RACE for 2030
RELIABLE
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H1 Opportunity Assessment

Residential solar pre-cooling and pre-heating

Final report November 2021

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What is RACE for 2030?

The Reliable Affordable Clean Energy for 2030 Cooperative Research Centre (RACE for 2030 CRC) is a 10-year, $350 million Australian research collaboration involving industry, research, government and other stakeholders. Its mission is to drive innovation for a secure, affordable, clean energy future. https://www.racefor2030.com.au

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Executive Summary

Introduction

This Opportunity Assessment is a scoping study to determine what is currently understood about residential solar pre-cooling and pre-heating (SPC/H) and therefore guide where RACE for 2030 should focus its research efforts.

The intended outcome of SPC/H is to cost effectively shift solar energy from when it is abundant to when energy is required for heating and cooling. The purpose is to achieve grid load smoothing which is expected to address and peak demand and minimum demand, leading to lower customer electricity bills, and improved solar hosting capacity.

Over the last decade significant rooftop solar photovoltaic (PV) capacity has been added in Australia, with new installations and a growth in average system size. SPC/H is increasingly seen as an effective demand response strategy, where the peak solar irradiance can be used to meet the peak electricity demand. It requires market-ready remote monitoring and control technologies as well as adequate thermal inertia of homes to reduce peak demand and therefore network infrastructure costs, consumers' energy bills and greenhouse gas (GHG) emissions.

Specifically, the concept of SPC and SPH requires two components:

- Reduce energy demand for home heating and cooling in the evening peak (when demand typically peaks), and
- Soak up daytime solar power capacity (when the solar resource is typically abundant) to supply cooling and heating.

The first focus of SPC/H is to use a household's own PV system to power cooling and heating, but it is also relevant for houses without PVs to soak up the excess capacity in the grid supplied by solar installations nearby. The technologies to facilitate these two approaches are similar but the incentives for householders will be different. Of particular concern is the ability of the building to retain the heating or cooling. Poor quality buildings will leak the heat or coolth so that little benefit remains into the evening when needed by the occupants. Testing this is the subject of the modelling documented in this report. The other major concern for successful implementation of SPC/H is how well it will be accepted by consumers, what incentives may be needed to recruit households in sufficient numbers and the possible cost and complexity of programs to achieve the desired impact.

Smoothing out the residential load profile provides the following network benefits:

- Allows more homes to install solar because reducing peak solar export increases solar hosting capacity, and it helps mitigate voltage rise, reducing curtailment of solar export.
- Reduces power (normal and peak) flows through transformers and cables, prolonging the life of these assets. Peak reduction defers expensive network upgrades.
- Modulates voltage variability from solar and voltage excursion generally, making voltage management easier
- Reduces reliance for PV inverters to engage Volt-VAr response voltage control, which in aggregate can exchange large amounts of reactive power from the grid, increasing losses and reducing power factor (PF).

The grid wide benefits which come from smoothing out the residential load profile include:

- Reduced load variation, increasing load forecast accuracy, and allowing for a more accurate allocation of generation and reserves
- Less peak demand means less need for expensive peaking plants (which can sell electricity at orders of magnitude higher price than baseload plants) and less capacity upgrades, resulting in an overall reduction in the cost of electricity

Methodology

This Opportunity Assessment constituted literature reviews and modelling. A desktop review of market status and industry practice identified the state of the industry, particularly what is working and not working. A further literature review, supplemented by interviews with experts and stakeholders representing consumer bodies and industry associations, studied the feasibility of SPC/H for Australian houses from the consumers' perspective, looking at their attitudes to remote control, comfort expectations, and incentives. The reviews inform the analysis of barriers and solutions.

As an input to the scenario analysis, a 'suitable' home was characterised by analysing the expected building performances at different house thermal efficiency levels. The scenario analysis estimated at high-level the number of homes with both air conditioning (AC) and PV systems that could effectively be pre-cooled or pre-heated to identify the technical and economic potential of SPC/H and indicatively quantify potential benefits and costs and the range of potential impacts on cost, peak load, potential for PV uptake, and emissions reduction.

Through a series of workshops, conversations and document reviews, the delivery team identified priority research questions and business opportunities, including specific identification of knowledge gaps, required enabling technologies, and desirable demonstrations and pilots. An Industry Reference Group was established for the project. This group was consulted during the project and given the opportunity to review the project findings before the report was finalised.

Current technology and market status

There is a diversity of control requirements for SPC/H depending on whether control is held by the householder, the network provider, or a third party bundler. The benefits are different for each of these actors, and whether the solar power is sourced from the householder's own rooftop or from excess grid capacity.

Market

The market for residential air conditioners is growing with market penetration stabilised to around 75% of Australian households but the total living area being conditioned continues to increase due in part to increasing construction and urbanisation. Split air conditioners dominated the Australian AC market in 2018 and are anticipated to maintain their dominance until at least 2024. In the coming years, technologies such as IoT, automated control systems, and remote-control access are expected to transform the HVAC industry, as are new developments in super-efficient and climate-friendly residential cooling solutions with much lower carbon emissions compared to regular air conditioners. Consequently, it can be expected that there will not be increased peak electrical demand commensurate with the increased usage. Although new constructions are proactively incorporating smart systems and automation systems, challenges in adopting AC controls include cost and technical installation complexity.

