,862.18	\$2,728.05	\$736.13	\$518.06
NSW	Rehabilitation	\$343.81	\$254.49	\$65.47	\$65.90
NSW	Refurbishment	\$56.17	\$97.57	\$30.05	\$80.03
NSW	Renovation	\$1,020.49	\$994.56	\$305.61	\$372.41
NT	Rehabilitation	\$361.29	\$239.58	\$392.93	
NT	Refurbishment	\$51.64	\$68.12	\$44.58	
NT	Renovation	\$825.07	\$736.23	\$856.81	
QLD	Rehabilitation	\$212.81	\$152.61	\$91.27	\$64.73
QLD	Refurbishment	\$15.11	\$25.57	\$13.64	\$36.85
QLD	Renovation	\$339.15	\$359.36	\$182.16	\$191.47
SA	Rehabilitation	\$534.92	\$392.46	\$102.56	\$290.09
SA	Refurbishment	\$50.40	\$82.42	\$27.30	\$5.36
SA	Renovation	\$1,156.68	\$1,143.63	\$317.49	\$708.53
TAS	Rehabilitation	\$481.52	\$480.39	\$269.33	\$158.49
TAS	Refurbishment	\$64.50	\$187.58	\$70.37	\$148.47
TAS	Renovation	\$1,343.32	\$1,568.00	\$850.01	\$994.51
VIC	Rehabilitation	\$633.82	\$566.26	\$287.22	\$259.60

VIC	Refurbishment	\$64.74	\$163.89	\$68.27	\$140.69
VIC	Renovation	\$1,422.24	\$1,783.39	\$751.26	\$990.38
WA	Rehabilitation	\$373.69	\$274.01	\$288.63	\$80.52
WA	Refurbishment	\$38.96	\$90.02	\$31.98	\$48.35
WA	Renovation	\$701.46	\$991.95	\$495.36	\$679.48

7.2.2 Overheating risks

For overheating risk analysis, the hourly air temperatures in each room of the dwellings were calculated and compared against the rating criteria. If one living room or bedroom fails either one of the overheating criteria, then the dwelling fails the overheating assessment.

7.2.2.1 Results by state

The percentages of Class 1 and Class 2 dwellings that fail and pass the overheating criteria in different states under different climates (that is, current, projected 2030, and projected 2050 climates) are shown in Appendix 7, Figure 2, and in Appendix 7, Figure 3. In all states and territories, there are always a percentage of dwellings predicted to fail the overheating assessment. This occurred across all improvement categories for both houses and apartments, and across all climate years modelled. The percentage of dwellings that failed the overheating assessment did vary depending on climate and was generally reduced as improvements are undertaken. For the Base design, Appendix 7, Figure 2 shows that for the current climate year, the Northern Territory has the highest percentage of Class 1 base design fails at almost 100 per cent, while Tasmania had the lowest (9.4 per cent). For most other states, the percentage failing the overheating assessment is close to 90 per cent. Appendix 7, Figure 3 shows that Class 2 base designs performed slightly better, but the Northern Territory, South Australia and Western Australia all had close to 100 per cent of dwellings failing the overheating assessment. Once again, Tasmania had the lowest percentage failing the overheating assessment (14.1 per cent) while ACT, NSW and Queensland had 65.7 per cent, 52.7 per cent, and 65.9 per cent respectively failing the overheating assessment.

As improvements were incorporated into the modelling, the percentage failing generally reduced. The relatively minor improvement scenarios (Rehab and Refurb) achieved only small reductions in overheating risks, while the major Renov improvement resulted in much more significant reductions in overheating risks. For example, in Victoria the Rehab improvement on Class 1 dwellings results in 69.9 per cent failing (down from the 88.2 per cent in the base design) and moving to Refurb improvement reduces the percentage fail further to 65.9 per cent. The full Renov improvement saw only 46.3 per cent fail. For homes on concrete slabs only 41.8 per cent were still breaching the overheating threshold. However, in the Northern Territory none of the improvements resulted in a decrease in the overheating failure rate.

Modelling against future climate years generally resulted in an increasing number of dwellings failing the overheating assessment. This is to be expected as future climate years have an upward trajectory on temperatures in line with climate change predications. The measure of whether a dwelling will breach the overheating criteria is rather blunt and does not necessarily reflect the extent of overheating to be experienced in the dwelling. The total number of overheating hours a dwelling could experience is variable and depends on the number of zones within a dwelling. Of all Class 1 dwellings, 12.2 per cent experienced less than a total of 50 overheating hours (which is the sum over all living rooms and bedrooms) in the current climate

year, and 19.7 per cent experienced less than 100 hours. The maximum hours modelled (again the sum over all living rooms and bedrooms) for a single dwelling was 13,881 overheating hours. Looking at the average number of overheating hours within a state gives a better perspective on the extent of these events. Appendix 7, Figure 4 shows the average number of overheating hours for Class 1 dwellings in each state, and splits overheating hours into day and night. Tasmania had the coldest climate of any part of Australia, and consequently, the average number of overheating hours was very small for all improvement scenarios modelled. The base design sees an average of 72 overheating hours, and this is reduced to 19 hours under the full renovation improvement. By contrast, South Australia had an average of 1,884 overheating hours for the base design, which reduced by 55 per cent to 839 hours for the renovation improvement.

The Northern Territory saw very high average overheating hours but the majority of these came from overnight overheating in the bedrooms. For example, for the average 4,601 overheating hours for the base design, 4,066 hours (88 per cent) came from overnight overheating. Queensland also modelled more overheating hours during night-time. In most other jurisdictions daytime overheating makes up the majority. Interesting too is that these modelled reductions achieved through various improvements are mainly through reductions in daytime overheating, whereas night overheating hours remain similar across improvements modelled.

Appendix 7, Figure 5, and Appendix 7, Figure 6, show the same analysis for projected 2030 and 2050 climates respectively, and show that as the climate warms the average number of overheating hours increases. Queensland shows a significant increase in the average from the 2030 climate year to 2050, almost doubling from 931 hours in 2030 to 1,753 hours in 2050.

Appendix 7, Figure 7 shows the same analysis for Class 2 dwellings. Again, the Northern Territory had the highest overheating event averages, made up almost entirely of night overheating. Queensland too is dominated by night overheating. Appendix 7, Figure 8, and Appendix 7, Figure 9, show the analysis results for the 2030 and 2050 climate years respectively. Like the Class 1 dwellings, Queensland shows a significant average increase from 2030 to 2050.

7.2.2.2 Results by NatHERS climate zones

Results by NatHERS climate zones reflect the trend seen at the state level with dwellings in cold climate zones experiencing the least amount of overheating. For example, for the base design, Class 1 dwellings modelled, Tasmanian climate zones 67 (Low Head), 68 (Launceston), and 26 (Hobart) recorded respectively only 0.8 per cent, 7.2 per cent, and 8.3 per cent of dwellings experiencing overheating.

As with the states, looking at the average number of overheating events gives a better understanding of where overheating is an actual issue. Appendix 7, Figure 10 shows the average overheating events for Class 1 base designs by climate zone and was restricted to climate zones with at least 10 dwellings. A simple cluster analysis reveals two clusters. Cluster 1 is climate zones with low to medium overheating hours (746 hours average), and is made up of climate zones in most of Australia's populated areas, including all capitals except Darwin. Cluster 2 has a high average of around 5300 overheating hours per dwelling, and includes climate zones from relatively low population central Australian areas and tropical climate zones.

Appendix 7, Figure 11 shows analysis for Class 2 dwellings, again restricted to climate zones with at least 10 dwellings, and showing the split between day and night overheating. Climate 1 (Darwin) dominates, again with night overheating. A cluster of climate zones have a total average overheating between 1,000-1,500 hours,

including Perth (13), Adelaide (16), Townsville (5), Wagga Wagga (20), and Cairns (32). Remaining climate zones generally have total average overheating below 500 hours, including Brisbane (10) and Sydney (17) at 144 hours, Melbourne (21) at 517 hours, and Hobart (26) with only 42 overheating hours on average and which are all daytime hours.

7.2.3 Business-as-Usual scenario

To calculate the potential savings across the entire existing stock, ABS data were used to determine dwelling numbers in each state as shown in Table 22. To determine the split between houses and apartments, the ABS average of 16 per cent of total stock being apartments was applied to all jurisdictions. It was assumed that in the Business-as-Usual scenario, approximately 5-10 per cent of dwellings will be retrofitted by 2030. Applying these savings in Table 21 to 5 per cent and 10 per cent of the entire stock gives the total cost saving in Table 23 and Table 24 respectively. This assumes all dwellings are on a concrete slab and upgrading is done for existing old dwellings.

Table 22. Distribution of apartments and houses in different state and territories

State	Apartments	Houses
ACT	27,996	146,976
NSW	489,323	2,568,946
NT	13,660	71,714
QLD	319,685	1,678,347
SA	115,705	607,453
TAS	36,708	192,719
VIC	401,222	2,106,414
WA	164,762	865,000
Total	1,569,061	8,237,569

Table 23. Energy cost savings, assuming improvements to 5 per cent of existing stock (AUD is written as \$)

Dwelling Type	State	Rehabilitation	Refurbishment	Rehab+Refurb	Renovation
House	ACT	\$4,749,618	\$457,097	\$5,206,715	\$13,684,833
House	NSW	\$44,161,466	\$7,214,885	\$51,376,351	\$131,079,183
House	NT	\$1,295,480	\$185,166	\$1,480,646	\$2,958,460
House	QLD	\$17,858,450	\$1,267,991	\$19,126,441	\$28,460,567
House	SA	\$16,246,930	\$1,530,781	\$17,777,711	\$35,131,421
House	TAS	\$4,639,895	\$621,518	\$5,261,413	\$12,944,143
House	VIC	\$66,754,374	\$6,818,463	\$73,572,837	\$149,791,329
House	WA	\$16,162,094	\$1,685,020	\$17,847,114	\$30,338,148
House	Total	\$171,868,307	\$19,780,920	\$191,649,227	\$404,388,084
Apartment	ACT	\$287,794	\$59,183	\$346,977	\$1,030,417
Apartment	NSW	\$1,601,799	\$735,208	\$2,337,007	\$7,477,101
Apartment	NT	\$268,368	\$30,448	\$298,816	\$585,194
Apartment	QLD	\$1,458,883	\$218,025	\$1,676,908	\$2,911,692
Apartment	SA	\$593,337	\$157,938	\$751,275	\$1,836,763
Apartment	TAS	\$494,333	\$129,158	\$623,491	\$1,560,122
Apartment	VIC	\$5,761,946	\$1,369,570	\$7,131,516	\$15,071,093

Apartment	WA	\$2,377,762	\$263,454	\$2,641,216	\$4,080,823
Apartment	Total	\$12,844,221	\$2,962,984	\$15,807,205	\$34,553,206
Grand Total	Total	\$184,712,528	\$22,743,904	\$207,456,432	\$438,941,290

Table 24. Energy cost savings, assuming improvements to 10 per cent of existing stock (AUD is written as \$)

Dwelling Type	State	Rehabilitation	Refurbishment	Rehab+Refurb	Renovation
House	ACT	\$9,499,237	\$914,194	\$10,413,431	\$27,369,666
House	NSW	\$88,322,931	\$14,429,769	\$102,752,700	\$262,158,366
House	NT	\$2,590,961	\$370,332	\$2,961,293	\$5,916,920
House	QLD	\$35,716,900	\$2,535,982	\$38,252,882	\$56,921,134
House	SA	\$32,493,861	\$3,061,562	\$35,555,423	\$70,262,841
House	TAS	\$9,279,790	\$1,243,035	\$10,522,825	\$25,888,286
House	VIC	\$133,508,747	\$13,636,926	\$147,145,673	\$299,582,659
House	WA	\$32,324,188	\$3,370,040	\$35,694,228	\$60,676,296
House	Total	\$343,736,615	\$39,561,841	\$383,298,456	\$808,776,168
Apartment	ACT	\$575,588	\$118,365	\$693,953	\$2,060,834
Apartment	NSW	\$3,203,598	\$1,470,416	\$4,674,014	\$14,954,201
Apartment	NT	\$536,736	\$60,896	\$597,632	\$1,170,389
Apartment	QLD	\$2,917,766	\$436,051	\$3,353,817	\$5,823,384
Apartment	SA	\$1,186,673	\$315,875	\$1,502,548	\$3,673,527
Apartment	TAS	\$988,665	\$258,316	\$1,246,981	\$3,120,244
Apartment	VIC	\$11,523,891	\$2,739,141	\$14,263,032	\$30,142,186
Apartment	WA	\$4,755,523	\$526,909	\$5,282,432	\$8,161,646
Apartment	Total	\$25,688,441	\$5,925,968	\$31,614,409	\$69,106,412
Grand Total	Total	\$369,425,056	\$45,487,809	\$414,912,865	\$877,882,580

Assuming improvements to 5 per cent of the entire building stock, energy cost savings are estimated to be around AUD185 million, AUD207 million, and AUD439 million per year for rehabilitation, refurbishment to major renovation respectively, in comparison with the base case (without any improvement). Assuming improvements to 10 per cent of the entire building stock, total energy cost savings are estimated to be around AUD369 million, AUD415 million, and AUD878 million per year for rehabilitation, refurbishment and major renovation respectively, in comparison with the base case.

Table 25 and Table 26 show the CO₂ emission reductions by assuming improvements to 5 per cent of existing stock and 10 per cent of existing stock respectively. Assuming improvements to 5 per cent of the entire building stock, total CO₂ emission reductions are 1.57, 1.76, and 3.6 Mt for rehabilitation, refurbishment, and renovation respectively. For improvements to 10 per cent of the entire building stock, energy cost savings and CO₂ emissions reduction are double those for improvements to 5 per cent of dwellings. It is assumed all improvements are carried out with existing old buildings.

Figure 9 and Figure 10 below show energy cost savings and CO₂ emission reductions for Class 1 dwellings by upgrading 10 per cent of the existing old building stock. Figure 11 and Figure 12 show the Energy cost savings and CO₂ emission reductions for Class 2 dwellings by upgrading 10 per cent of the existing old building stock. It is understood that the NatHERS Star rating assumes 24-hour occupancy for 365 days, and also assumes overnight heating and cooling in bedrooms throughout the year. This may overpredict the energy cost savings and CO₂ emissions reductions to some extent.

Table 25. Tonnes of CO2e reductions, assuming improvements to 5 per cent of existing old stock

Dwelling Type	State	Rehabilitation	Refurbishment	Rehab+Refurb	Renovation
House	ACT	38,824	3,417	42,241	104,236
House	NSW	378,020	60,113	438,133	1,070,865
House	NT	13,597	2,205	15,802	30,281
House	QLD	200,143	13,343	213,486	312,424
House	SA	149,069	13,759	162,828	315,815
House	TAS	35,499	4,741	40,240	98,951
House	VIC	509,647	53,398	563,045	1,128,617
House	WA	143,633	14,273	157,906	260,408
House	Total	1,468,432	165,248	1,633,680	3,321,598
Apartment	ACT	2,121	449	2,570	7,571
Apartment	NSW	13,579	5,945	19,524	60,113
Apartment	NT	3,028	340	3,368	6,575
Apartment	QLD	15,249	2,206	17,455	29,587
Apartment	SA	5,623	1,510	7,133	17,356
Apartment	TAS	3,772	969	4,741	11,927
Apartment	VIC	41,226	9,569	50,795	108,330
Apartment	WA	20,365	2,224	22,589	34,526
Apartment	Total	104,962	23,213	128,175	275,985
Grand Total	Total	1,573,394	188,461	1,761,855	3,597,582

Table 26. Tonnes of CO2e reductions, assuming improvements to 10 per cent of existing old stock

Dwelling Type	State	Rehabilitation	Refurbishment	Rehab+Refurb	Renovation
House	ACT	77,648	6,834	84,482	208,471
House	NSW	756,041	120,227	876,268	2,141,730
House	NT	27,194	4,410	31,604	60,563
House	QLD	400,286	26,686	426,972	624,849
House	SA	298,138	27,518	325,656	631,629
House	TAS	70,998	9,482	80,480	197,903
House	VIC	1,019,294	106,795	1,126,089	2,257,233
House	WA	287,267	28,545	315,812	520,817
House	Total	2,936,864	330,497	3,267,361	6,643,195
Apartment	ACT	4,241	899	5,140	15,143
Apartment	NSW	27,157	11,891	39,048	120,227
Apartment	NT	6,057	680	6,737	13,150
Apartment	QLD	30,498	4,412	34,910	59,174
Apartment	SA	11,247	3,020	14,267	34,712
Apartment	TAS	7,544	1,938	9,482	23,853
Apartment	VIC	82,451	19,138	101,589	216,660
Apartment	WA	40,729	4,449	45,178	69,052
Apartment	Total	209,924	46,426	256,350	551,970
Grand Total	Total	3,146,788	376,923	3,523,711	7,195,165

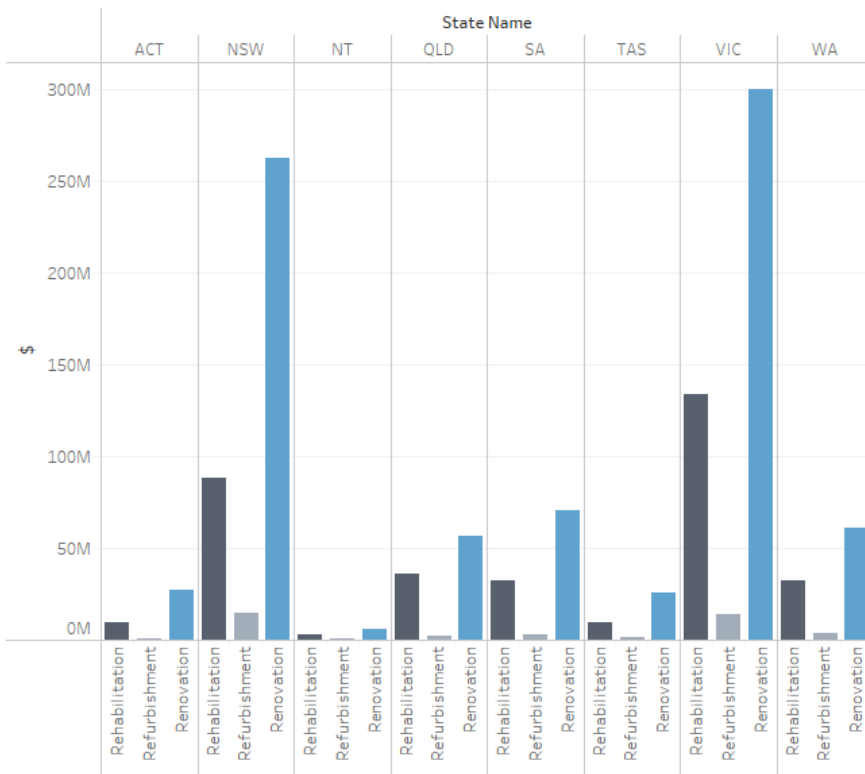


Figure 9. Energy cost savings for Class 1 dwellings from upgrading 10 per cent of existing building stock

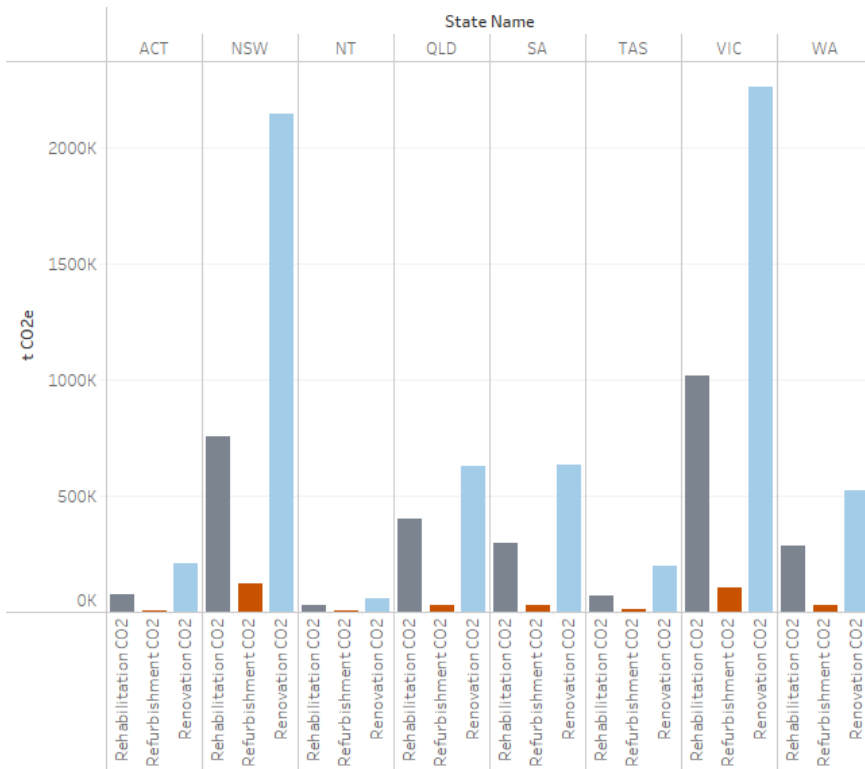


Figure 10. CO₂ emission reductions for Class 1 dwellings from upgrading 10 per cent of existing building stock

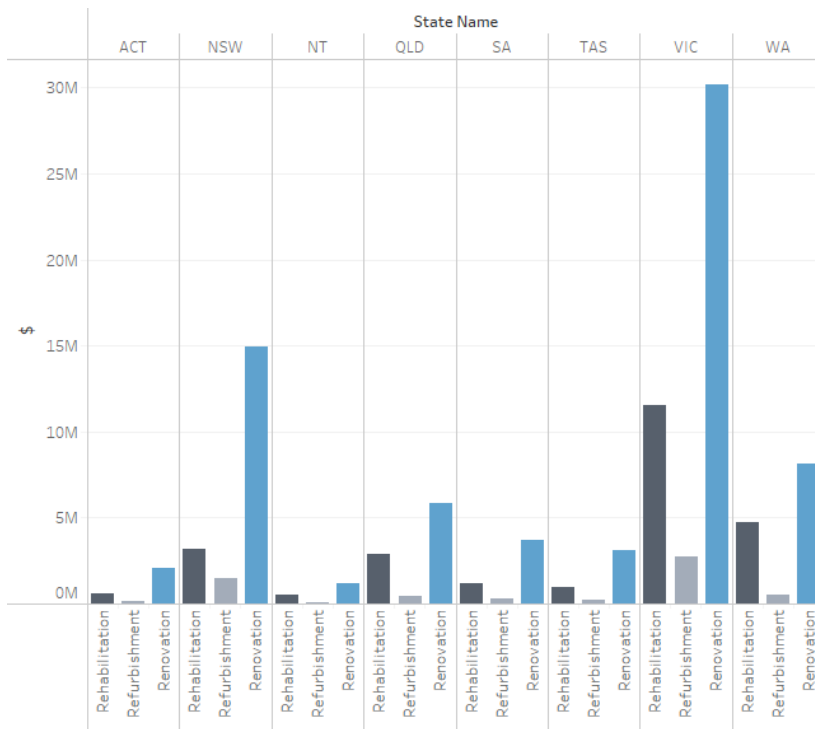


Figure 11. Energy cost savings for Class 2 dwellings from upgrading 10 per cent of the existing building stock

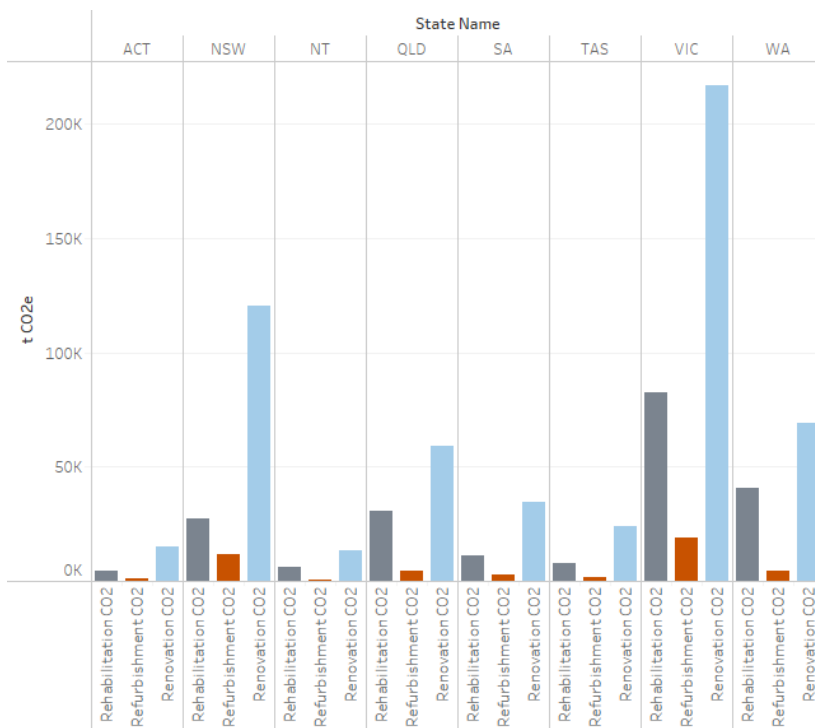


Figure 12. CO₂ emission reductions for Class 2 dwellings from upgrading 10 per cent of the existing building stock

7.2.3 Accelerated scenario

Improving 40 per cent of the entire stock can be assumed as an Accelerated Scenario. Table 27 shows energy savings with the Accelerated Scenario. Energy cost savings and CO₂ emission reductions for Class 1 dwellings from upgrading 40 per cent of existing old building stock are shown in Figure 13 and Figure 14 respectively. Figure 15 and Figure 16 show energy cost savings and CO₂e emission reductions for Class 2 dwellings from

upgrading 40 per cent of existing old building stock. Total energy cost savings are estimated to be around AUD1.48 billion, AUD1.66 billion, and AUD3.51 billion per year for rehabilitation, refurbishment, and major renovation in comparison with the base case. CO₂ emission reductions are estimated at 12.58 Mt, 14.09Mt, and 28.78 Mt CO₂ per year respectively in comparison with the base case.

Table 27. Energy cost savings, assuming improvements to 40 per cent of existing stock (AUD is written as \$)

Dwelling Type	State	Rehabilitation	Refurbishment	Rehab+Refurb	Renovation
House	ACT	\$37,996,948	\$3,656,775	\$41,653,722	\$109,478,665
House	NSW	\$353,291,724	\$57,719,078	\$411,010,802	\$1,048,633,465
House	NT	\$10,363,844	\$1,481,328	\$11,845,171	\$23,667,681
House	QLD	\$142,867,600	\$10,143,929	\$153,011,528	\$227,684,538
House	SA	\$129,975,444	\$12,246,247	\$142,221,690	\$281,051,365
House	TAS	\$37,119,160	\$4,972,142	\$42,091,301	\$103,553,143
House	VIC	\$534,034,989	\$54,547,703	\$588,582,693	\$1,198,330,635
House	WA	\$129,296,752	\$13,480,161	\$142,776,913	\$242,705,182
House	Total	\$1,374,946,460	\$158,247,362	\$1,533,193,822	\$3,235,104,674
Apartment	ACT	\$2,302,352	\$473,460	\$2,775,812	\$8,243,337
Apartment	NSW	\$12,814,392	\$5,881,663	\$18,696,055	\$59,816,806
Apartment	NT	\$2,146,944	\$243,582	\$2,390,527	\$4,681,555
Apartment	QLD	\$11,671,064	\$1,744,202	\$13,415,266	\$23,293,537
Apartment	SA	\$4,746,693	\$1,263,502	\$6,010,195	\$14,694,108
Apartment	TAS	\$3,954,661	\$1,033,266	\$4,987,927	\$12,480,976
Apartment	VIC	\$46,095,566	\$10,956,564	\$57,052,129	\$120,568,744
Apartment	WA	\$19,022,093	\$2,107,634	\$21,129,728	\$32,646,586
Apartment	Total	\$102,753,765	\$23,703,873	\$126,457,638	\$276,425,647
Grand Total	Total	\$1,477,700,225	\$181,951,235	\$1,659,651,460	\$3,511,530,321

Table 28. Tonnes CO₂e reductions, assuming improvements to 40 per cent of existing old stock

Dwelling Type	State	Rehabilitation	Refurbishment	Rehab+Refurb	Renovation
House	ACT	310,591	27,338	337,928	833,886
House	NSW	3,024,163	480,907	3,505,070	8,566,921
House	NT	108,776	17,642	126,418	242,250
House	QLD	1,601,143	106,743	1,707,886	2,499,394
House	SA	1,192,551	110,070	1,302,622	2,526,517
House	TAS	283,990	37,927	321,917	791,611
House	VIC	4,077,175	427,181	4,504,356	9,028,934
House	WA	1,149,066	114,180	1,263,246	2,083,266
House	Total	11,747,456	1,321,987	13,069,443	26,572,780
Apartment	ACT	16,965	3,595	20,560	60,571
Apartment	NSW	108,630	47,562	156,192	480,907
Apartment	NT	24,227	2,721	26,948	52,601
Apartment	QLD	121,992	17,647	139,638	236,695
Apartment	SA	44,986	12,080	57,066	138,846
Apartment	TAS	30,174	7,753	37,927	95,412
Apartment	VIC	329,804	76,553	406,357	866,639
Apartment	WA	162,917	17,794	180,711	276,207

Apartment	Total	839,695	185,704	1,025,400	2,207,878
Grand Total	Total	12,587,151	1,507,691	14,094,842	28,780,659

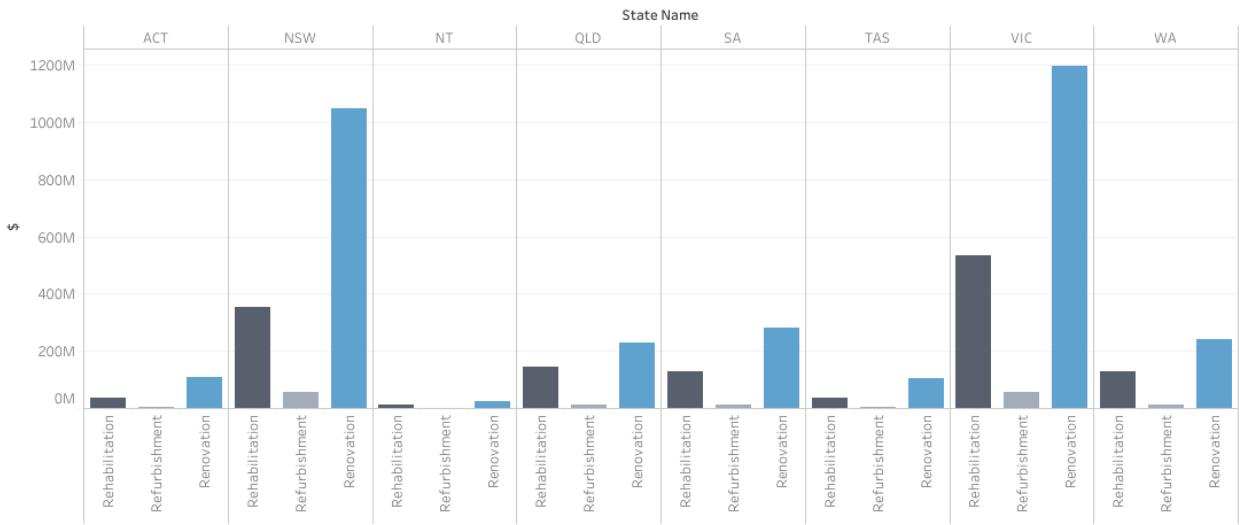


Figure 13. Energy cost savings for Class 1 dwellings from upgrading 40 per cent of existing building stock

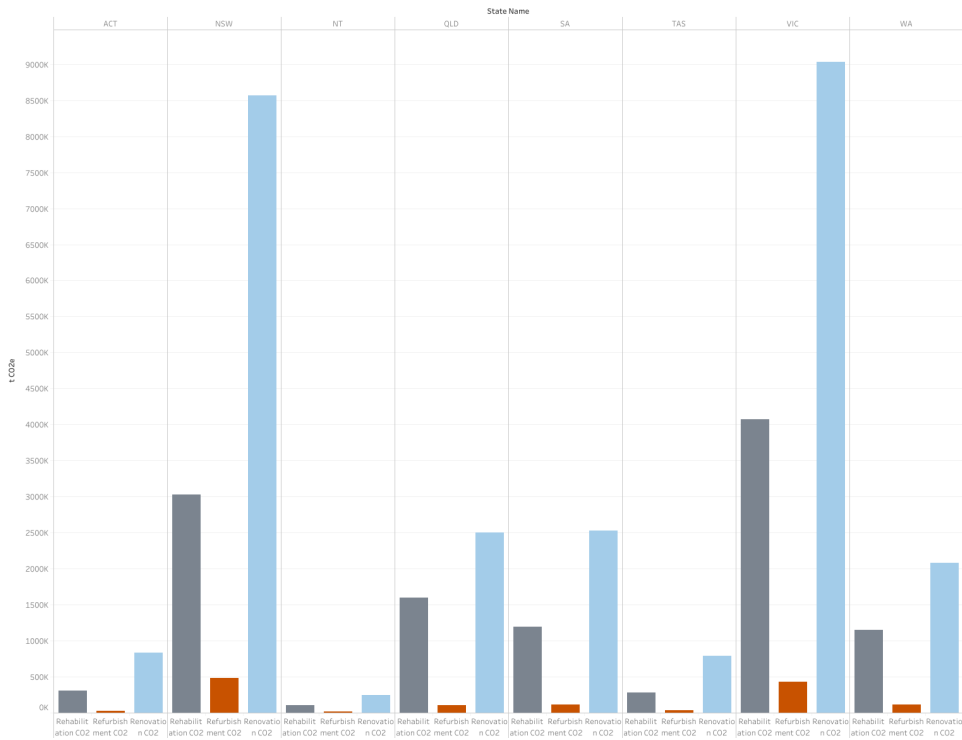


Figure 14. CO2 emission reductions for Class 1 dwellings from upgrading 40 per cent of existing building stock

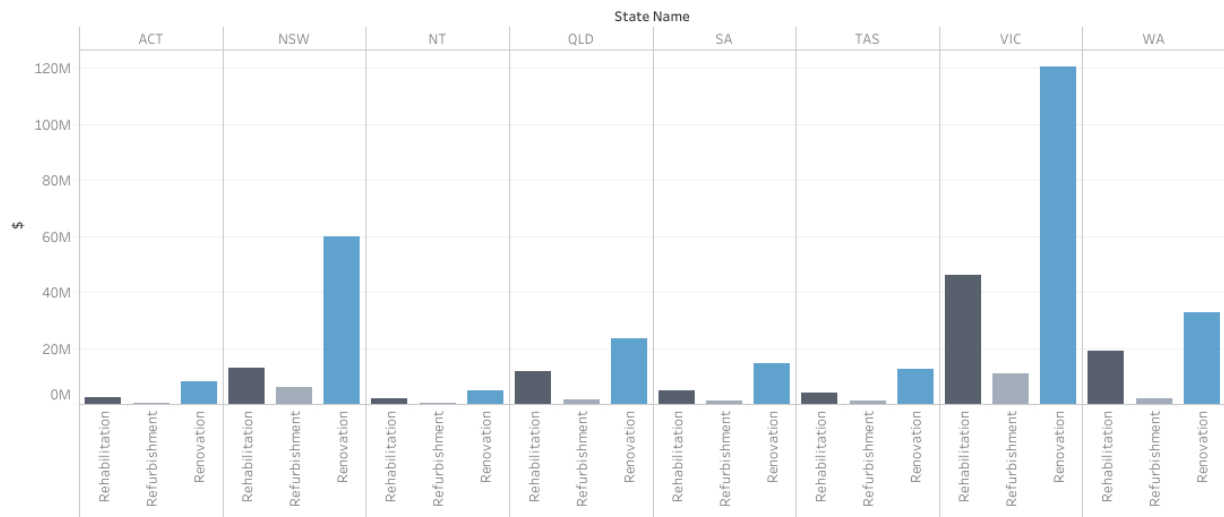


Figure 15. Energy cost savings for Class 2 dwellings from upgrading 40 per cent of existing building stock

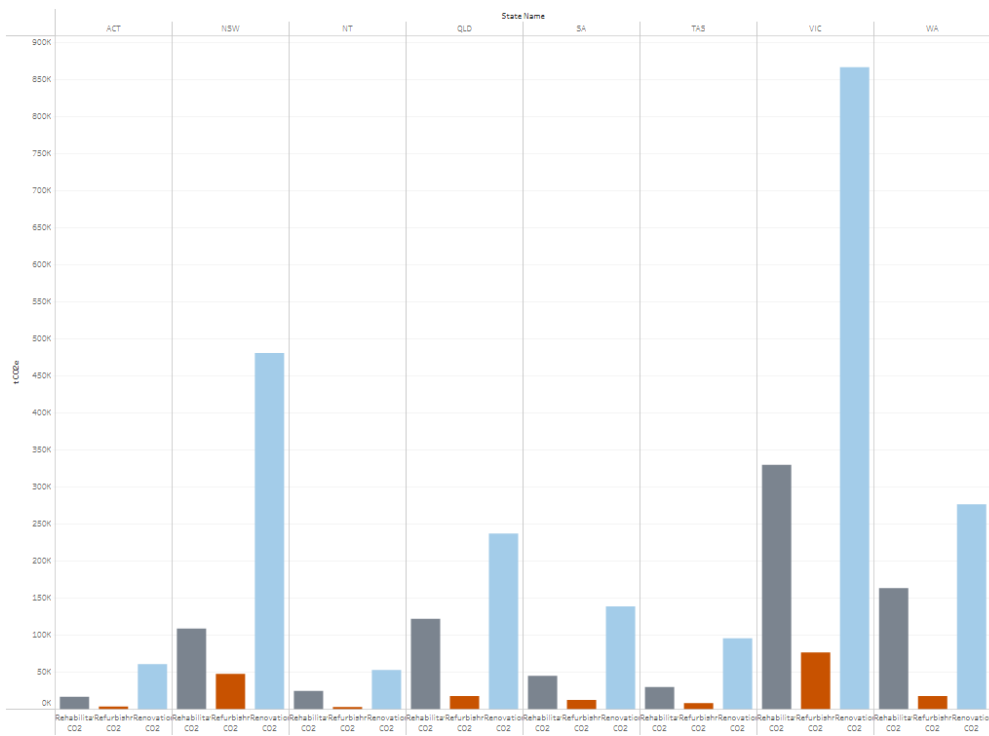


Figure 16. CO₂ emission reductions for Class 2 dwellings from upgrading 40 per cent of existing building stock

8 Barrier Analysis

The barriers identified in this Opportunity Assessment are classified into six broad themes, namely Technological, Capacity Building, Occupant Contribution, Research and Development, Policy and Regulation, and Market and Finance (see Sections 4 to 6). The barriers described below are further mapped out with the cognate research questions to organise research priorities (see Sections 9.3 and 9.).