Controls

The key technology for solar pre-cooling strategies are controls for AC systems. Demand response can work in two ways, each with different technological requirements. In cases where a remote agent (electricity distributor, electricity retailer, electricity system manager, or a demand response bundler) determines when SPC/H is required, they require a contractual relationship with the customer, prior consent to any remote operation, and agreed conditions.

Manual activation has the occupant turning their equipment on remotely or with a pre-set timer. This could be in response to a notification from a remote agent with whom they have the prior agreement. The notification may simply come in the form of an SMS message in advance of the SPC/H requirement. Alternatively, the occupant is motivated to act by tariff or payment incentives built-in to their electricity supply agreements. The technological requirements are therefore minimal.

Automation of demand response has equipment connected to suitable control and communications devices that allow remote operation by a remote agent or the occupant themselves. The Australian and international markets for air conditioners, have been anticipating demand response capabilities and gradually including this facility in their new products. AS4755 specifies the minimum functionality and optional capabilities of demand-response-capable ACs, but it has serious limitations that make it unsuitable for SPC/H control. For example, the standard explicitly forbids the capability to remotely commence operation, i.e. there can be no ‘on’ command. This standard will likely need to be reviewed if SPC/H is to become widespread.

Remote operation requires a communication pathway. Ripple control (signal caried by the powerline) is the most widely applied technology that utilities and demand response bundlers use to communicate with demand responsive smart appliances. Its drawbacks are that it does not allow consumers to override the settings and it does not offer the capability to be incorporated into an internet platform for an integrated flexible demand management program. Ausgrid has expressed concerns about ripple control sending signals to turn on or turn off air conditioners all at once, which would potentially exacerbate minimum demand. By contrast, internet addressable methods are capable of staging the turn-on or turn-off signals to achieve a gradual return to normal.

Wi-Fi enabled smart devices that send infrared signals to the AC unit, similarly to the unit’s own remote control, are the other commonly used technology. There are a number of products available on the market, most of which are compatible with popular AC brands and ductless types, often without needing to replace existing equipment. Ducted systems have to be hardwired to the smart controller. Users can control their connected devices through an app. Network providers have applied remote infrared controllers (such as Sensibo) to run direct AC control demand response programs, which allows them to adjust temperature settings on split system air conditioners during a peak event.

New smart AC systems have integrated controls and may provide much more advanced control and intelligent features than remote controls, although they require intervention by consumers on a daily basis or using ongoing settings that are difficult to understand, in comparison to a network-level controlled program.

Industry practice

Electricity distributors and retailers in Australia are currently offering a number of demand response programs, including direct control of air conditioners and more general behavioural demand response programs. These programs aim to improve the reliability of the grid, especially for extreme hot weather events. The growth of renewable energy sources, including rooftop PVs, have brought forward the idea of shifting peak demand to times when the sun is shining. These programs often offer the capacity for residential solar pre-cooling in terms of remote monitoring and controlling technicalities and business models, although their main focus is reduction of peak demand.

The Energex/Ergon PeakSmart Air Conditioning Program offered by Energy Queensland (EQ) is the largest of its kind for uptake of direct load control of air conditioners and the penetration progress of this program is considered as a success. Householders are offered a one-off cash incentive to join, but to leave the program participants must pay for an electrician to disable EQ’s control device. The key drawback of the program is that the signal is a one-way communication therefore it is not possible to know how much flexible demand was delivered from a given home. However, metering at substation level provides an aggregated view of achieved load reduction.

CitiPower and Powercor Energy Partner Program is an established AC demand control program run in Victoria during summer where electricity distributors adjust temperature settings on split system air conditioners on very hot days. Householders are sent email and/or SMS notifications detailing the event. Control is through a Sensibo unit supplied by the distributor, which was the only incentive offered.

The most extensive inquiry into demand response applications to date was administered by ARENA and AEMO which co-established a three-year Demand Response Short Notice Reliability and Emergency Reserve Trader (DR SN RERT) Trial in 2017 and developed 10 pilot projects. Electricity retailers AGL, EnergyAustralia and Powershop offered residential programs including behavioural demand response and controlled load programs. A key finding of this trial is that customers were much more interested in the behavioural demand response programs, because they have a wider range of eligibility and a lower level of technology requirement, while allowing customers the full control of their energy use and participation.

Learning from the trial, AGL, EnergyAustralia and Powershop are offering demand response programs. Barriers to program administration and customer uptake are that it is difficult to interpret the result of saved energy as forecast and explain it to customers as the amount of energy they would save; customers' demand response effort may be undermined due to the fluctuations of rooftop solar output; and there are also challenges to improve the penetration of smart meters as the current level is low. Notably, none of the three electricity retailers has continued to offer controlled load programs for air conditioners after the trial, as they conclude that direct load control of air conditioners is not viable due to complexity, high expenses, and erratic outcomes from controlling pre-existing air conditioners under AS4755.

Partnering with a US start-up company called OhmConnect, Origin Energy's Origin Spike platform applies gamification logic and prompts members via a weekly email or SMS to reduce their energy use through small behaviour changes. Origin Spike also has the capacity to connect to smart devices to automate members' participation. Members earn points that can be used to redeem PayPal cash or gift cards. Members who manage to reduce their energy use by 60% for more than 20 consecutive 'SpikeHours' could earn about $250 per year in rewards.