8.1 Technological barriers

- Lack of awareness, lack of information

Many people, including energy users, have insufficient or limited information about costs and benefits of energy efficiency. Energy consumers often have a general understanding of the benefits of energy efficiency investments, but may not want to go into debt to finance a major energy efficiency upgrade not currently eligible for government subsidies (for example, insulation in all states and territories except South Australia). All stakeholders may have varying degrees of knowledge about the benefits of energy efficiency. Many consumers are unaware that improving the energy efficiency of a home will improve their quality of life. Furthermore, real estate agents have little idea about energy efficiency. A survey conducted by Environment Victoria (2020) found that only 9 per cent of surveyed real estate agents understood the energy star ratings of their properties.

- Incentivising regulations

Though gaining in popularity, incentivising regulations, such as price-cap regulations, are not widely provided for innovative technologies in Australia. An innovative technology can become affordable and accessible if the uptake rate or innovation-cost reduction is controlled by regulated prices. Before taking action, users often need additional financial incentives such as rebates, and credible and reliable information sources.

- High upfront costs

High upfront costs, long payback periods, and lack of capital are some of the barriers to major investments in energy efficiency projects (see Section 5). Research shows that the barriers most frequently cited are capital availability, competing priorities, and lack of time (COAG Energy Council, 2018a, 2019a).

- Market not set for innovative solutions

Benefits of energy efficiency are well known to informed consumers (see Sections 4.1 and 4.2), but regulatory barriers need to be overcome to drive innovation (see Section 4.4).

- Lack of finance, lack of access to capital

For high capital cost interventions such as HRV or smart glass, lack of access to low-cost financial capital may be a barrier. Better access to low-cost capital is critical for improving affordability of energy efficient technologies and transition to net zero with decarbonisation. Also, perception of risks affects confidence to borrow.

- Payback gap

Financial difficulties constitute another commonly mentioned barrier to improving energy efficiency in dwellings. Energy efficiency goals are often secondary to economic considerations and health benefits. Moreover, aesthetic upgrades in homes such as kitchen or bathroom remodelling are taken up as these improvements translate to increased property values. The initial cost-premium barrier causes developers and investors to hesitate before adopting sustainable practices in investments. In lieu of 'payback period'

as an investment criterion, use of rate of return on investment in comparison with cost of borrowing could potentially be more balanced.

8.2 Capacity building barriers

- Underestimating benefits of energy efficiency

There are many stakeholders in the building sector, including designers and tradespeople, who often have insufficient information about what design, material, or technology options can improve energy efficiency, and what costs and benefits of these energy efficiency options are. They often lack the skills to apply this knowledge, or clearly communicate information to clients. This likely results in an underestimation of the benefits of energy efficiency across the building sector.
- Reluctance to adopt change

As the costs and benefits of energy efficiency improvements are not well understood by building sector stakeholders, there is a perception that any change from business-as-usual practices will add costs, time, and complexity to projects. This perspective has resulted in an industry typically reluctant to adopt change. This is evidenced with resistance of key building sector stakeholders to previous improvements in minimum performance requirements in the National Construction Code.
- Limited awareness of upskilling incentives

At state and federal levels, Australian governments' commitment to workforce upskilling has created a framework for funding upskilling programs, and incentives for stakeholders to undertake relevant professional development opportunities. However, there appears to be limited awareness among key building sector stakeholders of the range of support and incentives for upskilling and training. Even where this support is known, additional challenges include stakeholders finding time to attend any upskilling or training opportunities, or reluctance to change practices unless changes are mandated.
- Barriers at the government level

Governments have an increasingly detailed understanding of the benefits of energy efficiency. However, translating that understanding into changes across the building sector through policy mechanisms has been challenging due to limited resources, and politicisation of potential policies and on the ground solutions.
- Lack of access to support and evaluation tools

Consumers make informed decisions on purchases when supported by reliable information. The absence of reliable assessment tools, monitoring and feedback misdirects investments and purchase. Consequently, manufacturers lack incentive to produce more efficient goods. Excessively complex or comprehensive support and evaluation tools tend to be less user-friendly. To be accessible to customers, tools must be concise and effectively summarise vast amounts of data. They also need to be accessible: some tools are not affordable for use by some customers, nor by people in the industry.

8.3 Occupant barriers

- Lack of awareness

Households generally have insufficient information about the benefits of energy efficiency upgrades and are uncertain about the quantifiable outcomes (Sustainability Victoria, 2022d). Benefits may not be noticed; for example, when moving to a new home the improved comfort may be attributed to the local climate, not the building. Savings on energy bills may be offset or masked by increases in prices after the

investment (see Section 4.2). An industry focus group organised by Design Matters National (DMN) noted that consumers are usually the most uninformed stakeholder in the home building process, particularly regarding building energy efficiency. Though consumer awareness is essential for effective thermal performance, we cannot rely solely on consumers.

- Bounded rationality

Bounded rationality is evident when households systematically underestimate benefits of energy efficiency and ignore small opportunities. Households may not invest due to perceived lack of information, contradictory information, or perceived constraints and limitations. They are limited in their ability to process and evaluate information. Apparently irrational behaviour cannot be attributed to too little information, but to the fact that, due to cognitive limitations, people cannot process all the information available to them. Economists and engineers are also limited in their outlook due to bounded rationality.

- Cultural values and misconceptions

There is a significant cultural bias in the energy efficiency industry. This is not necessarily recognised by regulators whose assumptions about market behaviour being economically rational and about a 'level playing field' go far beyond rationality. Present-bias and lack of foresight are other behavioural factors that influence energy efficiency investments. As a result of present-bias, people often prefer to postpone effortful tasks such as investing in energy efficiency into the future.

8.4 Research and development barriers

- Financial constraints

Limited capital and business tax incentives are some of the barriers to major investments in energy efficiency projects. As noted in an IRG meeting, until recently ARENA could not invest in energy efficiency R&D. The Research and Development Tax Incentive offers a tax offset for companies conducting eligible R&D activities. The Incentive encourages investment in R&D that helps companies grow and to innovate. However, the non-refundable R&D tax offset is among the lowest when compared with other international jurisdictions (Peter & Ee, 2018). RACE for 2030 Opportunity Assessment, Developing the Future Energy Force (Rutovitz et al., 2021) notes that maintaining diversity in available financial mechanisms is essential for ensuring adequate and suitable funding is available to support the broad range of energy innovations required to meet net zero ambitions.

- Hidden costs and risks

There are hidden, unnoticed barriers in addition to conventional, well-known barriers like high initial costs. These hidden barriers prevent widespread investment in building energy efficiency. There is a class of barriers not caused by market failures that have been the subject of so many studies. Rather, there are underlying concerns, like regulatory uncertainty, outdated or legacy legislation, and unreliable ratings and standards. This category of unknown barriers increases cost and potential risks.

- Sustainability impact of new materials

The selection of sustainable building materials, along with their impact, is recognised as an important strategy when designing buildings. Perceptions of additional costs, and lack of information about sustainable materials, have been identified as major barriers to choosing sustainable materials. Factors such as embodied carbon (Pomponi & Moncaster, 2016, 2017) and circular economy (Pomponi & Moncaster, 2017) are increasingly considered in material selection. Though many technologies are available to make a home energy efficient, some materials used to build them are themselves energy and

emissions intensive to make. For example, thicker insulation leads to higher embodied energy. As buildings become more energy-efficient, the proportion of embodied will rise making it of similar proportion to operational energy. Therefore, more attention should be paid to embodied emissions.

8.5 Policy and regulation barriers

- Lack of as-built verification

Lack of as-built verification was highlighted by IRG members as one of the key barriers to overcoming the performance gap. As discussed in Section 4.3.7, important factors contributing to the performance gap between design and performance include lack of sufficient knowledge and skills in design and construction teams, and lack of accountability post-construction.

- Regulatory barriers

Policy tools address a variety of market shortcomings and have the potential to serve as complementary regulations. The benefits of certain policies are well-realised if these are complementary. But regulations associated with policy integration are challenging. Regulatory barriers also seem to persist in promoting new solutions for energy efficiency improvements.

- Acceptance of new methods and policies

Policy makers, government organisations, and industry stakeholders may have varying degrees of motivation to change policies or adopt new policies. The involvement depends on the awareness of the knowledge and financial capability of consumers, suppliers, government stakeholders, and consultants. Powerful forces (like businesses and political groups) oppose change in many situations.

- Standards and compliance

Energy policymakers around the world have the challenging task of determining the combination of policies, standards, and compliance measures which will most effectively enhance the current building stock.

8.6 Market and financing barriers

- Payback period

Some energy efficient designs, materials, products, and technologies currently have a higher upfront cost compared to standard options. Consumers want to understand why they would potentially pay more for something, and what the benefits would be for them. Neo-classical market theory holds that consumers will only invest if they believe there is some benefit for them. Within the energy efficiency space, the 'rational consumer' mindset is that they need to receive financial returns (that is, payback) within a short timeframe, and certainly within the period they expect to own, or be in, the building. When the cost of energy efficiency reduces to the point that the wider public sees financial value, this can help scale up adoption, as has been seen with residential solar panels and LED lighting. Typically, consumers have limited understanding about full costs (for example, through-life) and benefits of energy efficiency which limits their capacity to adequately calculate financial payback periods. Furthermore, many consumers do not want to go into debt to secure energy efficiency, or they may have limited available cashflow to spend on upgrades.

- Unreliable pricing

Energy efficient products have typically been more expensive than the products they are meant to replace. This is partly due to limited market penetration, including lack of competition and Australia's

small population compared to some other regions. Furthermore, pricing can vary between similar products or technologies without clear evidence as to why one product or technology may cost more or less than another. The residential solar market is an example of confusing market pricing in Australia. The reliance on an international market for many energy efficiency options also means pricing for these items is often outside the control of market mechanisms in Australia.

- Split incentives

Previous research has indicated a challenge around the 'split incentive' of energy efficiency upgrades, particularly between landlords and their tenants, but also more broadly between builders and dwelling owners. When the owner (that is, landlord) of a home does not pay the energy bills, they usually have little financial incentive to make energy efficiency improvements. The tenants, who pay the bills, do not want to, or are unable to, make major energy efficiency investments in property they do not own. The barriers to split incentives are complex. Many energy efficiency investments can be unaffordable for low-income people and other tenants. Even when a tenant can afford an upgrade, or can access a financial incentive to help cover the costs, they can be reluctant to undertake such activities due to the uncertainty of how long they will be able to stay in the property, or the concern that improvements to the property will result in higher rent. Additionally, there are limitations to what a tenant can do physically to a property. So many upgrades require landlord approval or must be smaller, temporary measures which a tenant can remove when they leave. While there have been recent attempts to provide specific financial incentives in the rental sector, there are ongoing challenges in addressing this split incentive issue.

- Lack of confidence in suppliers

Given the sustainability sector is relatively young in Australia, there is a lack of established, trusted stakeholders. Ongoing issues with quality and accountability from some stakeholders in the energy efficiency space (e.g., previously with some residential solar installers, issues with previous incentive schemes) has caused consumers to lack confidence in suppliers and key trades. While this is being addressed through requirements for certification, training, and improved minimum standards of practice across the industry, consumers are still cautious. This also relates to limited information available to help them evaluate different stakeholders or opportunities. Consequently, consumers often make decisions based upon information from family, friends, or other trusted members of their networks.

- Access to, and uptake of, financial incentives

There is a range of financial incentives provided by different levels of government to help reduce the cost of energy efficient outcomes. Nonetheless, there are ongoing challenges to increasing consumer uptake. This is partially due to lack of awareness of such incentives. There are also concerns about the incentives themselves which inhibit uptake: for example, the paperwork for accessing the incentives is seen as too hard to complete, the incentives are not available to everyone, requirements or eligibility for the incentives change at short notice. Financial incentives are an important mechanism for driving uptake and helping to reduce costs overall through wider market penetration. For rental properties, there are no financial incentives or tax rebates for landlords to replace old appliances with energy efficient ones. Financial incentives must be easier for consumers to access.

- Plethora of small, local suppliers

The commercial building sector has large, state-based and national suppliers which open up opportunities for financial and process efficiencies of scale, particularly market purchasing power through large orders of materials, products, and technologies. There are no such suppliers in the home upgrades market, or even in the new home building market, these markets lack opportunities granted by scale.

9 Research Priorities and Industry Development Opportunities

The Research questions discussed in this section result from an analysis of industry capabilities, taking into account the barriers mentioned in Section 8. Twenty-two research questions were identified through an extensive assessment process which included industry collaboration. These research questions were created to clarify and advance project teams' and industry stakeholders' understanding of the most important research that needs to be done. The research questions were a crucial first step in creating the research priorities presented in Section 9.4. A final IRG workshop was held at which the list of research questions was presented. The list of research questions and industry development opportunities were ranked by IRG members in order of priority.

9.1 Research areas and Research questions

This section will focus on a list of research questions and industry development opportunities that emerged after a detailed analysis of the barriers identified in the earlier sections. Ten specific research areas were recognised from the barrier analysis. Each research area was populated with a number of research questions and they are listed below in Table 29.

Table 29. Summary list of Research questions

Item	Specific Research areas	Research questions
1	Benefits of improved thermal performance	RQ 1 - How can non-financial and co-benefits (comfort, health, and well-being) from improved thermal performance be quantified?
2	Existing home thermal performance assessment	RQ 2 - What reliable tools are available for assessing and evaluating both actual thermal performance of homes, and opportunities for cost-efficient retrofit and improvement?
		RQ 3 - What is required to create a one-stop shop for homeowners which will assist them in undertaking energy efficiency assessments and retrofits?
3	Policy evaluation – impact of mandatory schemes	RQ 4 - How is the existing mandatory disclosure requirement in the ACT facilitating and furthering the energy efficiency agenda?
4	Building fabric (windows/glazing, airtightness, condensation, pre-cooling)	RQ 5 - How can policy makers and the Australian window industry find ways to encourage the adoption of high-performance windows (including glazing) to improve the building fabric?
		RQ 6 - How can air tightness levels be included in NatHERS Star rating to increase the reliability of rating and promote building well-sealed houses as essential and a requirement?
		RQ 7 - How can vapour diffusion and vapour management be identified responsively in building fabric performance? What can we do for the residential construction industry to address airtightness and condensation during the construction stage and during operation?

5	NatHERS tool update	RQ 8 - What research is required to ensure NatHERS responds to new information, evidence, and innovation in design, technologies, and materials?
6	Thermal comfort (vulnerable group, extreme climate event)	RQ 9 - What common heat management strategies are adopted during days of extreme heat? What are the implications of occupant behaviour for energy and comfort?
		RQ 10 - How do extreme summer temperatures impact vulnerable groups in comparison to extreme winter temperatures? How can thermal comfort be addressed under such conditions?
		RQ 11 - How do elderly people respond to extreme temperature conditions? Are those in the low-income category concerned about high electricity/energy bills during extreme temperature conditions?
		RQ 12 - Are 'refuge rooms' a viable, reliable, and affordable option for maintaining safe thermal conditions in extreme weather conditions and/or bushfire smoke events? What pilot project design would support such an evaluation of refuge rooms?
		RQ 13 - Can ASHRAE adaptive model be adopted for Residential buildings in Australian climate zones?
7	Ventilation strategies and air quality	RQ 14 - What are the levels of ventilation and air quality in Australian homes?
		RQ 15 - What are the implications of increased ventilation on thermal comfort and energy consumption during various seasons? How can energy consumption and ventilation be optimised across Australia's varied climates?
		RQ 16 - How are Heat/Energy Recovery Ventilation systems being used and controlled by occupants? What roles can these systems play in both summer and winter?
8	Skills and trades development	RQ 17 - What are the common building specifications, practices, and workmanship for installing airtightness and insulation, air barriers/retarders, and vapour barriers as a basis for improvement?
		RQ 18 - For thermal performance and building construction practices, what are the gaps in existing tertiary education programs (including trades education), and in continuing professional development (CPD) courses?
		RQ 19 - What is required to produce a guide that aids design of course materials and learning environments that meet the diverse needs of tradespeople in the residential building sector?

9	Uptake of incentives/grants and financing options	RQ 20 - What is a current level of uptake by homeowners of incentives/grants for technologies that improve the thermal performance of homes? If the level of uptake needs to be increased, how can that increase be achieved?
10	Home retrofits and decarbonisation	RQ 21 - How can home retrofits support Australia's decarbonisation targets? What is required to achieve a sectoral net zero target? How many houses need to be retrofitted by 2030 to meet decarbonisation targets?
		RQ 22 - What is the role of building thermal performance in the transition from gas to electricity, and the optimisation of future electricity infrastructure and its operation?

The research questions outlined above were further refined to clarify the perspectives of the project team and industry stakeholders on the key research to be conducted. The research questions are therefore an essential component in developing the research priorities presented in Section 9.4.

Benefits of improved thermal performance

RQ 1	How can the non-financial and co-benefits (comfort, health and well-being) from improved thermal performance be quantified?
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- **Strategies to improve the replicability of energy efficiency studies.** The evidence for a causal influence of energy efficiency improvement on better health is inconclusive. The heterogeneity of studies makes it difficult to synthesise the impacts of residential energy efficiency improvements across time, place, population, and housing characteristics. Studies are often limited in outcome measures and restricted to evaluating short-term outcomes using different ways to assess and report the energy efficiency of homes. Strategies to improve the replicability and synthesis of energy efficiency studies are proposed.
- **Mixed method studies for health impacts.** The research revealed that contextual factors are hardly considered in previous studies. The majority of studies are quantitative in nature, looking for summative assessments. However, participant expectations, the quality of homes before the retrofit, workmanship, handover, or the placebo effect receive limited consideration. Also, many studies focused on low-income households, and involved improving the housing of particularly poor-quality houses, but revealed little about program implementation. Mixed methods studies that explore context and try to explain surprising findings are rare.
- **Link between health and residential energy efficiency in warmer climates.** Most retrofit intervention studies, including those completed by Sustainability Victoria (2018), have been conducted in colder seasons and climates where health benefits are derived via improved winter warmth. Such studies should also be conducted during summer seasons. This is particularly important for a country like Australia that has a range of climates, where there is emerging evidence on overheating in well-insulated buildings, and where future climates are likely to be warmer.