Business models

Potential is seen in third parties managing a cooling load shift and supporting households to manage their solar PV electricity consumption. By bundling a group of households, taking responsibility for recruiting and maintaining communications, bundlers may help to mitigate the risks and costs for networks to maintain controlled load SPC/H programs.

Current state of research

Technologies

A Brisbane study that evaluated the effect of adopting cold storage on the peak demand of AC systems where it is integrated with a 5-star house thermal storage and roof-top PV system in a residential AC system indicated that it greatly reduces summer grid-based energy consumption and shifts the peak load. The authors concluded that this distributed thermal storage coupled with PV system is expected to be a potential new generation of thermal comfort system for residential dwellings.

PV-assisted cooling systems can take advantage of the high cooling efficiency (energy input to cooling output) benefits offered by compressor-driven air conditioning systems although more data is still needed to assess the viability and feasibility of integration and optimal design alignment of these systems in the Australian context.

One study found the optimal combination of embedded phase change materials, convection mode, and pre-cooling schedule can completely shift cooling energy use during a three-hour demand period, producing maximum cost savings up to 29.4%, while increasing the occupant comfort.

Another study found that without storage, PV could directly power approximately 50% of cooling demand, and that is set to increase as cooling demand grows in locations where PV and cooling have a higher synergy.

Benefits

A number of studies investigated the benefits of reducing cooling loads in commercial buildings, however, there is very limited literature on pre-cooling residential buildings and the work that has been done is typically restricted to the US. Simulation results from studies in California demonstrated that pre-cooling using mechanical air-conditioning could reduce annual peak period residential air-conditioner operation by between 75% and 84% and another suggested that, when combined with night ventilation, pre-cooling could save up to 97% of residential peak electricity consumption. Computer modelling in 15 different US climates confirmed these reductions however they are heavily dependent on climate zone, the length of the pre-cooling period and the pre-cooling set point.

Energy performance of the optimal pre-cooling strategy can be benchmarked with an optimisation model however further research is needed to investigate the impact of different sets of conditions such as the thermal properties of a specific home, HVAC system capacity, utility rate structure, and weather conditions. More research is also needed to understand the benefits of SPC strategies and the technology alignment and compatibility.

Consumer benefits and acceptance

Consumer attitudes play a critical role in any demand management program. While SPC/H programs have the potential for both cost and energy savings for consumers, their success depends upon attracting sufficient consumer engagement to achieve peak demand reduction targets. Key factors that influence consumer engagement and acceptance of solar pre-cooling include perceived consumer benefits and motivations to participate, their housing quality and thermal comfort preferences, as well as the differences between solar and non-solar households.

Perceived consumer benefits

Reducing peak demand and reducing energy bills are identified as the most significant benefits for consumers to engage in solar pre-cooling. Consumers contribute to a more reliable and stable electricity network by switching their peak load and benefit from a resulting lower electricity price. Other benefits include reduced carbon emissions, allowing for an ‘instant’ thermal comfort, and increased awareness of their energy use and energy bills.

Motivations to participate

Financial incentives are typically the most common and important motivation for residential consumers to participate in solar pre-cooling, especially for non-solar households. Other motivations include increased control over energy use and energy bills, social good from participation, and reduced technology costs such as solar PV, smart control and smart meter devices. Solar households would participate to make the best use of their PV and to be energy independent, although they may feel blamed for network problems.

Housing quality

There is an argument that consumers would be more inclined to participate in SPC/H if they have a thermally well-performing home that would retain the heat or the coolth whereas those with energy inefficient houses may think SPC/H is not efficient and may result in energy use and bill increases. On the other hand, houses with high thermal performance need less active heating and cooling, making them preferable to consumers, but in these cases SPC/H may have less value to consumers and for load shifting.

Thermal comfort preferences

Consumers have a diversity of thermal comfort preferences and can and do exhibit adaptive behaviours in response to climate, cultural and social practices and their individual circumstances. This means that there is no single ‘set point’ for cooling, on which to base any evaluation of the potential benefits of a pre-cooling program at a national level.

Occupancy behaviours

SPC/H will be affected by occupancy (how homes are occupied in terms of times, days, number of occupants) and occupant behaviour due to cultural, climatic and household differences, and different approaches to using air conditioning to meet their thermal comfort needs.

Scenario modelling

A scenario analysis was undertaken to build a foundation for the quantifiable economic benefits of solar pre-cooling and solar pre-heating for households and network providers. It indicates the options for network providers to manage load profile.

Suitable Home

For this Opportunity Assessment, based on information in the Australian Housing Data (AHD) Portal, CSIRO developed a sample house design suitable for assessing the feasibility of SPC/H, and for estimating the opportunities to reduce peak load and energy costs. The thermal performance of the house design was simulated for four cities where PV energy consumption data was available to the study (Sydney, Adelaide, Brisbane and Melbourne), with light-weight, medium-weight and heavy-weight construction, and representing existing (2 star), new (6 star) and future (8 star) housing stock.

Scenario modelling

Business as usual (BaU) and accelerated scenarios were modelled for 2021 and 2030 using solar household consumption data provided by Solar Analytics. An accelerated scenario presumed improvements to technologies and building materials defined as an improvement in star-rating across the housing sector for the purpose of this analysis. Two forecasting strategies were simulated, considered to represent the two control scenario extremes. In scenario F1, occupants divert all solar excess to AC during the day, foregoing feed-in tariffs and not controlling for comfort. Scenario F2 assumes a perfect forecast of both solar generation and evening AC consumption, optimising the amount of PV energy diverted for SPC/H.