Existing home performance assessment

RQ 2	What reliable tools are available for assessing and evaluating both actual thermal performance of homes, and opportunities for cost-efficient retrofit and improvement?
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- **Independently verified, reliable, clear, and accurate housing energy assessments.** Housing energy assessments that provide independently verified, reliable, clear, and accurate information are needed for homeowners to make retrofit decisions. However, designing an effective assessment tool at an affordable cost is challenging. Households may not know what is required, what would be the benefits of particular actions, or how to prioritise and specify improvements. A number of tools exist. Identifying a reliable tool and testing the tool are important steps. Methods of evaluating financial and other benefits require refinement to quantify multiple benefits accurately.

RQ 3	What is required to create a one-stop shop for homeowners which will assist them in undertaking energy efficiency assessments and retrofits?
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- To assist homeowners to complete a retrofitting journey, **a one-stop shop offering all the services required for a complete home energy upgrade** is necessary. This will manage home energy upgrades from start to finish and offer a smooth customer journey to ensure a better outcome in the end. It will also provide ongoing evaluation and enhance capacity for 'learning by doing.' Such a facility can provide homeowners with various contractors and specialists to guide them in the initial home assessment and design through to completion and verification. This includes identifying the best solutions for the house, providing quotes, organising and managing works completion, presenting finance options, and applying for grants on the homeowners' behalf.

Policy evaluation – impact of mandatory schemes

RQ 4	How is the existing mandatory disclosure requirement in the ACT facilitating and furthering the energy efficiency agenda?
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- **Policy evaluation – impact of mandatory schemes.** Energy efficiency disclosure in Australia has been limited to a few temporary voluntary regional trials, and to one long-term mandated scheme under which the Australian Capital Territory House Energy Rating Scheme (ACTHERS) seeks to create an informed housing market by mandating disclosure of residential property energy efficiency performance at the point of sale and rent. A comprehensive review of the ACT mandatory disclosure scheme should be carried out to provide an in depth understanding of the lessons learnt in implementing the scheme. This will assist in understanding the opportunities for rolling out mandatory disclosures in other states. This review will provide insights about the policy infrastructure that can support mandatory disclosure roll out in other states.
- **Evaluation of National Energy Efficiency Scorecard to support mandatory schemes.** The National Energy Efficiency Scorecard is also an important item to consider in the discussion of mandatory disclosure, as it acts as a potential piece for development. It does not identify a performance benchmark but establishes the foundation for mandatory standards to be implemented nationwide. While some stakeholders are reluctant to support a mandatory scheme that would increase the regulatory burden on some industry participants, many stakeholders believe that a mandatory home disclosure scheme is required to adequately transform the energy efficiency of the residential sector.

If disclosure of household energy efficiency ratings becomes required at the time of sale or lease, the market for Scorecard assessments would grow significantly. This would necessitate meticulous management of the pool of Scorecard assessors, including training and quality monitoring.

Building fabric (windows/glazing, airtightness, condensation, pre-cooling)

RQ 5	How can policy makers and the Australian window industry find ways to encourage the adoption of high-performance windows (including glazing) to improve the building fabric?
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- Windows have a significant effect on thermal performance as they are an important source of heat gain and loss. It is widely accepted that high-performance windows in Australia are considered standard practice elsewhere. Based upon the research, the following questions are identified as needing to be addressed. What are the lessons from other jurisdictions to scale up the use of advanced window systems? How can the industry make its products more affordable? How can the public be encouraged to adopt efficient window units? There are some cost-effective methods of retrofitting existing glazing, such as adding an IR anti-reflective coating or an additional glass pane on top of the existing window units. Do they perform as intended? Are they durable? How can their health benefits be assessed?

RQ 6	How can air tightness levels be included in NatHERS Star rating to increase the reliability of rating and promote building well-sealed houses as essential and a requirement?
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- NatHERS methodology assumes better airtightness than the industry can typically provide and therefore underestimates annual heating energy consumption. NatHERS airtightness assumptions should be set to an average level that the industry can achieve, are relevant for each climatic zone, and with options for higher standards of air tightness levels to be included in the software. For builders there is no incentive to build well-sealed houses as currently they are not receiving any benefit for constructing them. Research is required to assist NatHERS team to incorporate better representative air tightness in the prediction. Such provisions are essential to be included in the research to increase the reliability of NatHERS Star rating.

RQ 7	How can vapour diffusion and vapour management be identified responsively in building fabric performance? What can we do for the residential construction industry to address airtightness and condensation during the construction stage and during operation?
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- Vapour diffusion and vapour management are significant issues in the building envelope in Australia. Various local and international research has found that it may take up to ten years for building fabric decay to be visible. Vapour resistance data is needed for all Australian climates in order to simulate hygrothermal analysis within floors, walls, and roof spaces.

NatHERS tool update

RQ 8	What research is required to ensure NatHERS responds to new information, evidence and innovation in design, technologies and materials?
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- Research is required to understand how the existing tool should be developed according to regulatory and policy context. Products and technologies should be constantly updated in the existing tools. NatHERS software tools allow selection of a generic products by assessors. New commercial products

can be included in the database by providing acceptable certified testing results if it is evident the assessor cannot select a generic product for modelling. Improvement and innovation in technologies and products must be linked with site installation and stakeholder requirements. Poor-performing materials (such as poor quality windows, insulation) should be removed from the database progressively. Future climate data inclusion is important as part of the ongoing development. Also, there must be a provision of sensitivity testing to understand the effect of changing climates.

Thermal comfort (vulnerable group, extreme climate event)

RQ 9	What common heat management strategies are adopted during days of extreme heat? What are the implications of occupant behaviour for energy and comfort?
RQ 10	How do extreme summer temperatures impact vulnerable groups in comparison to extreme winter temperatures? How can thermal comfort be addressed under such conditions?
RQ 11	How do elderly people respond to extreme temperature conditions? Are those in the low-income category concerned about high electricity/energy bills during extreme temperature conditions?
RQ 12	Are 'refuge rooms' a viable, reliable, and affordable option for maintaining safe thermal conditions in extreme weather conditions and/or bushfire smoke events? What pilot project design would support such an evaluation of refuge rooms?
RQ 13	Can ASHRAE adaptive model be adopted for Residential buildings in Australian climate zones?

- **Thermal performance during extreme climate events.** Recent research has focused on the concept of 'refuge rooms' that allow occupants to access a limited area of the home that is capable of maintaining, reliably and at an affordable cost, safe thermal conditions in extreme weather conditions and/or bushfire events. Detailed research and pilot projects on building improvements for extreme climate and bushfires are required to analyse and trial their performance.
- **Thermal comfort – vulnerable groups.** In the Australian context, the impact of extreme summer temperatures is becoming more pertinent. Despite the difficulty of managing both underheating and overheating, it seems to be more difficult for older Australians to deal with the summer heat than the winter cold due to less capacity to cope with extreme hot days. Furthermore, climate change is increasing the intensity, duration, and frequency of extreme weather. Extensive research is required for all vulnerable groups as defined in Section 6.2. Ageing populations are globally recognised as an important issue due to increasing pressure on health and social services. Thermal comfort is one of the most researched topics in age-related research in the built environment, reporting some inconsistency in results. Vulnerable populations are most concerned about rising prices, rental availability, and health (Energy Consumers Australia, 2022). Further research should aim to identify the extent to which vulnerable groups are experiencing thermal discomfort due to concerns about high electricity bills.
- **Social housing thermal comfort.** The relationship between extreme weather conditions, poor thermal efficiency of housing, and health risks are well-established for low-income households. Such households could live in thermally poor housing stock and experience trade-offs between energy expenditure and thermal comfort. It is noteworthy that many social housing residents are elderly, thus most of the research reviewed concerns about both elderly people and social housing.

- **Adaptive comfort for energy saving.** International research has aimed at reducing the energy consumption of heating and cooling in the building sector with less sacrificing of occupant thermal comfort. One of the approaches is to re-examine the ASHRAE adaptive model (De Dear & Brager, 2001) as it has been extensively tested in non-residential buildings.
- **Interventions of heat management.** Energy use and thermal comfort of homes are strongly dependent on occupant behaviour. Adjusting setpoint temperatures can lead to energy savings in mechanically conditioned homes. However, some occupants prefer more economical options over energy-based ones. The options used and their effectiveness are not well understood and require further research to understand which interventions could be most effective and appropriate.
- **Winter underheating.** There is an increasing body of research investigating the association between indoor thermal conditions and the elderly in their homes. The first large scale randomised trial into the health impacts and health cost impacts of residential energy efficiency improvements during winter was recently completed in Victoria. The Victorian Healthy Homes program (Sustainability Victoria, 2022c) involved free thermal retrofits and appliance upgrades in the homes of 1000 Victorian Home and Community Care recipients, who are owner-occupiers and suffer from a chronic respiratory condition. However, the potential to generalise findings from this study to the whole Australian population is limited due to the scope of the study. Australia is commonly regarded as summer-climate dominated country having relatively mild climates. Despite this, cold housing is a real and immediate problem for many households as reported in a study of 19 households in Adelaide (Daniel et al., 2019). Further studies involving large sample should be carried out to capture housing quality and the experience of people within their homes.
- **Summer overheating.** The impact of extreme summer temperatures is becoming increasingly important, particularly in densely populated urban centres affected by urban heat island phenomena. Research has started considering both underheating and summertime thermal discomfort (overheating) in temperate climates dominated by heating requirements. However, the results of the current studies are not consistent and less generalisable due to a short monitoring period or small sample sizes. It is recommended that a large scale retrofit trial into the health impacts of energy efficiency improvements during summer be conducted.

RQ 14	What are the levels of ventilation and air quality in Australian homes?
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Ventilation strategies and air quality

Ventilation is often neglected in the design of home heating and cooling. Increased ventilation increases energy consumption as unconditioned, outside air has to be heated or cooled as it replaces conditioned, indoor air that is being exhausted. How is air quality being managed actively (for example, with the use of exhaust/extractor fans, mechanical HRV/ERV (heat/energy recovery ventilation))? What are the needs for cost-effective retrofit options for improving and monitoring ventilation?

RQ 15	What are the implications of increased ventilation on thermal comfort and energy consumption during various seasons? How can energy consumption and ventilation be optimised across Australia's varied climates?
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- Mechanical ventilation systems have been widely used in extreme climates. Methods of optimising their design, control, usage and maintenance in variable and moderate climates of Australia are not well understood.

RQ 16	How are Heat/Energy Recovery Ventilation systems being used and controlled by occupants? What roles can these systems play in both summer and winter?
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- Heat Recovery Ventilation systems are being used to improve ventilation in airtight homes. How do these systems affect the temperature, humidity, and thermal comfort? How do they perform during extreme events such as bushfire smoke, heat, and precipitation events? How can these systems be designed to suit varied Australian climatic conditions?

Skills and trades development

RQ 17	What are the common building specifications, practices, and workmanship for installing airtightness and insulation, air barriers/retarders, and vapour barriers as a basis for improvement?
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- The performance gap between predicted and actual building energy consumption can be significant. Infiltration and thermal bridging from poor design, specification, and construction practices are major causes of energy wastage. A comprehensive and mandatory system which specifies, surveys, and monitors practices, as well as comprehensive building commissioning, will lead to better onsite construction quality control, along with mandatory training, accreditation, and ongoing annual CPD requirements.

RQ 18	For thermal performance and building construction practices, what are the gaps in existing tertiary education programs (including trades education), and in continuing professional development (CPD) courses?
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- Improved training of all trades, highlighting the consequences of poor construction practices, is essential to make sure they are delivering as per the specifications. There may be limited time allocated for going extensively into construction practices in relation to thermal performance. A mapping of existing tertiary education programs (including trades education), training courses and CPD courses to review learning content and skills assessments related to thermal performance and building construction practices is required to do a gap analysis and explore priority areas/actions for capacity building. This can include climate zone specific training materials, practical installation issues and correct ways to address them.

RQ 19	What is required to produce a guide that aids design of course materials and learning environments that meet the diverse needs of tradespeople in the residential building sector?
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Uptake of incentives/grants & financing options

RQ 20	What is a current level of uptake by homeowners of incentives/grants for technologies that improve the thermal performance of homes? If the level of uptake needs to be increased, how can that increase be achieved?
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- Australia needs to dramatically scale up deep renovation and adoption of high-performance solutions. We need to better understand the factors that support or undermine the adoption of measures, such as incentives and subsidies and associated complementary or support mechanisms. Research needs to be undertaken on any legal barriers to the provision of low cost/no cost loans and a new suite of green mortgages and other instruments being adopted by the financial sector.

Home retrofits and decarbonisation

RQ 21	How can home retrofits support Australia’s decarbonisation targets? What is required to achieve a sectoral net zero target? How many houses need to be retrofitted by 2030 to meet decarbonisation targets?
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- The Victorian Gas Substitution Roadmap Report (DELWP, 2022) has identified a combination of energy efficiency, electrification, and alternative gases (such as hydrogen and biomethane) as the best pathway to decarbonise the gas sector. Targeting high gas consumers and high winter electricity consumers for retrofitting to 100 per cent electric, coupled with thermal efficiency upgrades, could accelerate change and optimise cost-benefits.

RQ 22	What is the role of building thermal performance in the transition from gas to electricity, and the optimisation of future electricity infrastructure and its operation?
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As regions with high gas penetrations for space heating shift to electric heating, it will be important to manage winter peak electricity demand, not just for short periods, but also during extended periods of cold, cloudy weather, when variable renewable energy may be limited. This will focus attention on several factors:

- Improved winter thermal performance of buildings. For example, a 6-Star dwelling may require around a third as much thermal energy on a peak winter day as a 2-Star home.
- Replacement of resistive electric space and water heating, which creates high electricity demand in winter when electricity supply and network capacity may be constrained.
- Selection of flexible and efficient electric space and water heating equipment to support demand management and reduce consumption.
- Develop transition strategies to assist with fuel switching. For example, an existing reverse-cycle air-conditioner can be used in parallel with a gas heater to reduce gas consumption and operating costs.
- Consideration will be needed regarding retrofitting upgrades to electrical wiring and appropriate sizing of wiring in new homes, to cope with expected electricity demand. Note that there are ways to reduce these costs through appliance design and control systems.
- Vulnerable households and apartments will require tailored strategies.
- Interactions between building thermal performance and energy supply, storage, and management systems.

Modelling is needed to improve the understanding of the significance of these factors and to develop appropriate priorities.

9.2 Research opportunities – Workshop outcomes

A final workshop was held with the aim of presenting the research findings. Key recommendations were presented, and feedback was welcomed to understand if the opportunities assessed aligned with industry views and priorities, and to determine if anything was missed. IRG members were asked to prioritise and rank the opportunities assessed through the research. The priority research areas are shown in Table 30. ‘Building fabric’ was ranked as the highest priority item, followed by ‘Existing home performance assessment,’ ‘Home retrofits and decarbonisation,’ and ‘Benefits of improved thermal performance.’ The research areas that were analysed and formulated into research questions (Section 9.2) are used to develop research priorities in Section 9.4.

Table 30. Outcomes from research opportunities workshop

Votes for priority research areas	Priority
Building fabric (windows/glazing, insulation, airtightness, condensation, pre-cooling)	1
Existing home thermal performance assessment	2
Home retrofits and decarbonisation	3
Benefits of improved thermal performance	4
Skills and trades development	5
Ventilation strategies and air quality	6
Thermal comfort (vulnerable groups, extreme climate event)	7
Uptake of incentives/grants and financing options	8
Policy evaluation – impact of mandatory schemes	9
NatHERS tool update	10

9.3 Barriers and opportunities

The research areas are streamlined into eight themes for focused intervention, as shown in Figure 17. Barriers and research questions were also grouped accordingly. Accompanying knowledge gaps that still exist today were verified through a discussion with industry stakeholders. These shortcomings, which also emphasise the opportunities now available in the industry are described in the Research questions. The Research questions are also mapped into relevant themes with their linkages.

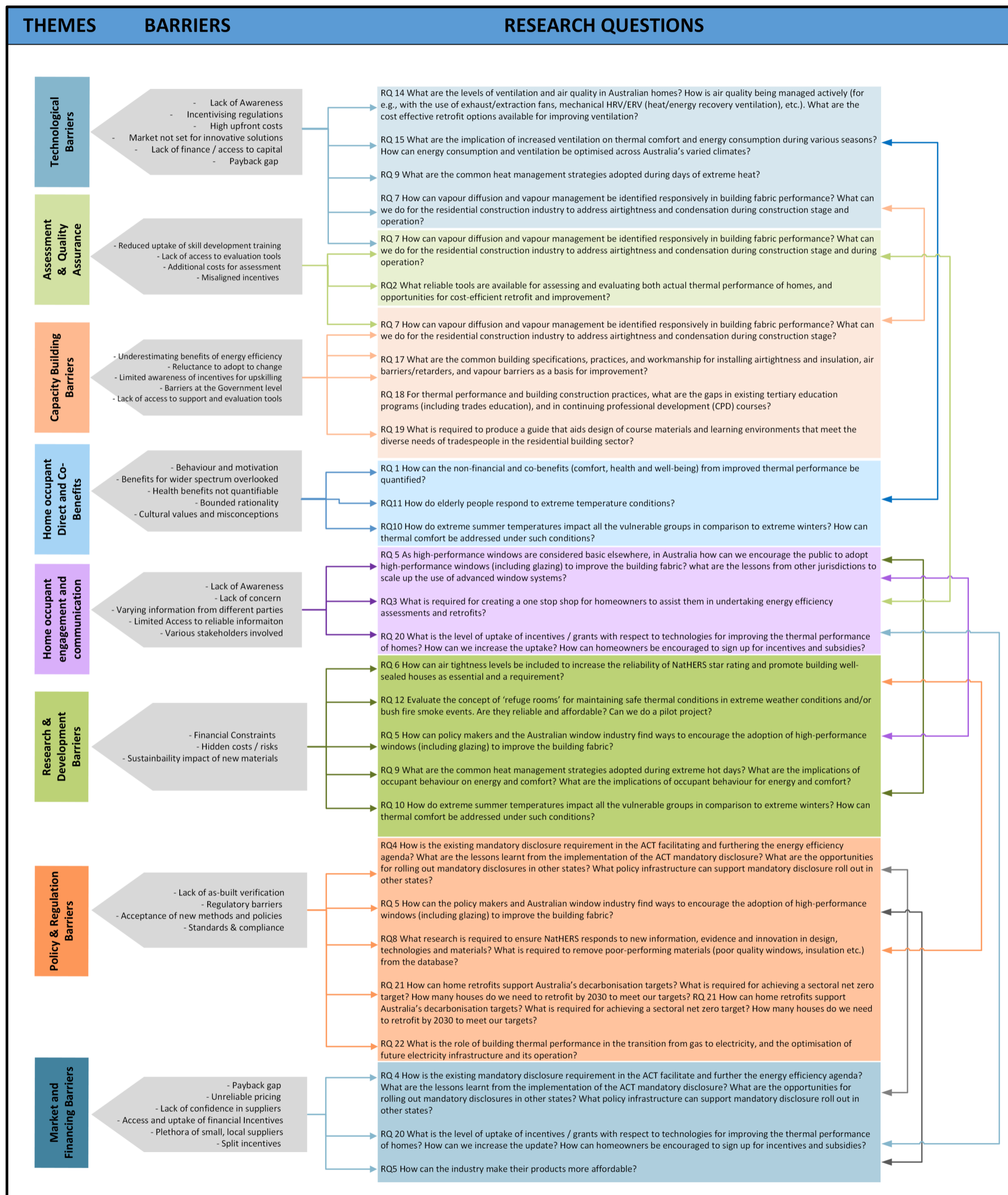


Figure 17. Research questions linked with themes and barriers

9.4 Research priorities

This section outlines eight main themes recognized from the barriers in Figure 18 above, with 22 research questions identified through an extensive assessment process and industry collaboration. The research priorities presented in Table 31 highlights a series of milestones to achieve by 2030 across three timeframes: short-term (1-3 years), medium-term (5 years), and long-term (8-10 years). Each milestone is linked to the Research questions addressed earlier in Section 9.