Key findings of modelling

Effect of house quality on impact

In general, decay rates are sufficiently low (approximately between 4-12% per hour on average) such that SPC/H can influence temperatures a significant number of hours into the future.

As the star rating of the home increases, the amount of energy used for SPC/H during the day more closely matches the reduction of energy needed in the peak, that is, its efficiency increases. However, the difference in efficiency between 6-star and 8-star homes is relatively small (compared to the difference between 2-star and 6-star homes), suggesting diminishing returns as the star rating increases.

As home star ratings increase, the amount of evening AC energy use decreases, particularly between 2-star and 6-star homes. The difference in decrease between 6-star and 8-star homes is marginal. Aside from SPH for Brisbane, the differences in energy reduction between light, medium and heavy construction is small.

The reduction in solar export does not vary much according to building star rating or construction weight, or for each city.

Upgrading all old homes, representing more than 50% of the housing stock, from 2-star to 6-star (2030 accelerated scenario), only marginally increases the reduction in evening AC consumption relative to the 2030 BAU scenario. This may be due to the available evening AC consumption gradually becoming exhausted. Brisbane shows the greatest benefit, largest reduction in evening AC consumption, from an increase in home star rating. Similarly, there is only a slight reduction in solar export between the 2030 BAU and 2030 accelerated scenario. Brisbane exhibits the largest reduction, indicating the SPC/H efficiency of Brisbane homes increases the most with an increase in home star rating.

Modelling of 8 star homes was constrained by the small dataset due to these homes having fewer cooling events. Whilst this is unhelpful for analysis of load shifting, it clearly shows that well designed, efficient homes in Australia have little need of any AC. Upgrading homes can remove the heating/cooling load altogether.

Effect of climate on impact

The climate of Brisbane looks to be suitable for SPH, while the climates of Melbourne and Adelaide look to be more suitable for SPC. Sydney does not demonstrate any strong tendencies for either SPC or SPH, with SPH only slightly more effective than SPC.

Effect of occupancy on impact

There is significant spread in the data for each star rating and construction type due to the large variation in household consumption behaviour, implying that occupancy behaviour has a significant impact on the efficiency of SPC/H.

Financial viability

For SPC/H to be financially viable for a household, the evening tariff needs to be higher than the solar feed-in tariff. The difference needs to be by a proportion greater than the amount of evening energy saved compared to the solar PV used.

Using forecasting of both AC consumption and solar export to optimise SPC/H significantly improves SPC/H efficiency. Perfect forecasting (F2) was shown to be twice as efficient as basic forecasting (F1). This impacts the financial viability for consumers because forecasting means the amount of solar power used for SPC/H is only what is helpful, and as much as possible is still fed to the grid to earn a return.

Household savings from SPC/H under current tariffs are modest. Adelaide demonstrated the most savings from SPC/H, using forecasting, and only saved households around $25/year on average. Tariffs will need to change, and/or customer-based incentives offered to financially motivate households to participate in SPC/H.

Impact of SPC/H on the grid

A reduction of around 40% in peak AC consumption, as anticipated for Melbourne and Adelaide from SPC (and about 20% in Sydney and Brisbane), is significant. As evening AC consumption is a major contributor to peak electricity demand during summer, these results show that SPC can potentially significantly reduce peak loads on the electricity grid if utilised properly. There also appears to be significant potential for SPH in Brisbane with estimated peak demand reduction of 40 to 50%.

Impact of SPC/H on CO2 emissions

The potential benefits of SPC/H in reducing carbon emissions requires further analysis. SPC/H increases energy consumption and potentially CO_2 emissions if excess solar export used for SPC/H could otherwise have been used elsewhere in the network. However, if SPC/H reduces solar curtailment and increases solar hosting capacity, then it can reduce CO_2 emissions, even if total energy consumption increases.

Barriers and Solutions

The following table summarises barriers raised in this study, paired with possible solutions.

Barriers	Solutions
Social	
Poor public perception, trust and awareness	Improve understanding and trust between the consumers and electricity suppliers by providing more transparent feedback technologies and contracts
Consumers' knowledge, experience, and familiarity with demand control/solar pre-cooling technology is very low	Education; Pilot programs to build familiarity; information about optimal operation strategies
Conflicting needs for level of control by consumers and networks – predictability, ease of use, lack of understanding or care, losing control	Balance network control with a degree of freedom for householders; allow consumers to select control types & times; to test & get feedback from selected control, allow for consumer opt out or override Convenience also plays a key role for consumers, particularly when technology is cheap and management is app-based
Consumer perception of risk regarding safety, affordability, security, and sustainability	Keep it simple: reducing the complexity for consumer engagement Clear incentives; positive messaging For solar PVs household, ensure the policy that requires their participation in the program aims to support the network performance and does not contradict to their initial motivation to participate in renewables energy (solar panel program)
Lack of understanding of consumer behaviour after the uptake of solar pre-cooling	A pilot program to understand the impact of solar pre-cooling on load shift in terms of quantum and timing

Barriers	Solutions
Consumers may prefer activating alternative appliances to shift load to solar power instead of cooling or heating	Not a problem; can be an extension of any program or approach
Technical	
Technical complexity and effort for consumers to participate	Automation, programmable thermostat, and direct load control are designed to reduce the complexity and effort; smart metering and control infrastructures, and communication infrastructures are base requirements
AS4755 forbids ACs from having the capability to be turned on or turned up remotely	Amend AS4755, taking into account all concerns that resulted in the original standard barring remote control of AC units in the first place; or mandate compliance with ‘DR capabilities’ or with an international standard without the limitations of AS4755.
Lack of storage and direct coupling between solar PV and the cooling energy demand may deliver limited benefit in terms of reducing peak demand	New technologies to directly couple either through storage or smart controllers is required between onsite PV generation, and heating/cooling loads and storage to maximise the benefits of solar PV-driven heating and cooling solutions. More data is still needed to assess the viability and feasibility of these systems in the Australian context
Sub-optimal control of SPC/H may result in SPC/H having a detrimental effect on energy consumption, running cost and thermal comfort	Improve understanding of the influence of SPC/H control strategies and forecasting on the thermal, economic and grid benefits of SPC/H through a combination of modelling and demonstration/pilot projects
Control modifications to existing residential air conditioners may be costly and carry some risk as modifications are not supported by the AC manufacturer potentially voiding warranties	Using demand response ready ACs means that the manufacturer’s warranty remains valid and the AC is designed to operate in these modes
Ducted systems require hardwiring from the thermostat to the smart controller	Technology development opportunity
Pre-cooling of highly energy efficient homes is not effective	Increase the number of homes that are energy efficient to mitigate the need for cooling overall Give incentives for improving home-energy performances (e.g., from 6 to 8, etc.)
Economic	
SPC/H may increase total household energy use and/or reduce thermal comfort	Determine and provide public information on optimal temperature and time settings for different climate zones and house types; develop model-based pre-cooling strategies that consider the complexity of climates, housing features, and residents’ diversities and prioritise thermal comfort.
High costs and risk demonstrated by earlier trials indicated that air conditioning load control did not offer a cost-effective demand	Keep it simple. Use price signals.

Barriers	Solutions
management solution under certain program models	
Consumers need incentives to participate	Falling daytime demand may lead to lower solar feed-in tariffs. If self-use of solar for pre-cooling is more valuable than grid-export, then the value of solar increases with the volume of self-use Implement appropriately structured time of use tariffs or dynamic peak pricing. Network providers need to provide additional financial incentives (rebates or rewards) to share the network benefits of SPC/H
Consumers may need additional equipment such as smart meters and smart devices for the remote control. Networks concerned they are ineligible to claim “behind the meter” investment (providing in-home technologies)	Clarify situation; policy/regulatory change may be needed
Energy costs are a disincentive for AC use by low to middle income households	Positive messages about free, cheap or guilt-free thermal comfort combined with appropriate tariffs
Current measure of AC penetration rates may be insufficient to forecast future electricity demand	A new measure may be required to adequately track the influence of air conditioners on peak electricity demand

Path to impact

Impact framework

An impact framework was developed for this theme to strategically plan how it seeks its desired impact and articulates the various impact pathways projects may take. The framework is also a tool for projects to help identify and plan for impact over and beyond their lifecycle. The detailed impact framework is reproduced on the following page.

Key metrics

Indicators and metrics were identified, categorised under knowledge and technology diffusion, industry development and societal impact. From these, a set of criteria can be assembled to assess the potential impact of future proposed projects. The metrics were specified as quantifiable as possible.

H1 Residential SPC/H Impact Framework

Inputs

People (Staff + Non Staff)

Funding (CRC + other: government, private sector)

In-kind

Knowledge base

Infrastructure

Test sites

Activities

- Modelling, forecasting, data analysis, data collection (energy loads, financial implications)
- Feasibility studies, desktop studies, cost benefit analysis, etc.
- Demonstrations and pilot projects
- Business/ pricing model development
- Standards / protocols development
- Software / hardware development and integration
- Customer studies (energy use behaviours, DR messaging and acceptance)
- Public awareness campaign (understanding of DR, improved acceptance)
- Skills / Capacity development (construction industry)

Outputs

- Modelled potential for SPC & SPH - targeted and detailed
- Measurement and verification of load shifting
- Technical Standards
- Inform building standards
- Updated building energy ratings schemes/models
- Detailed measurements and verified pricing models / value stacks
- Market ready SPC & SPH hardware / software /control strategies
- Customer engagement and participation strategies
- Understanding of how house construction influences solar pre-cooling/pre-heating; influence of thermal mass
- Energy usage patterns for all major Australian cities and non-PV households/solar database
- Understanding of how the HVAC system usage and performance affects SPC & SPH (e.g. effect of COP as a function of ambient conditions)

Decreasing control / Increasing uncertainty of project contribution

Outcome – Impact

Short

- **Better industry understanding** through knowledge diffusion
- **Better consumer understanding** of SPC/H operation, how it can save them money and benefit the network
- **Skill development**
- **Technology development**
- **Technology** & process innovation **diffusion**
  - Uptake of products & services
  - Mainstreaming business models
    - Equitable pricing models tailored to time and location
    - AC control technology standardisation and uptake
    - Low cost ability to manage fleets of AC to drive business models
    - Innovative consumer and network services
- **Barriers** to mainstreaming SPC/H identified
- **Informed policy/regulation** to mainstream SPC/H (tariffs, building upgrades, technologies, products, services)