The eight research themes are as follows.

Technology and envelope performance focuses on the baseline set up of Australian housing thermal performance, including ventilation, indoor air quality, and vapour management.

Assessment and quality assurance will identify and test reliable assessment tools for home thermal performance and select tools for cost-efficient retrofit strategies. This theme also focuses on the assessment of air tightness and condensation in the residential construction industry during design, specification, and construction stages to ensure building fabric performance.

Capacity building and delivery seeks to formulate a guide for developing courses for home thermal performance through investigating building specifications and practices and mapping existing courses for home thermal performance.

Home occupant direct- and co-benefits aims to assess non-financial and co-benefits from improved home thermal performance in ways that more effectively communicate positive outcomes. This includes risk assessment and heat management under extreme weather conditions.

Home occupant engagement and communication will improve public awareness of home retrofit by introducing information and resources such as the 'one-stop shop' and incentives/grants.

Research, development, and innovation aims to provide new research evidence to support home thermal performance. It evaluates new concepts and methods of home retrofit to improve standards, guidelines, and regulations.

Policy support and regulatory framework will support Australia's decarbonisation target by 2030 through home retrofit and product/service innovation.

Market, funding (subsidies) and financing aims to encourage the industry to supply more affordable and more effective products to achieve residential energy efficiency.

Table 31. Research priorities and milestones

RESEARCH THEMES	MILESTONES		
	2025	2028	2030
Technology and envelope performance	<ul style="list-style-type: none"> • Baseline of ventilation and IAQ in Australian housing (RQ14) • Use of heat recovery ventilation systems in Australian housing (RQ16) • Examination of vapour management (RQ7) 	<ul style="list-style-type: none"> • Optimisation of ventilation and energy consumption (RQ15) 	
Assessment and quality assurance	<ul style="list-style-type: none"> • Identification of reliable assessment tools for home thermal performance (RQ2) • Assessment of air tightness and condensation during construction and renovation (RQ7) 	<ul style="list-style-type: none"> • Tool selection for cost-efficient home retrofit strategies (R2) 	<ul style="list-style-type: none"> • Widespread adoption of home retrofit Tools (R2)
Capacity building and delivery	<ul style="list-style-type: none"> • Investigation of building specifications, practices, and workmanship for managing air tightness and condensation (RQ17) 	<ul style="list-style-type: none"> • Mapping existing education, training, and continuing professional development (CPD) courses for home thermal performance (RQ18) 	<ul style="list-style-type: none"> • Formulation of a framework to guide development of courses for home thermal performance (RQ19)
Home occupant direct- and co-benefits	<ul style="list-style-type: none"> • Risk assessment for extreme weather conditions (RQ10, RQ11) • Assessment of non-financial and co-benefits from improved home thermal performance (RQ1) 	<ul style="list-style-type: none"> • Examination of heat management for vulnerable groups (RQ10, RQ11) 	<ul style="list-style-type: none"> • Development of guidelines for heat management of vulnerable groups (RQ9)
Home occupant engagement and communication	<ul style="list-style-type: none"> • Public awareness of adopting advanced high-performance window systems (RQ5) • ‘One-stop shop’ for home retrofit program (RQ3) 		<ul style="list-style-type: none"> • Public benefit campaigns for home retrofit incentives/grants (RQ20)
Research, development, and innovation	<ul style="list-style-type: none"> • Examination of the ASHRAE adaptive thermal comfort model in Australian homes across different climate zones (RQ13) • Examination of common heat management strategies during extreme hot days (RQ9) • Thermal comfort under extreme weather conditions (RQ10) 	<ul style="list-style-type: none"> • Evaluation of the ‘refuge rooms’ concept for extreme events (R12) • Evaluation of new methods of retrofitting existing glazing (RQ5) 	<ul style="list-style-type: none"> • Quantification/inclusion of air tightness in NatHERS (RQ6)

Policy support and regulatory framework	<ul style="list-style-type: none"> • Examination of lessons learned from the ACT energy efficiency disclosure requirements (as being discussed in the Residential Energy Efficiency Disclosure Initiative government forum) (RQ4) • Identify the role of home thermal performance in the transition to electrification (RQ22) • Review of mandatory energy efficiency schemes and gap analysis for maximum impact for households (RQ4) 	<ul style="list-style-type: none"> • Promotion/inclusion of new design, technologies, and materials in NatHERS and/or alternative assessment tools (RQ8) • MEPS for homes at point of sale & rental (RQ4) 	<ul style="list-style-type: none"> • Support Australia’s decarbonisation target through home retrofit (RQ21)
Market, funding (subsidies) and financing	<ul style="list-style-type: none"> • Impact assessment of rolling out mandatory residential energy efficiency disclosure in other states (RQ4) 	<ul style="list-style-type: none"> • Encourage the industry to supply more affordable products. Explore sources of funding – existing and new (e.g., EUAs in Vic for homes) (RQ20) 	<ul style="list-style-type: none"> • Suitable financing options and incentives available for each type of household and ownership models (private & public renters; landlords; owner-occupiers; those experiencing financial hardship; indigenous housing) (RQ20)

10 Appendices

Appendix 1: Workshop participants & IRG members

- Australian Glass & Window Association (AGWA) – Clinton Skeoch (Executive Director)
- Australian Institute of Refrigeration, Air conditioning and Heating (AIRAH) – Tony Gleeson (CEO)
- Australian Sustainable Built Environment Council (ASBEC) – Alison Scotland (Executive Director)
- Brighte – Riccardo Pagliarella (Energy Regulatory and Policy Manager)
- Climate-KIC – Karla Fox-Reynolds (Principal Innovation Projects); Katie McKenzie (Principal Project Developer)
- Department of Planning, Industry and Environment, NSW – Kevin Yee (Senior Policy Officer-BASIX)
- Department for Energy Efficiency and Climate Action, Victoria – Alberto Garza Barragan (Manager, Residential Energy Efficiency); Romney Bishop (Senior Project Officer-Scorecard)
- Department of Industry, Science, Energy and Resources – Claudia Papandrea (Assistant Manager, Residential Energy Efficiency; David Rochford (NatHERS Operation)
- Design Matters National – Vicky Marshall (Senior Manager, Thermal Performance and Sustainability)
- Energy Consumers Australia – Kerry Connors (Director, Energy Inclusion)
- Energy Efficiency Council – Rob Murray-Leach (Head of Policy); Julianne Tice (Project Officer)
- Fletcher Insulation – Roger Pecnik (National Marketing Manager)
- Green Building Council of Australia (GBCA) – Elham Monavari (Senior Manager – Green Star Operations Transformation)
- Insulation Council of Australia and New Zealand (ICANZ) – Dennis D’Arcy (President)
- Jason Windows – Joe Reardon (Product Development and Quality Manager)
- Master Builders Association (MBA) – Max Rafferty (National Manager)
- MIRVAC Group – James Harvey (Senior Portfolio Manager)
- Pro Clima Australia – Jesse Clarke (Innovation and R&D Manager)
- RMIT – Alan Pears (Senior Research Fellow)
- RMIT – Priya Rajagopalan (Professor)
- RMIT – Mary Myla Andamon (Senior Lecturer)
- RMIT – Kretheke Natarajan Rajeswari (Research Assistant)
- RACE for Homes, RACE for 2030 – Ilaria Barletta (Program Manager) observer only
- Sustainability Victoria – Toby Cumming (Team Leader, Research)
- The Air Tightness Testing and Measurement Association (ATTMA) – Sean Maxwell (Scheme Manager)

Appendix 2: IRG Workshop 1 – Output

The H2 OA’s first IRG workshop was held on 13th April 2022 with 17 participants. The workshop’s purpose was to understand the research project scope and intended outputs, provide input to the expected project outcomes, and answer direct industry-related questions.

The key suggestions and points are outlined below.

- To consider Mark Dewsbury’s (TAS) research on mould and condensation and the impact of 7 Stars
- Evaluate the value of thermal assessors in the early stages as currently thermal efficiency elements are being overlooked onsite

- Lack of as-built verification and care factor is a key barrier
- Retrofitting existing homes is critical as ~90% of the homes that will exist in 2030 already exist

Expected project outcomes

- Energy efficiency must not be looked at in isolation – include building physics principles
- Common agreement across all states and territories via research
- Highlight adjacent industry opportunities and independent perspective
- Guide future research and policy objectives
- Vulnerable group can be a broader group than low-income households
- Enable policymakers to see effective solutions, and linkages with complementary programs
- Training on installation practices, scoping of training, and skill shortfalls required to build an energy-efficient future.
- Educate industry well to achieve net-zero carbon targets
- Investigate whether Deemed to Satisfy (DTS) or performance-based approaches have different real-world outcomes
- Map of the supply chain (materials, labour) and links to the regulatory environment. E.g. training and product adaptations to Australia
- Incentivising homeowners with rebates to take action with examples from USA Energy Star
- Support upsizing as-built verification sectors like blower door testing
- Robust Evidence base which can also resolve the nexus between efficiency, health, and finance
- Challenge the Australian standards to improve build quality
- In the Alts and Adds space, the value of retrofit thermal window film appears to have been overlooked in the discussion
- Use healthy building backdrops to drive energy efficiency. E.g. minimum U-values on windows & frames to prevent condensation
- Define “building quality”. Drive building quality in which energy efficiency is part of it, but also includes health, durability, weatherproofing, fire acoustics, etc.
- Ensure there is no overlap with the upcoming Australian Energy Employment Report

Information / Insight Received

Costs – Current supply chain issues with material costs increase – experienced up to 65% increase in the cost of glass (since April last year), due to supply and demand changes, as ongoing fluctuations impact on current cost estimate modelling (Components & Materials).

Thermal Solutions

- Insights into NatHERS thermal performance assessor industry.
- Inclusion of solar thermal solutions & heat pumps – Electrically heating water can account for between 30 – 40% of a home’s energy consumption.

ECA insights - with consumer surveys and research on consumer preferences and values about the energy efficiency of housing

Benefits of this Opportunity Assessment

- Insights into multiple policy levers to justify and support energy efficiency improvements for new and existing buildings.
- Inform programs now and into the future with many low-hanging fruits focusing on improving home thermal efficiency with building fabric and standards.
- Support thermal performance assessor accreditation and the elevation of the value of the thermal performance element of building design and construction.
- Supports our advocacy to the government to prioritise housing energy performance standards.
- Develop scope and clarify a direction of opportunities for progressing the initiative.
- Something alike to The Power Shift Multiple Impacts Framework (Multiple Impacts Framework (energyconsumersaustralia.com.au)).
- Robust construction details that provide actual outcomes and delivery energy efficiency without excessive energy losses and thermal bypass.

Practical Barriers for Retrofits

- Poor quality information/confusing information for consumers.
- Challenge to move industry skills into computerized numerical control manufacturing at scale for window upgrades.
- Complex scope and lack of understanding of the value of investment.
- Different jurisdictional regulatory regimes/policy settings serve to weaken incentives for change.
- In design, passive elements are well captured - active controls more poorly offered generally.
- Lack of regulatory requirements for skills development, impacts the lack of capability or knowledge.
- Lack of capability or knowledge of the tradespeople due to the lack of regulatory requirements.
- Trades not equipped to verify what's on the ground.

Market Readiness of Energy efficient technologies

- The necessary materials and technologies are available from abroad, but need some adaptation to Australian standards (e.g., be tested to get a Regulatory Compliance Mark).
- Cost understanding of consumers' choice is confused by different supplier opinions which can be due to supplier ignorance or consumer ignorance or method for verification. Misinformation confuses consumer opinion of the justification for the spending.
- Trades have the right skills and certainly not enough to properly inform a homeowner.
- The retrofit market will be difficult to regulate if there is no performance reference data to compare what the 'expected' performance improvement would achieve. Currently no available historical data for retrofits.

Technological barriers to improving home thermal efficiency

- Active technology⁹ control schemes are expensive even if properly integrated.
- Three costliest items with the biggest pushback are double glazing, MVHR, and condensation management, due to lack of supplier knowledge and product availability.
- Some necessary technologies (e.g., vapour retarders on wall assembly interiors) considered so basic in building codes of other countries, are considered an added cost here due to a lack of awareness of sustainability principles and energy efficiency.
- Some systems of products (ventilation for example) have been in codes abroad for many years, so they have a whole industry that organised itself to provide solutions. Example: Home Ventilating Institute in U.S. rates fans for sound, energy, and performance. Private industry body, providing product solutions for a code requirement for ventilation.

Impact of 7 Star Homes and choice of materials

- Window industry can meet the industry capacity.
- Site orientation is a critical fact that needs to be considered by town planners and developers.
- 7-Star homes look different on every block. As the minimum energy Star rating for new homes is increased to 7 Stars, exact shift on how buildings will change is unknown.
- 8-Star homes are possible with affordable materials and has been practically proven.
- Government's role and plan - Government mandates with a clear pathway will bring in training infrastructure and skills. Mandatory testing will identify the issues and the next step is to upskill.
- Cultural change without policy and regulation is possible when people understand the need for thermal comfort, which happened during Covid lockdown and increased expenditure on home comfort.

Increasing consumer knowledge

- Design Matters have been engaged to deliver NZE training to the builder.
- Load shifting knowledge is required to match usage with solar energy.
- Clean information without any ties with products or price; helps make a good investment.
- Voluntary schemes need marketing backing for greater uptake.

Miscellaneous Comments

- Move to improve dynamism of energy tariffs from both network and retail tariffs. Consumers subjected to greater price volatility. What gets overlooked is thermal storage (e.g., water tank or bricks in a box or HVAC or understanding thermal leakage).
- Work in unregulated finance space. Have 6 digits of customers just for solar PV.
- Need to make connection with finance system. Government can probably get green bonds as well.
- Rehab, refurb, renovate – 3 types of retrofits. Some housing stock is so bad that can spend AUD4k and really transform it.
- The value of affordable efficient solutions compared to expensive ones are unknown.

⁹ Active Technology - Buildings operate based on a mix of passive and active systems. Active systems include provision of artificial lighting, heating, cooling, ventilation, and operation of household appliances and equipment. In relation to thermal performance, active systems refer to heating, cooling and ventilation.

Appendix 3: Government Workshop - Output

The H2 OA's Government workshop was held on 18th May 2022 with 23 participants. The workshop's purpose was to understand the research project scope and intended outputs, provide input to the expected project outcomes, and answer direct government related questions.

Inputs for Research

- Healthy Homes results on thermal comfort over winter, energy use, health, quality of life
- Information on industry skill gaps and opportunities for training in NZE Homes
- VEU upgrades data, available from VEU website
- Energy Savvy Upgrades evaluation due second half of 2022 will give insights into motivations of low-income households to person upgrades including level of financial assistance, impacts of Covid

Expected Outcomes (What would be good research proposal outcomes?)

- Customer segmentation (willingness to pay for energy efficiency improvements) and related barriers
- Cost-benefit modelling of retrofits, with benefits widely defined
- How to create upgrades market in apartment sector and overcome some of the barriers?
- Clear guidance on highest impact/most 'cost-effective' retrofit options
- How does Energy efficiency support the transition to electrification?
- Learnings from overseas and options to move forward from policies and programs outlined in the Trajectory report - how can we move forward?
- Product supply chain analysis on cost and availability - do we need to manufacture here?
- A pathway to up-skilling trades for this scale of program and how many of each, where and by when
- Pathways for disclosure frameworks
- Behaviour change interventions - identifying what interventions can be implemented, which are the role of government, and which are the role of industry
- We still lack clear data on the Energy Rating status of existing 9.5mill homes. Hard to sell the retrofit story while the problem is not understood

Benefits of Research (*What outputs would be useful to you and your department?*)

Quantitative Data

- Quantitative information on costs and benefits of improving thermal performance of existing housing, jurisdiction specific.
- Some mapping of the retrofit industry - where are the biggest gaps in skills and capabilities?
- Some breakdowns of the impact of different upgrade types, with a focus on electrification.
- Government will be reviewing the Trajectory for Low Energy Buildings in the next 12 months. This research will support that work.
- Number of households requiring upgrades by jurisdiction and by cohort (financial level).
- Identifying the broader economic benefits of retrofitting inefficient homes (~8 million in Aus). Impacts on jobs, industry, etc.
- Research that advances the implementation of thermal efficiency upgrades (e.g., focus on trials).
- Hard data we can use to enlist commitment to NZE Homes from both homeowners and industry delivery.

- Seeking funding for future programs to assist low-income/vulnerable households.
- To inform the regulatory standards of thermal efficiency and energy efficiency from upgrades/renovations of existing homes (NCC or BASIX in NSW).

Social License

- If improvements are voluntary, how do we motivate people to perform upgrades - missing link between a public call for more action on climate change and personal responsibility to implementing change.
- What is the vision that will get people to act?

Current policy gaps

Mandatory Disclosure

- Mandatory disclosure of energy efficiency is needed.
- The potential of mandatory disclosure as a market and industry DRIVER not receiving enough prioritisation by the government in bigger picture.

Standards

- More comprehensive and national minimum rental standards
- Standards for assessment of insulation install using tools such as thermal cameras
- Ensuring verified energy efficiency compliance in NCC
- Compliance of energy efficiency upgrades that require development approvals

Incentives

- Electric vehicle uptake incentives as part of the home energy efficiency picture.
- No minimum emissions standards for vehicles.
- To drive 'mandatory disclosure' retrofits we will need financial/Council rating/tax incentives.

Gas

- In VIC policy to connect gas to new housing developments
- Gas substitution roadmap being developed in VIC, but still not finalised (will be finalised during submission)
- The Hydrogen gas options (e.g., in SA) are not clearly part of the electrification/de-gasification discussion.