Medium

- **Reduced barriers** to mainstreaming SPC / SPH
  - Tariffs and payments/ credits that incentivise consumer participation
  - Established and well understood SPC/H technologies and products
  - Improved network/ consumer relationship
  - New level of consumer understanding of their role in network operations
- **Network Benefits**
  - Increased solar hosting capacity, mitigate voltage excursion and variability, reduced curtailment of solar export.
  - Reduced power (normal and peak) flows through transformers and cables, prolonging the life of these assets.
  - Peak reduction defers expensive network upgrades
- **Policy** & **regulation** to support informed **decision making** & planning
- Improved **quality of house** construction
- Increasing **consumer and industry confidence** in technologies & application of technologies

Long

- Lower energy bills ($)
- Lower network costs ($, LCOE)
- Increased energy system reliability (Disruption Index)
- Reduced emissions (CO2eq)
- Increased energy / network efficiency
- Jobs created (FTE)
- Skilled job creation (FTE)
- **Customer satisfaction** & **equity**
  - Social acceptance of SPC/H
  - Equitable access to network resources and benefits
  - Improved home comfort / thermal efficiency
  - Improved solar house design
- **Other Social impacts:**
  - Health & wellbeing
  - Household resilience to hot weather events
  - Increased thermal comfort

Research roadmap

Research priorities to progress SPC/H, using methods such as modelling, pilot programs, and demonstration projects to inform stakeholders and validate modelling, should address the following:

Design of a SPC/H program

- What are the key considerations to overcome technical limitations, consumer reticence, and the risks and costs for networks of running a program? Determine:
    - Control methods and strategies
    - Customer incentives and messaging
    - Program management including participant recruitment and communications
- What is an equitable pricing model?
- Quantify the value to the electricity network
- Quantify the grid management impacts

Impact of SPC/H on thermal comfort

Collect/create additional data such as

- Residential energy usage patterns for all Australian climate zones for PV and non-PV homes
- Existing house thermal mass conditions
- Information on HVAC COP under different weather conditions

Load management and verification

- If, and how to remotely verify load response
- Appropriate standard and capabilities for control devices

For the complete Research Roadmap, refer to section 8.

Contents

Figures

Tables

Abbreviations

AAC	Autoclaved aerated concrete
ABCB	Australian Building Codes Board
AC	Air conditioning
AER	Australian Energy Regulator
AFLC	Audio frequency load-control
AHD	Australian Housing Data
APVI	Australian PV Institute
AWS	Amazon Web Services
BaU	Business as usual
CEC	Clean Energy Council
COP	Coefficient of performance
DMS	Demand side management
DR SN RERT	Demand Response Short Notice Reliability and Emergency Reserve Trader
DRED	Demand response enabled device
EQ	Energy Queensland
F1	Basic forecasting
F2	Perfect forecasting
FiT	Feed in tariff
FR	Free-running
GHG	Greenhouse gas
HAN	Home area network
IFTTT	If This Then That
IR	Infrared signals
IRG	Industry Reference Group
NatHERS	Nationwide House Energy Rating Scheme
PCMs	Phase change materials
pf	Power factor
PJ	Petajoules
PV	Photovoltaic
RCP	Representative Concentration Pathway
SPC	Solar pre-cooling
SPH	Solar pre-heating
SPC/H	Solar pre-cooling and pre-heating

1 Introduction

This Opportunity Assessment is a scoping study to determine what is currently understood about residential solar pre-cooling and pre-heating (SPC/H) and therefore guide where RACE for 2030 should focus its efforts. This report reviews the state of technology and the market for SPC/H in homes for consumers and the electricity supply system. It estimates the scale of potential benefits and costs, identifies specific targeted impacts and proposes research priorities to achieve these impacts.

The intended outcome of SPC/H is to cost effectively shift solar energy from when it is available to when energy is required for heating and cooling. The purpose is to achieve grid load smoothing which is expected to lead to lower customer bills and peak demand, and improved solar hosting capacity.

Australia has abundant solar energy resources while at the same time is facing the challenge of dramatic peak electricity demand due to a high penetration rate of air conditioning (AC), especially for residential buildings [1-3]. SPC/H is increasingly seen as an effective demand response strategy, where the peak solar irradiance can be used to meet the peak electricity demand [1, 4, 5]. This requires market-ready remote monitoring and control technologies as well as adequate thermal inertia of homes to reduce peak demand and therefore network infrastructure costs, consumers' energy bills and greenhouse gas (GHG) emissions. A broad application of SPC/H can also facilitate greater network hosting capacity for rooftop solar PVs.

1.1 Scope of study

Specifically, the concept of SPC and SPH requires two components:

- reduce energy demand for heating and cooling in the evening peak (when demand typically peaks),

and

- soak up daytime solar power capacity (when the solar resource is typically abundant) to supply cooling and heating.

It is not about efficiency of equipment or operation, although these are helpful. It is about time shifting heating and cooling and using the thermal inertia of the building to retain the thermal benefits until the occupants return later in the day. Research and trial programs have been conducted on energy efficiency and demand response approaches to reduce peak demand. These may include such measures as the use of efficient equipment, modifying set temperatures, or incentivising powering equipment down or off. But to meet the criteria of this study, additionally the heating or cooling task must be actively shifted to the middle of the day, at times of high solar capacity, whilst the home is unoccupied. If the home were occupied, thermal comfort would be a key consideration, as then it would be direct cooling and heating, not 'pre'.

The first focus of SPC/H is to use a household's own PV system to power cooling and heating instead of feeding electricity to the grid during the day when the grid already has excess capacity. For houses without PVs, SPC/H is also relevant because it can help to soak up the excess capacity in the grid supplied by solar installations elsewhere. The technologies to facilitate this are similar but the incentives for householders will be different.

Standard heating and cooling technologies are suitable for the purpose of SPC/H, although some innovative alternatives, such as active thermal storage, open new opportunities. It is the control technologies that affect the capacity of a household to efficiently participate in SPC/H.

Of particular concern is the ability of the building to retain the heating or cooling. Poor quality buildings will leak the heat or coolth so that little benefit remains into the evening when needed by the occupants. Testing this is the subject of the modelling documented in this report.

The other major concern for successful implementation of SPC/H is how well it will be accepted by consumers, what incentives may be needed to recruit households in sufficient numbers and the possible cost and complexity of programs to achieve the desired impact.

1.2 Background

The built environment is one of the largest consumers of energy in Australia accounting for nearly one quarter of total emissions [6]. Space conditioning represents the single largest energy user, comprising 41% of all energy use in the residential sector [7]. HVAC consumption and hot water usage constitute over 60% of typical residential energy use [8]. Driven largely by energy efficiency measures, energy intensity has shown a decline in the last decade with residential buildings achieving a 15% improvement in energy use [8]. However, overall energy use in residential and commercial building sectors will continue to grow in the coming years, driven solely by overall population and economic growth.

In the last decade, overall residential sector energy consumption increased from 402 Petajoules (PJ) in 2008 to 441.1 PJ in 2017. A key driver is the growth in occupied residential households in Australia and the increasing size (floor area) of these households. The cost of energy also increased disproportionally to its use. In the residential sector, per-household electricity consumption declined by 4.7% and its expenditure grew by 69.3% from 2008 to 2013 [9]. Onsite energy generation technologies can play a major role in protecting end users from escalating energy costs.

The use of residential air conditioners during the afternoon hours of hot summer days is seen as the main contributor to network peak demand periods [10]. Electricity supply utilities invest in maintaining and expanding infrastructure that is used for only few days a year. Demand response initiatives such as ‘PeakSmart air conditioner’ programs have been used to avoid expensive network upgrades and the addition of peaking power generation capacity [11]. Solar energy-based air conditioning has been shown to reliably reduce the peak demand [12].

One opportunity to reduce peak demand on the network and soften the ‘duck curve’ (Figure 1-1) is through solar pre-cooling of homes. Traditionally households utilise air conditioners throughout the day but especially in the late afternoon and evenings to heat or cool their properties. Pre-cooling (or heating) utilises the surplus power generated by renewables earlier in the day to lower (or raise) the ambient air temperature within houses, shifting time of usage and alleviating somewhat the network load at demand peaks. Not only does this reduce network loads, costs and use of fossil fuels, it also provides another potential avenue for demand management and response for the network operators.