Other

- Lessons learnt with past mistakes
- Lack of inclusion of social housing in energy policy debates
- Structural disconnect in most jurisdictions between those committed to building performance and those responsible for the implementation of building standards
- Taxation reform to support landlords upgrading rental appliances with more efficient models, rather than like-for-like

Relevant schemes currently active in respective regions

- Environmental Upgrade Finance - not currently used
- Minimum rental standards - heating + dishwashers
- VEU, Solar Homes, Home Heating and Cooling Updates, Residential Efficiency Scorecard
- NSW Energy Security Safeguard - methods for residential to create Energy Saving Certificates
- NatHERS, inc. The Whole-of-Home and In-Home (underway)
- Energy efficiency upgrades in Social Housing (thermal and appliance upgrades)
- SA Retailer Energy Productivity Scheme (REPS)
- BASIX in NSW - setting the thermal performance and energy efficiency standards of alterations and additions of existing homes with cost of works of at least AUD50k, or pool/spa with a capacity of at least 40,000L.
- WA Household Energy Efficiency Scheme (HEES)

Transition to electrification

- Policies are more technology-neutral - due to the political nature of the gas.
- Policies will need to incentivise battery storage (e.g., EVs with vehicle-to-grid capacity).
- Policies around specific renewable energy zones that integrate with the existing electricity network.
- Solar Homes rebates, including home heating and cooling upgrades.
- We need to remain cognizant that the Whole-of-Home rating is for a building's lifetime (50 to 70 yrs) but PV systems may deteriorate between 15 to 20 years. So LONG-TERM supply planning is critical
- Cost-benefit modelling to inform policy development.
- Very important that cost-benefit analyses consider benefits holistically – energy savings, health benefits, quality of life gains – over the full life of the upgrade's effects (e.g., 30 years).
- The cost of doing nothing – currently the base case in CBA assumes that net costs and benefits are 0. In the context of thermal performance and energy efficiency policy (new + existing homes), this assumption may not be appropriate. Doing nothing may result in additional costs – health costs due to heat stress for example.

Data Availability to Inform policy decisions

- Not enough data is available for existing homes in NSW. Only available for Victoria.
- One of the objectives of the disclosure framework is to create a database of the ratings of existing homes.
- Ratings are important in understanding the quantum of funding required to lift home ratings from one band to another and support policy decisions.
- Data currently available is focused on new homes - such as CSIRO AHD dashboards and NSW BASIX data for new homes. We need data related to existing homes to inform policy decisions such as disclosure.
- New home data can be used as the starting point of existing homes if we are certain that their construction is completed.

Industry training addressed through government schemes

- No incentives, no drivers, and no mandating of CPD in the vast majority of construction.
- One good Covid outcome is greater on the lining of training. Builders previously had a strong resistance to “self-learning” but with the right design, we should be able to reach more practitioners online.
- A lot of training in the trade sectors is very poorly delivered.
- The Workforce Skills Set Fund (WSSF) is a funding program that will invest in targeted training to meet emerging industry needs, as well as specialist and regional needs for employment outcomes.
- The Regional and Specialist Training Fund (RSTF) is a targeted funding stream that supports training for specific skills in regional and specialist areas that are not being met by the current training market.
- Sustainability Victoria’s 7-Star plus program is working with builders to upskill them to get to 7 Stars with full as-built verification. This is only for new builds, though.

Appendix 4: IRG Workshop 2 – Output

The H2 OA’s second IRG workshop was held on 15th June 2022 with 22 participants. The workshop’s purpose was for the research team to present the research project update and research outcomes so far. The IRG provided feedback to the research team and the research team asked further direct industry related questions.

Comments on Research Opportunities Assessed So Far

1. Information on the benefits of installation of “advanced” window technologies
 - Item one is important as it is often the last item to be considered
 - The standards for window installation needs to be re-written for high-performance windows. The target would be to standardise these details for different framing technologies, but the driver is weather tightness not energy. High performance windows need high performance installation
2. Minimum standards for windows
 - Remove the worst performing products from the market to improve consumers ability to choose well, and designers/builders/installers ability to provide the best solution
3. Clear cost-benefit analysis information with updated cost figures
 - Cost comparison between actively designing new buildings for better energy efficiency compared to upgrading an existing stock building design
4. Quantifying non-financial benefits (health, comfort) of improved thermal efficiency
 - Yes
5. In-depth study on reasons behind reduced uptake of incentives
 - It would be good to know the impact of initiatives such as Green Home Loans on driving demand and value of buildings that can demonstrate better performance
6. Training – Updating formal curriculum for trades
 - Management of thermal insulation installation for builders and project managers
 - Creating education for trades is difficult due to the high degree of flexibility in the system especially with NatHERS
 - Education should be climate zone specific
 - Although standards are not meant to be a training manual, they are! So we need high performance standards developed outside of Standards Australia

7. Training – Correct installation of thermal insulation materials and sealings
 - Training for management and sign off of thermal insulation installation for builders and project managers
8. Australia should develop a national construction supply chain strategy – procurement issues and Australian manufacturing
 - Forestry & milling to meet the supply needs for sustainable construction – timber is considered the most sustainable structural material for housing
9. Policy evaluation – Evaluation of mandatory disclosure using ACT as a case study
 - What has been the impact of having mandatory disclosure for homes in the ACT for energy efficiency?
 - The ACT as a base case is a good plan. However, they used a different metric for new and existing homes which just created confusion in the market
10. Policy support – Minimum Energy Efficiency Standards for Rental housing
 - It is important that the MEESRH are clear and measurable (or verifiable) standards. NatHERS is amorphous. E.g. making window standards will signal to the supply chain that this is the market standard and give them certainty. This example is true for the whole market – this is a cultural transition, the expectation needs to be clearly set
11. Policy support – Mandatory disclosure for rental homes
 - Representative of DISER stated that their understanding is that the intent of mandatory disclosure is to declare the energy efficiency performance at both point of sale and rental
 - Mandatory disclosure should be considered for all residential properties
12. Policy support – Apartment energy benchmarking and retrofitting in states other than NSW
 - Very difficult space (new and existing) with effort from DISER active
13. Defining multiple occupancy standards. E.g. occupancy schedule for various vulnerable people etc.

Largest Gaps to be filled by RACE research projects as a whole

- Tools for finding the visible weak points of airtightness
- Use thermal cameras to assess the building's thermal performance
- Education on ROI for new build and refurb
- Air leakages and thermal performance to be disclosed at the point of sale or rental
- New technologies are a distraction. All the technologies are already existing, and they need to be first implemented on a mass scale and integrated together correctly.

Reasons for Reduced Uptake of Incentive Schemes and Skills Training

- Complacency, resistance to change, lack of robust and consistent policy, lack of consumer understanding that will create market-driven change
- Skills training key focus has become about making money and not gaining knowledge
- Tension between in-person and virtual training
- Home thermal efficiency is amorphous, especially when using tools like NatHERS, geographically reliant and it's different everywhere
- Lack of understanding from consumers and industry does not let them weigh the benefits
- Policy makers are always short capping energy use but this problem is complex

Availability of Education Material

- Adequate information in the Australian context is not available as most are guidance from suppliers. Development of high-performance standards that can then be “adopted” into Australian standards is required
- Education is essential for tradespeople who deliver them

Appendix 5: Final IRG Workshop – Output

Introduction

The H2 OA’s final IRG workshop was held on 31st August 2022. The workshop’s purpose was for the research team to present the final research project update including the project report priorities and opportunities that have been highlighted as part of the projects research. The IRG provided feedback to the research team and the research team asked a question relating to priority of the opportunities presented.

Research Project Report Overview

- Introduction and methodology
- Market status review
- Technology and market potential assessment
- State of research
- Scenario modelling
- Research priorities and industry development opportunities
- Conclusions and recommendations

Questions and Feedback

A request was made for a copy of the scenario modelling draft report prepared by CSIRO. Noting that it was likely that the renovation trigger point being AUD50,000 meant that it was likely that many renovations would meet that trigger point.

There were no further questions regarding the report overview.

Research Project Report Priorities and Opportunities - Questions and Feedback

- **Benefits of improved thermal performance**

No specific questions or comments.

- **Existing home performance assessment**

Existing home performance assessment activity that is happening at state government level should be considered and understood, as well as CSIROs work (AI assessment tool).

- **Policy evaluation – impact of mandatory schemes**

No specific questions or comments.

- **Building fabric (windows/glazing, airtightness, condensation, pre-cooling)**

AGWA would be happy to discuss windows - we are stuck in a world of cart vs horse. The products are there but we need scale and certainty otherwise the industry will once again invest without the real drivers of demand in this space, which is regulation.

Green Star Homes has been available for a year. Industry provides opportunity for research. There has been push back especially regarding vapour management, there is a lot that needs to be taught to industry. Practices are not yet mature to meet technology.

Managing heat is very important but thought a lot of research was showing that vulnerable groups are impacted by the cold in Australia. Extreme heat and cold means that we consider resilience alongside efficiency.

Comfort? Thermally healthy conditions. How do we design housing for heat and cold? Comfort is a luxury, the discussion should consider thermally healthy.

Moisture design calculations failed in the USA. USA is a good case study because of their range of climate zones, alike to Australia. Can you integrate moisture management and thermal efficiency or should they remain separate and work together?

- **NatHERS tool**

No specific questions or comments.

- **Thermal comfort (vulnerable groups, extreme climate event)**

Need to design and build homes that can handle both hot and cold conditions and everything in between. Avoid heat and cold stress for building occupants.

WHO Guidelines a good start.

Change the language to 'thermally healthy conditions' and acknowledge that comfort is a luxury.

Agree that comfort is perhaps not a clear term, but ECA/Renew forthcoming research doesn't indicate people see comfort as luxurious - they use terms like airy, cozy, light to describe comfort.

Curtains can be used as a band aid and not a solution, can also create other issues such as mould around windows. Fix the window!

Support more research on items 9-11: Vic Healthy Homes research hopefully fills some of that evidence gap, but is restricted to Vic. There's a lot of work underway re bushfire resilience (e.g. Monash Fire and Flourish).

- **Ventilation strategies and air quality**

It is good to talk about what is cost-effective. How do we address what is not cost-effective, consider the full spectrum? What about what is beyond minimum and regulation, how do we consider those that will happily spend more?

Cost-effective upgrades can stop payback periods for more meaningful upgrades. Consider the hierarchy of choices, you can make meaningful investments, but it may stop you making investment further down the track which are really needed.

Acknowledge cost-effectiveness while understanding that some will spend more for a suitable and better solution.

GBCA offered to share the draft *Sustainable Home Renovation Guide* that is currently being written for existing homes, intended as a technical guide.

- **Skills development**

It is good to understand where we are currently at, but it isn't sufficient. We need to align and train people for what we need to be doing in the future. Where do we need to be?

Training material needs to go beyond the minimum version, consider broader array of climate zones and what a system looks like beyond a base specification. It is impossible to upskill a sector when they do not have any specifics, the sector needs to know what it is they need to know and how to do it. Book end the information. Point people in the direction we want them to be. Builders will deliver what we tell them we want. Others felt that builders feel that they don't know what they are doing is wrong.

Builders need to understand when what they are doing is wrong and how to do it right.

ABCB is looking at Section J and it may be worth understanding how the trade takes these changes on board.

Department of Climate Change, Energy, the Environment and Water. The report is National Construction Code Training Engagement.

Practical upskilling is a subject with work in the pipeline, coordinate with or not mimic.

Training and skills development needs to go beyond the minimum requirements. We need to upskill sectors for what is needed for the future. Provide education and training for future proof solutions.

ASBEC skills content:

[130619-ASBEC-Jobs-and-Skills-Task-Group-Skills-Collaboration-Framework-Report.pdf](#)

ASBEC ratings snapshot:

https://www.asbec.asn.au/wordpress/wp-content/uploads/2021/08/210727-ASBEC_RatingsSnapshot_website-upload.pdf

Pro Clima will release an Australia based study into air tightness and moisture management in October. You are all invited to the launch.

- **Uptake of incentives and grants**

A barrier to uptake of incentives/grants might be because they're not meeting consumer needs - part of the research should be whether barriers too high, and/or focusing on one tech as opposed to giving householders a choice. When should these be co-designed?

Incentives drive all the other inputs - the products are available; the energy assessment tools for building performance assessments are also available. The skills and labour force will be developed if there are commercial incentives to do so. Education can be driven by educational institutions, government campaigns (and policy to regulate) and even the private sector, again if there are incentives to do so. It's a simplified approach, however a credible business case, presented to government agencies, if there is genuine payback justification, then the incentive schemes should justify the commercial growth of the opportunity to drive retro fit solutions.

It depends on what we are asking people to do, what is the point of testing incentive models from yesterday's model? More value would be about testing grants that are relevant to today and tomorrow.

The nuance that could benefit with this research would be about the implementation of a scheme, how to effectively roll something out and manage it properly.

When looking at reducing tariffs and providing subsidies, economic modelling to see the results of when you target one or more products and to understand how long a technology needs to be subsidized for before it becomes BAU or expected by homeowners. Solar is a good example.

- **Home retrofits and decarbonisation**

No specific questions or comments.

Final Questions and Feedback

NatHERS is probably at the bottom of this vote because NatHERS needs to be working right now to inform their tool and probably RACE isn't the place to be doing the work.

It is hard to make priorities between the research questions because they are all important. Is it a case of what comes first? Do we need to figure out some priorities that need to happen before others can move forward? The research priorities are different to the industry priorities.

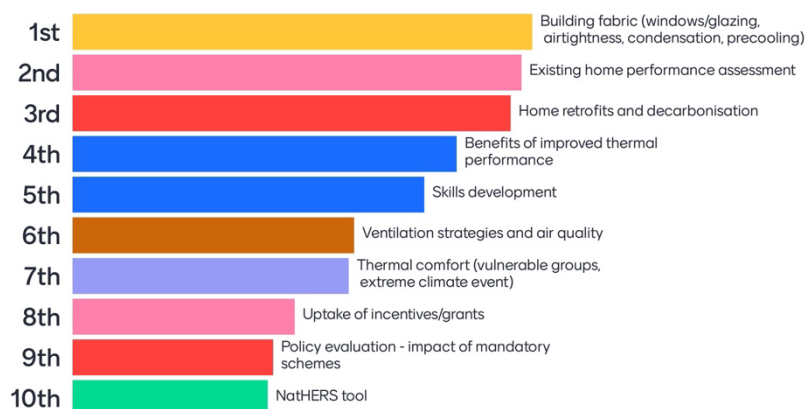
Building fabric being highest priority, followed by the 2nd, 3rd, 4th and 5th priorities potentially highlights a thought process; how do we put buildings together? What benefit does it bring to us? How do positively impact the crucial as built outcome and therefore performance?

NatHERS is a theoretical energy tool and may not deliver the as built result that we want and need.

The results of the Mentimeter question are shown below:

Rank the research opportunities discussed in today's workshop according to industry priority

Mentimeter



Appendix 5 Figure 1: IRG Research Opportunities Ranking

Appendix 6: Housing condition data and retrofit trials

Data type and assessment	Sample size and target group	Conditions	Outcomes/opportunities and savings
Performance data from Australian Energy Regulator; all states; Residential energy consumption benchmarks (Frontier Economics Pty Ltd, 2020)	6,465 electricity dataset count and 3,148 gas dataset count	In all regions, average gas consumption is highest in winter, and lowest in summer. Autumn and spring are similar in most regions and sit in between. Electricity consumption is lowest in the cool temperate Climate Zone 6, which includes Melbourne (and also has a high penetration and consumption of mains gas).	Consider developing consumption benchmarks that account for factors that are observable by retailers. The purpose of the electricity benchmarks is to allow residential consumers to compare their usage with similar households in their area. Households with solar PV consume less electricity from the grid on average than households without it in every climate zone, typically about 5–15% less.
Performance data from CSIRO; all states; House Energy Efficiency Inspections Project (Dec 2015) and air infiltration results for 129 Australian dwellings (Ambrose, 2019; Ambrose & Syme, 2015)	125 dwellings (from all capital cities except Darwin); three years old and more than 6 Star NatHERS with Melbourne houses up to 10 years old and 4 and 5 Stars	The average air change rate was 15.4 ACH at 50 Pa (ACH ₅₀) (slightly higher than the upper range assumed in the NatHERS software). A third of the houses had results lower than 10 ACH ₅₀ . Several houses recorded air change rates above 30 ACH ₅₀ . Overall weather stripping on windows was found to be good (91%) with only 3.5% rated as average and 1.8% rated as poor.	No immediate cause for the variations in air change rates has been identified. General build quality and attention to detail seem to be significant factors. Houses with uPVC window frames recorded much lower air change rates than most other houses.
Performance data from Sustainability Victoria (2015); Energy Efficiency Upgrade Potential of Existing Victorian Houses—Building Shell, On-ground Assessment (OGA)	60 existing (pre-2005) class 1 Victorian dwellings; stand-alone and semi-detached houses. Based on registration of interest and house which did not have a ‘green bias’	Average HER was: <ul style="list-style-type: none"> • 1.81 Stars for the study houses • 1.57 Stars for houses constructed prior to 1990 • 3.14 Stars for houses constructed between 1990 and 2005 Natural average air leakage rate was: <ul style="list-style-type: none"> • 1.90 ACH for the study houses • 2.02 ACH for houses constructed prior to 1990 • 1.20 ACH for houses constructed between 1990 and 2005 	<ul style="list-style-type: none"> • Wall insulation (1.02 Star increase), draught sealing (0.69 Stars), double glazing (0.63 Stars) and drapes and pelmets (0.58 Stars) were the building shell upgrade measures that had the biggest impact on increasing the average HER of the OGA study houses. • Ceiling insulation measures had a large impact when implemented but as they had a much lower level of applicability—most houses already have a certain level of ceiling insulation—they had a lower impact on the average HER of the houses. • Average HER improvements with application of all interventions can be increased from: <ul style="list-style-type: none"> – 1.81 to 5.05 Stars for 11 different building shell upgrades to study houses – 1.57 to 5.00 Stars (an increase of 3.42 Stars) for houses constructed prior to 1990

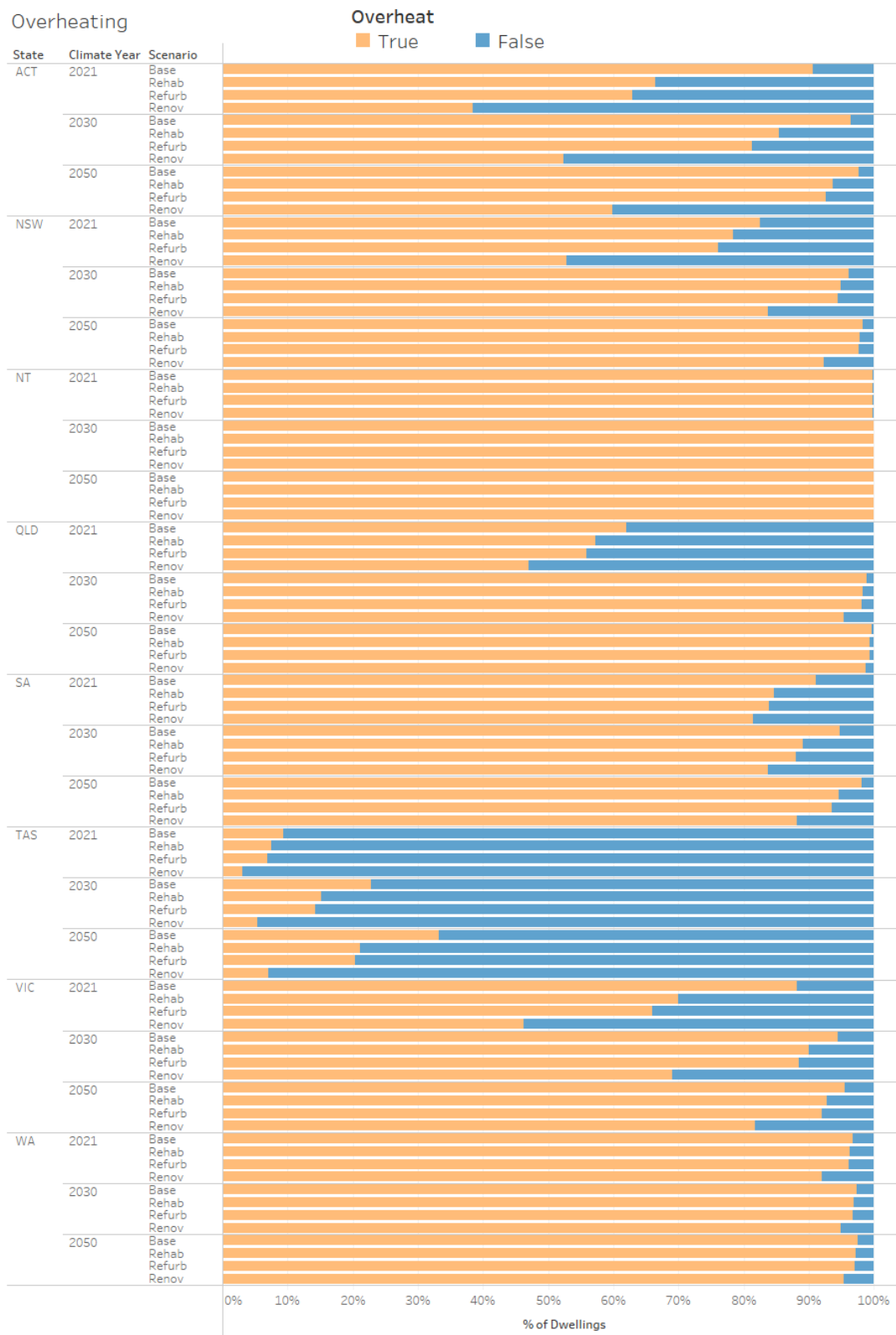
Data type and assessment	Sample size and target group	Conditions	Outcomes/opportunities and savings
Performance data from Sustainability Victoria (2015); Victoria; Energy Efficiency Upgrade Potential of Existing Victorian Houses—Lighting and Appliance Upgrades—On-ground Assessment (OGA)	60 existing (pre-2005) class 1 Victorian dwellings; stand-alone and semi-detached houses. Based on registration of interest and house which did not have a 'green bias'	Heating—gas ducted (central) heating: 3.1 Stars, Gas room heating: 2.8 Stars, Reverse-cycle air-conditioners: 3.3 Stars (2000 rating scale) Cooling—Refrigerative air-conditioners: 3.2 Stars (2000 rating scale) Water heating—Gas storage water heaters: 3.6 Stars, Gas instantaneous water heaters: 4.8 Stars, five houses with electric storage water heaters	<ul style="list-style-type: none"> – 3.14 to 5.37 Stars (an increase of 2.23 Stars) for houses constructed post 1990. <p>The average cost of these upgrades was AUD5,882, making the lighting and appliance upgrades more cost-effective overall than the building shell upgrades.</p> <p>Additional energy savings with installation of rooftop PV panels, replacement of old existing gas heating ductwork with high efficiency new ductwork, Standby Power Controllers (SPCs), remediation of ceiling insulation, solar air heating devices to provide supplementary heating, 'grey water' heat recovery systems, and the use of voltage optimisation devices. Lighting and appliance upgrade measures to the study houses estimated to achieve average energy savings of around 13,200 MJ/year (more evenly split between electricity and gas), average energy (and water) bill savings of AUD558 per year, and annual greenhouse gas saving of around 2.0 t/year.</p>
Performance data from Sustainability Victoria (2016b); Victoria; Draught Sealing Retrofit Trial	16 houses in 2011 and 2012; From OGA Study with gas ducted heating and above-average leakage rates	Average natural air leakage rate air changes per hour (ACH) was <ul style="list-style-type: none"> • 1.90 ACH for the study houses • 2.02 ACH for houses constructed prior to 1990 • 1.20 ACH for houses constructed between 1990 and 2005 	<p>The natural air leakage rate of the houses was reduced from an average of 1.80 ACH (or 762 m³/h) to 0.83 ACH (342 m³/h), or a reduction of around 54% for an average cost of AUD1001. In most houses the draught sealing reduced the air leakage rate by around a half. It was not possible to achieve a natural air leakage rate of 0.5 ACH in any of the houses, with the efficient one to be 0.53 ACH.</p> <p>Average heating energy saving of 13.2% was achieved across these houses leading to average annual energy bill savings of AUD150.10 per year based on energy tariffs current at that time. Based on an average retrofit cost of AUD938, this gives an average payback across the eight 2011 houses of 6.2 years.</p>

Data type and assessment	Sample size and target group	Conditions	Outcomes/opportunities and savings
Performance data from Sustainability Victoria (2016a); Victoria; Cavity Wall Insulation Retrofit Trial	15 houses in 2012 and 2013; houses with uninsulated walls, wall type suitable for installation of granulated rockwool cavity wall insulation and with gas ducted heating	Average rating of 3.3 Stars prior to the retrofits.	Overall the retrofits resulted in an increase in the perceived level of comfort to an average rating of 3.9 Stars. The estimated average annual gas use for heating for the houses was 47,585 MJ/year. Insulating existing external wall cavities is an effective strategy to reduce energy consumption in existing Victorian houses. Average estimated energy saving of at least 15.5% of heating energy use for an average commercial cost of around AUD4,440. Estimated annual energy bill savings were at least AUD150.90 per year, giving a payback on the investment in cavity wall insulation of around 29 years.
Performance data from Sustainability Victoria (2016c); Victoria; Gas Heating Ductwork Retrofit Trial	Eight houses in 2013; older gas ducted heating systems, and a winter gas consumption of at least 300 MJ/day	Gas ducted heating used as the main form of heating in around 41.9% of homes, compared to gas room heating which is used in around 24.3% of homes.	Average heating energy savings of around 14.1% and average greenhouse savings of 570 kg per year were achieved in this trial. Average annual energy bill savings of AUD177 per year. The average cost of the ductwork retrofits was AUD2,849, giving an average payback of around 16.1 years.
Performance data from Sustainability Victoria (2016d); Victoria; Gas Water Heater Retrofit Trial	Six houses in 2015; minimum three occupants with existing 3-Star gas water heater that was at least 12 years old	Existing old 2- to 3-Star gas storage water heaters. Gas water heating is currently the main form of water heating used in Victorian households.	Five houses fitted with 5.1-Star gas storage water heaters and one house fitted with a 6.1-Star equivalent gas instantaneous water heater. Average annual gas saving was 3921 MJ per year (18.8% of the pre-retrofit energy consumption), resulting in average GHG emission savings of 271 kg/year CO ₂ -e, and average energy bill savings of AUD78.40 per year. Savings were estimated to be highest (10,854 MJ/year) in the one house where a 6.1-Star equivalent gas instantaneous water heater was installed.
Performance data from Sustainability Victoria (2017); Victoria; Window Film Secondary Glazing Retrofit Trial	Eight houses in 2013; large single-glazed windows in heated living areas with little winter heat loss protection, a gas heater which used a fan to circulate heated air, and a winter gas consumption of at least 300 MJ/day	Existing single glazed windows.	Applying the film to existing windows in the living areas of the houses resulted in thermal comfort of their houses increasing from an average score of 3.1 to 3.6 Stars. Reduction of winter heating energy use, in the range of 3–4% on average (although at one house estimated savings of 12.1% were achieved). Annual gas use for heating of the houses was 52,499 MJ/year.

Data type and assessment	Sample size and target group	Conditions	Outcomes/opportunities and savings
Performance data from Sustainability Victoria (2019b); Victoria; Comprehensive Energy Efficiency Retrofits to Existing Victorian Houses	14 houses retrofitted; five in 2013, five in 2014 and four in 2015; Average floor area of 132 m ² , average 3.9 occupants, wall and floor not insulated	Average annual gas consumption of the houses was 70,196 MJ/year, estimated annual average gas use for heating was 50,712 MJ/year (72%) and the estimated annual electricity consumption of the houses was 4,655 kWh/year.	<p>On average, the retrofit packages are estimated to have resulted in total annual gas savings of 20,016 MJ/year (28.5% of initial average gas use) and annual electricity savings of 794 kWh/year (17.1% of initial average electricity use). The average reduction in energy related GHG emissions was 2.05 t/year.</p> <p>The average energy bill saving was AUD663 per year (based on current energy prices); this gave an average payback period of 19.7 years on the cost of the retrofit packages.</p>
Retrofit trial by Energy Consumers Australia. Victoria; Home Energy Efficiency Upgrade Program (Sullivan et al., 2017)	793 households; low-income owner occupier households and community housing	The trial involved upgrading to more efficient hot water systems. Natural gas storage was the most prevalent existing system across all participants and the major installation streams, followed by electric storage and natural gas instantaneous.	<ul style="list-style-type: none"> • The upgrade paths yielding significant decreases in daily electricity consumption were: electric storage to heat pump (29%), electric storage to gas instantaneous (42%), electric storage to gas solar (41%). • The upgrade paths yielding significant decreases in daily gas consumption were: gas storage to gas instantaneous (15%) and gas storage to gas solar (13%). • Annual financial saving from electricity reductions equivalent to AUD244.14 (electric storage to heat pump), AUD303.89 (electric storage to gas instantaneous) and AUD295.65 (electric storage to gas solar). • Annual financial saving from gas consumption reductions equivalent to annual financial savings of AUD114.45 (gas storage to gas instantaneous) and AUD101.96 (gas storage to gas solar).
Stock Modelling using ABS data; all states; Department of Industry and Science, Residential Energy Baseline Study: 2000–30 (Energy Consult, 2015)	Building stock model, appliances, 125 residential products modelled: ABS data	Average energy use per dwelling has been falling since the year 2004 and is expected to continue to decline to 2030, though less rapidly in the 2020s, based on projected trends	Space conditioning contributes the greatest amount to the decline in total energy use per dwelling, followed by lighting and then appliances and water heating.

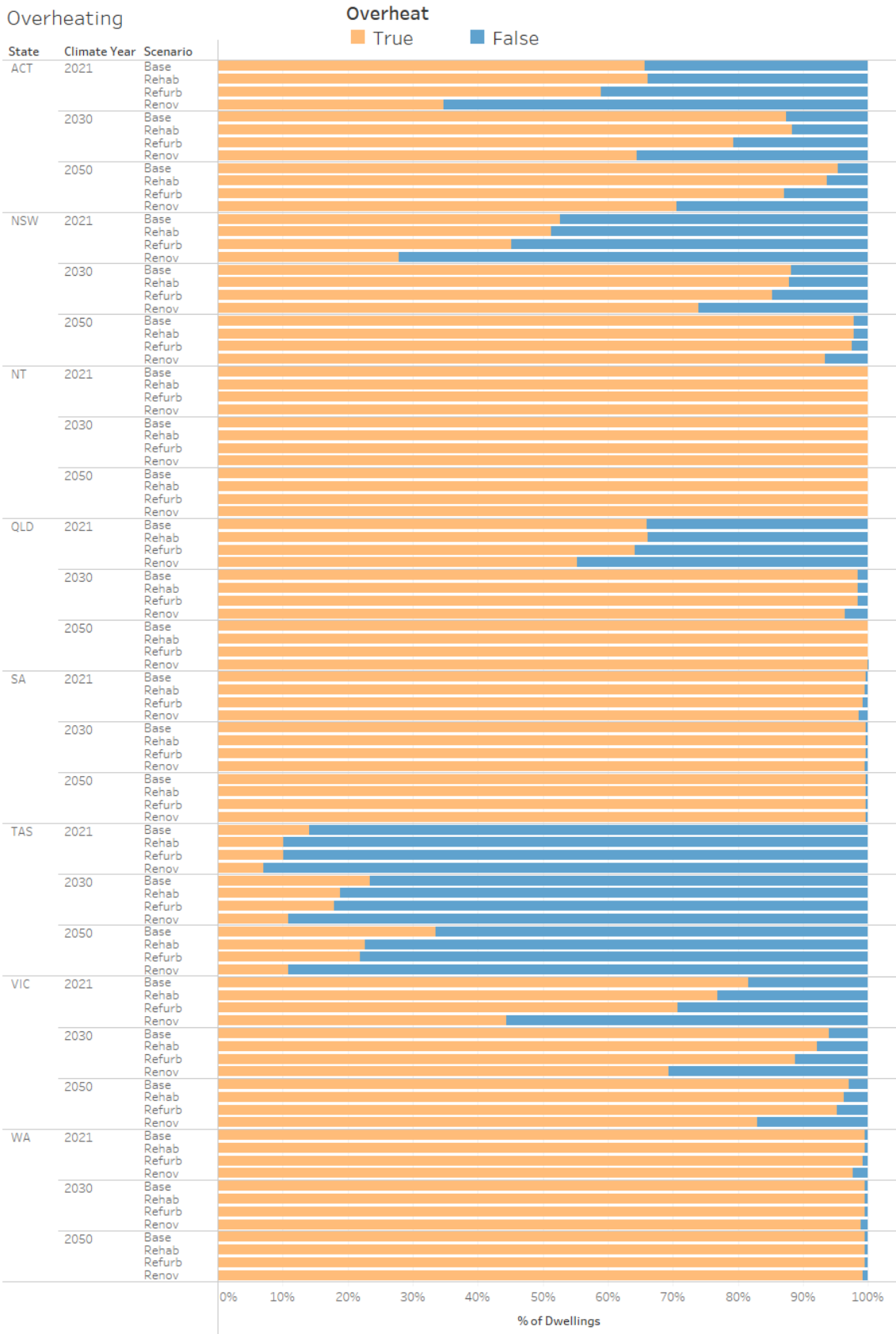
Data type and assessment	Sample size and target group	Conditions	Outcomes/opportunities and savings
ABS Data from SBRC; NSW housing typology development project (Daly et al., 2016)	ABS data source and surveys; Different housing typologies and their upgrade potentials	NSW Housing stock – 2.8 million dwellings (70% detached dwellings – 45% BV, 20% DB, 15% Fibre, 13% Timber; 11% semi-detached dwellings – 56% BV, 39%DB; and 19% units – 19%BV, 74% DB). Average 69% of dwellings have insulation, 14.3% are without insulation and 16.7% unknown.	Suggested retrofitting opportunities—top up roof insulation, pump in wall insulation, add suspended floor insulation, weather-strip openings, install new shading to west and east depending on location of living. Recommendations: develop education materials to support retrofitting for each typology, dwelling characterisation and upgrade tool, on-ground building and upgrade assessments, social and community housing upgrades, energy performance benchmarks for dwelling typologies and improve data accessibility.
Performance data from Victorian Energy Upgrades (VEU); (Energy Services Commission, 2022)	Dashboard data	Lighting upgrades are the dominant activity under the VEU program. Weather sealing accounted for 1.2 M households, which is only 1% of the total upgrades.	Upgrades undertaken by these consumers is expected to generate approximately 5.5 million MWh of electricity savings and over 591 TJ of gas savings over the lifetime of the upgrades. Annual energy savings for households that undertook an upgrade in 2020 would save an average of AUD229.
Performance data from Victorian Residential Efficiency Scorecard; (COAG Energy Council, 2019c)	1,871 Scorecard assessments from April 2017 to April 2019; Average house area =113 m ²	<ul style="list-style-type: none"> • 57% of the energy cost came from heating, 29% from hot water, 8% lighting and 5% cooling. • 75% of houses assessed had a very low or low building shell rating, mainly due to poor insulation and low air tightness (draughts). 	The annual energy cost saving from 3 Stars to 10 Stars is AUD2,000 per annum. The payback period is approximately six years. As 29% had inefficient heaters, these homes had an excellent opportunity to upgrade heating to efficient appliances.

Appendix 7: Scenario modelling results

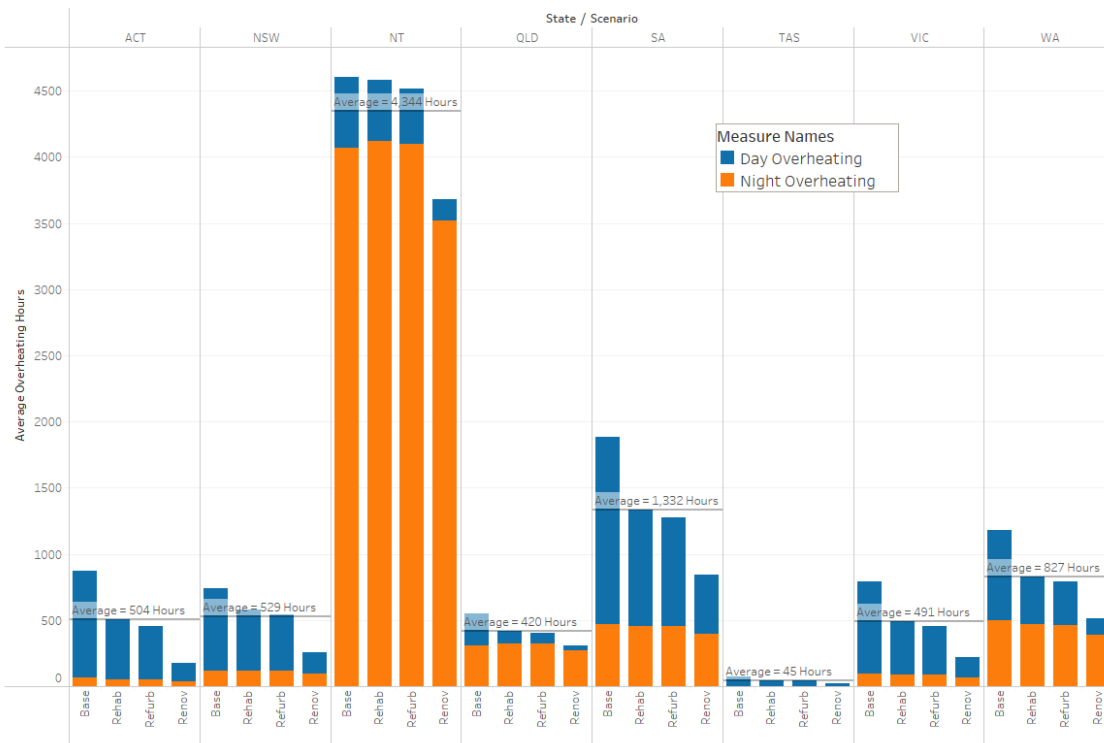


Appendix 7. Figure 1. Percentage fail/pass overheating assessment by state for Class 1 dwellings

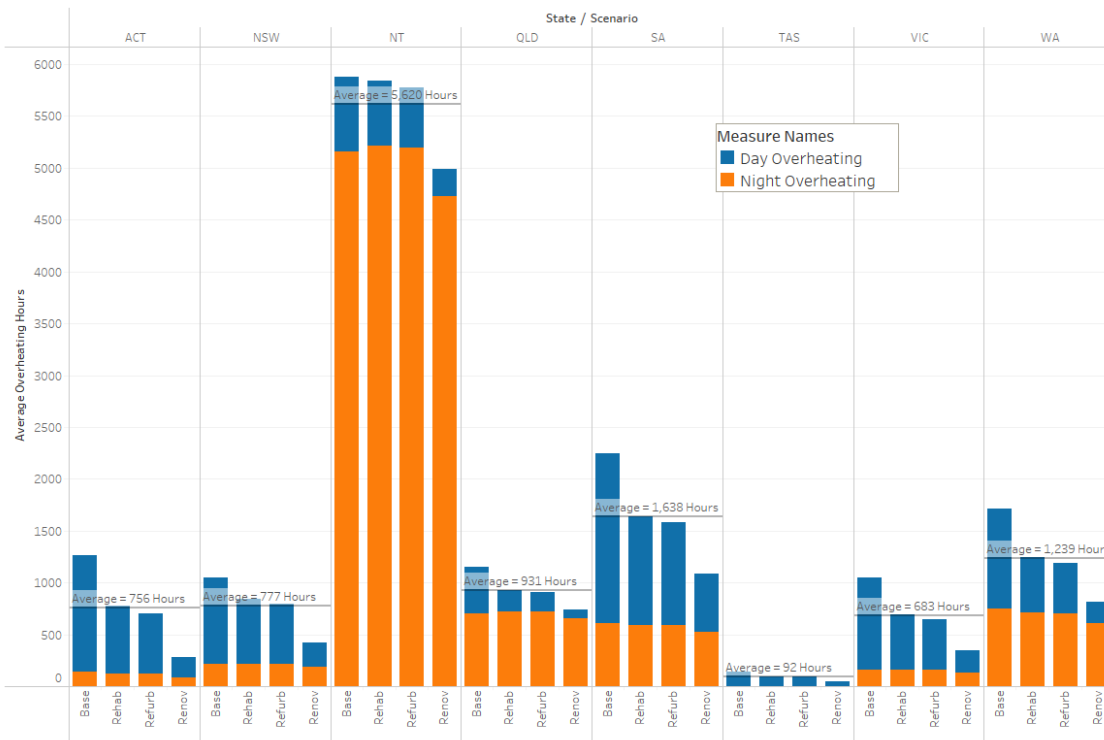
Overheating



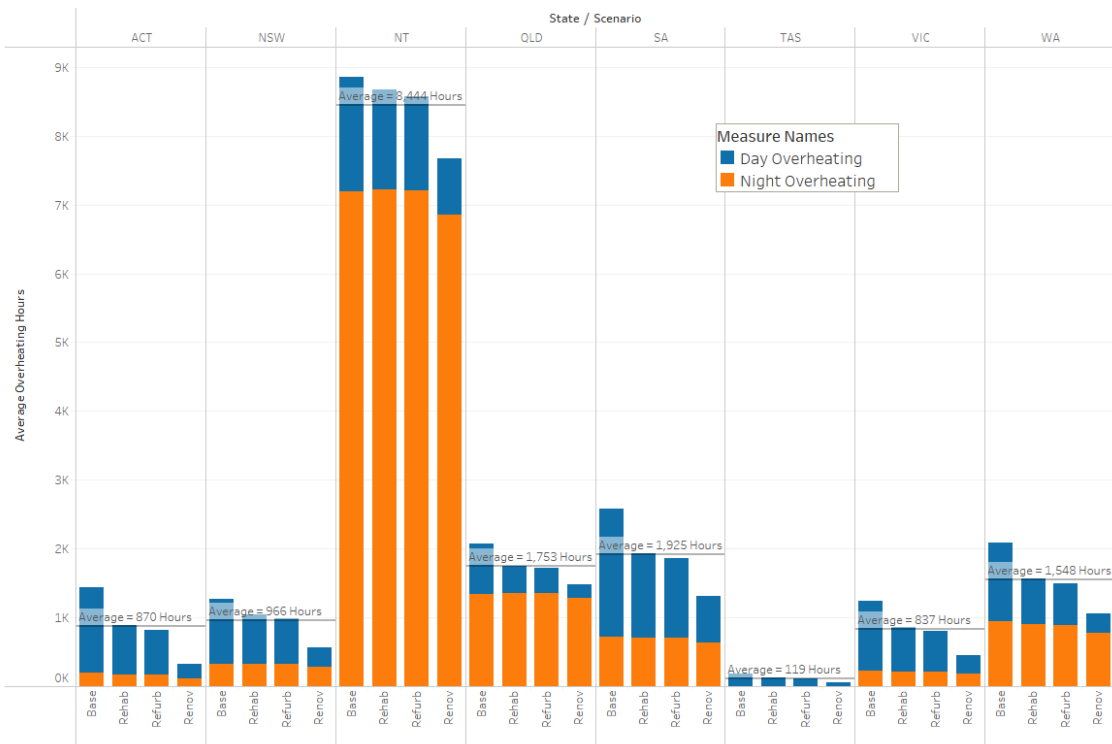
Appendix 7. Figure 2. Percentage fail/pass overheating assessment by State for Class 2 dwellings



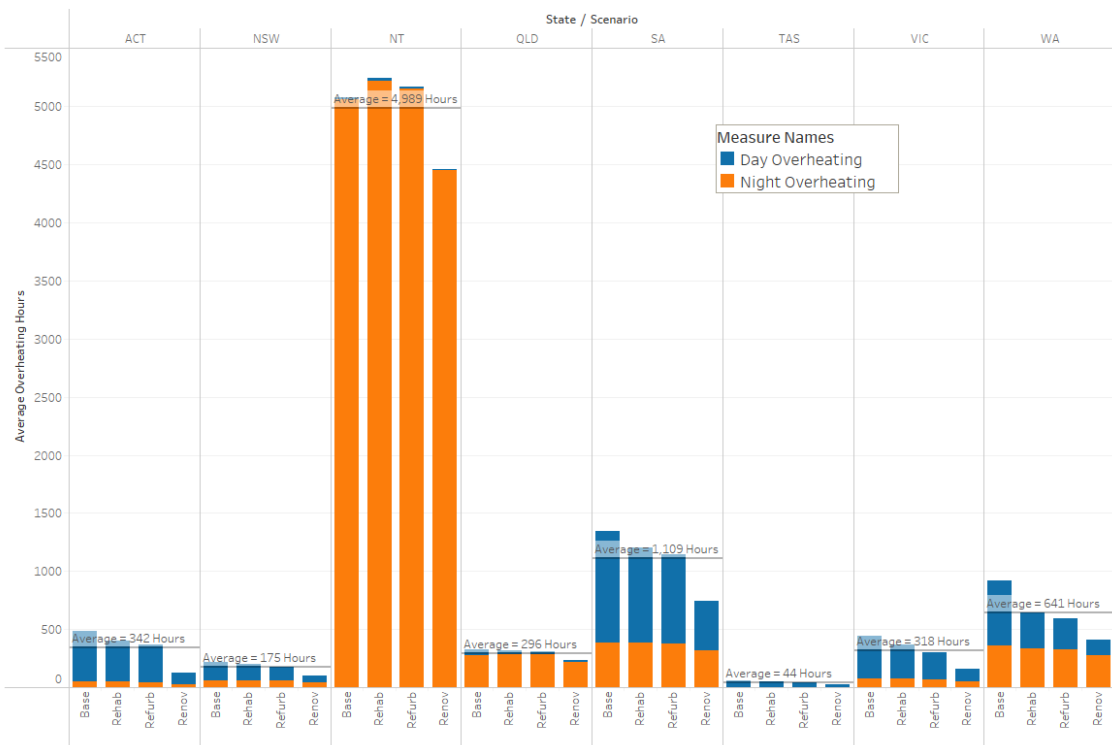
Appendix 7. Figure 3. Average overheating hours by state for class 1 dwellings in the current climate



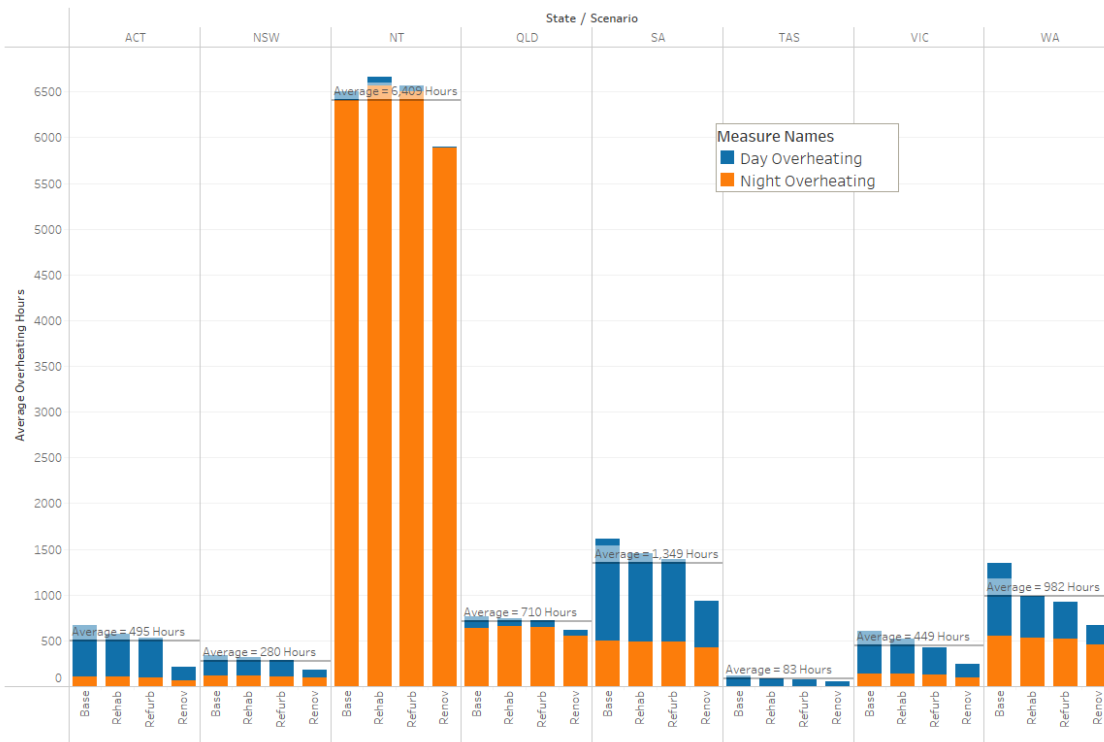
Appendix 7. Figure 4. Average overheating hours by state for Class 1 dwellings in the projected 2030 climate



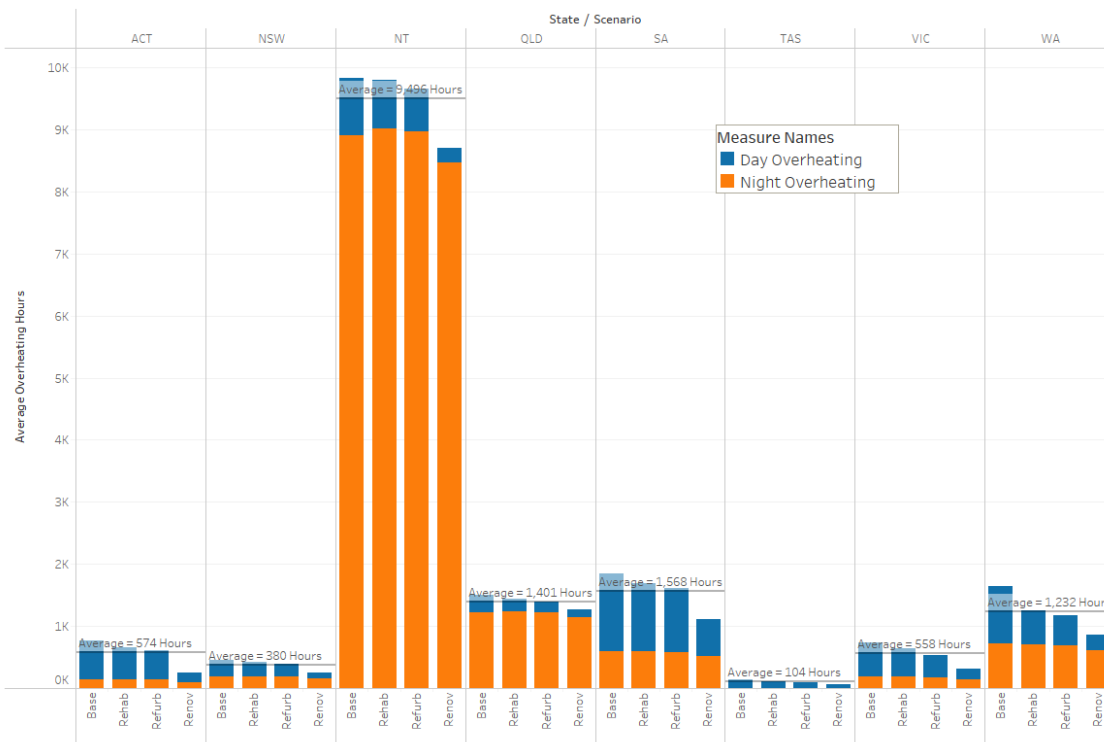
Appendix 7. Figure 5. Average overheating hours by state for Class 1 dwellings in the projected 2050 climate



Appendix 7. Figure 6. Average overheating hours by state for Class 2 dwellings in the current climate

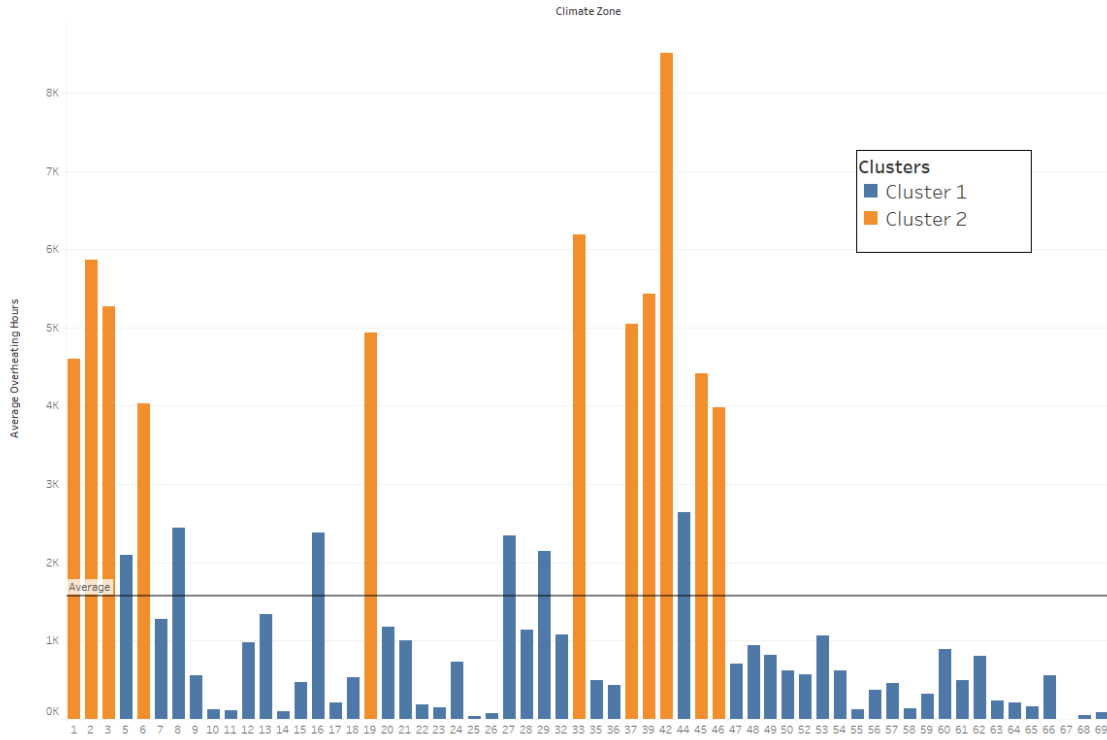


Appendix 7. Figure 7. Average overheating hours by state for Class 2 dwellings in the projected 2030 climate

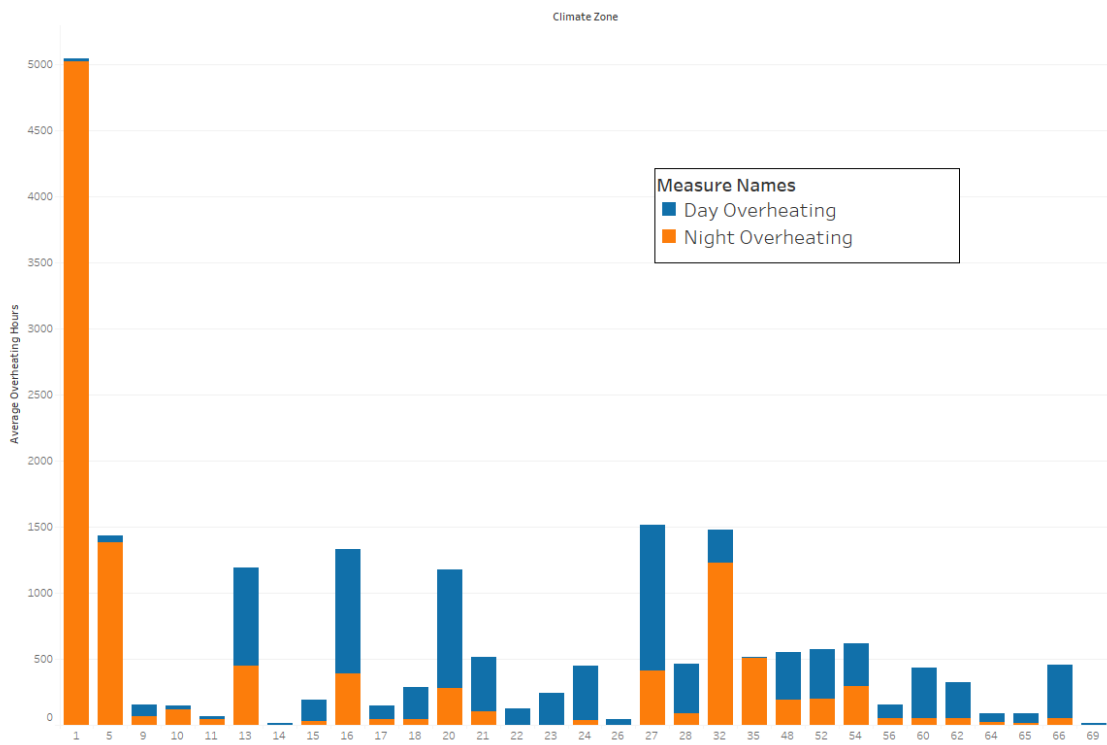


Appendix 7. Figure 8. Average overheating hours by state for Class 2 dwellings in the projected 2050 climate

Average Overheating by Climate Zone



Appendix 7. Figure 9. Average base overheating hours by climate zone for Class 1 dwellings in the current climate



Appendix 7. Figure 10. Average base overheating hours by climate zone for Class 2 dwellings in the current climate

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