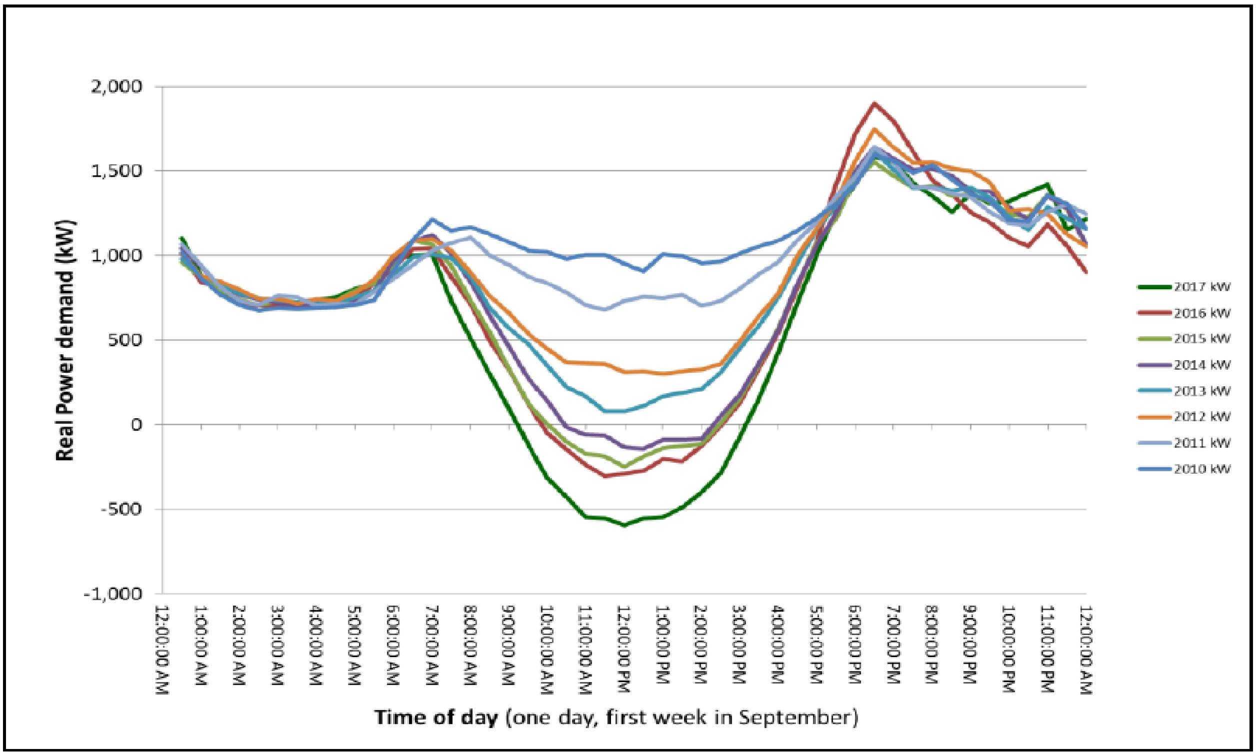

Figure 1-1. Transformation in the Australian National Electricity Market and the resulting duck curve
Source: Energy Queensland Burrum Heads feeder profile, 2010-2017 [13]

2 Methodology

2.1 Research methodology

The Opportunity Assessment was divided into work streams to gather data which was then brought together to create the project outputs.

2.1.1 Desktop review of industry practice internationally and locally

This work stream has identified the state of the industry, particularly what is working and not working. The desktop review has examined the market scale and cost of technologies (particularly control systems and interactions with thermal storage), current practice and best practice, and technical and institutional barriers, incentives, and policies influencing the utilisation of SPC/H. Global and Australian leaders in technology and best practice have been identified. In reviewing both academic and grey literature, the project seeks to clarify the technological and market potential for SPC/H, as well as provide an overview of the current state of research.

2.1.2 Consumer benefits and acceptance

This work stream has studied the feasibility of SPC/H for Australian houses from the consumers' perspective. It has reviewed previous research on consumer attitudes to SPC/H, including remote control, comfort expectations, and incentives to inform the analysis of barriers and solutions for the market potential and provide guidance to some of the theme specific scope. The study has been conducted by a comprehensive review of research literature, government publications, social media, grey literature, and supported by stakeholder interviews.

2.1.2.1 Stakeholder interviews

To support the desktop literature review, semi-structured stakeholder interviews were conducted. The interview participants were experts and stakeholders representing consumer bodies and industry associations and selected for their insights into consumer benefits and acceptance. They were recruited from organisations that participated in the project's Industry Reference Group (IRG) and from organisations that were members of RACE 2030 CRC. Overall, 10 invitations were sent out and 5 were successfully interviewed (3 organisations did not respond and 2 organisations declined). The interview was conducted one-on-one, on-line, and was recorded by Zoom. Each interview took about 30 to 60 minutes at a time that was convenient to participants. The ethics approval for the interview study was approved under UTS Project No. 20246, and ratified by QUT.

The stakeholder interviews sought insights into consumer attitudes to solar pre-cooling, including remote control, comfort expectations, and incentives, in order to supplement the findings of the desktop review. Research data were the interview transcripts and video files. The research data is stored as per QUT research data storage policy on a QUT server (U drive). No personal data was sought and all interviews were de-identified. Participants were contributing as experts or professionals related to their employment and responses were not attributed to individuals. Main questions discussed in the interview consisted of:

Q1 What motivates consumer/prosumer for solar pre-cooling?

Q2 What are the enablers/barriers to consumer/prosumer participation in solar pre-cooling?

Q3 How may household characteristics and housing quality influence consumer/prosumer's decision to enrol in solar pre-cooling?

2.1.3 Characterisation of a 'suitable' home

This work stream has explicitly analysed what change can be expected at different house thermal efficiency levels, while identifying information gaps. The outcome of this workstream has provided inputs to the scenario analysis workstream.

A representative four-bedroom, single storey sample house plan was selected as a basis for an assessment of solar pre-cooling. This representative home was selected based on the Australian Housing Data (AHD)

Portal, which has a total of around 10,000 existing old dwelling designs, 20,000 renovated dwelling designs, and 840,000 new dwelling designs from May 2016 to March 2021.

Based on this sample house plan, 2-star, 6-star and 8-star (NatHERS star) house designs with light-weight, medium-weight and heavy-weight constructions were developed for Sydney, Adelaide, Brisbane and Melbourne climates. These sample houses represent old, new and high-end energy efficient housing stock with different thermal mass constructions respectively.

Building performance simulations were then carried out with both air-conditioning and free-run operations for pre-cooling benefit analysis using current weather files as well as future projected weather files under RCP2.6 and RCP4.5 in 2030 and 2050 respectively.

2.1.4 Scenario analysis

This work stream has identified the technical and economic potential of SPC/H, which involves a high-level estimate of how many homes with both AC and PV systems could effectively be pre-cooled or pre-heated (i.e., where this would result in a significant reduction in energy required during peak times and “valley filling” in the middle of the day). Scenarios have been defined in consultation with the IRG in order to indicatively quantify potential benefits and costs. The scenario analysis has considered the definition of alternative scenario(s) to determine the range of potential impacts on cost, peak load, potential for PV uptake, and emissions reduction. It has also considered the correlation of solar PVs with AC unit installation data, building on the CSIRO Atlas of AC and postcode data for PV installation.

Business as usual (BAU) (building trends, expected energy rating of new builds – high-level estimate of homes which could effectively solar pre-cool/pre-heat up until 2030) and accelerated scenarios (assuming take-up of technologies, incentives and new materials) have been considered using simple scaling of existing models.

Additional details relating to the modelling methodology are provided in the Appendices.

2.1.5 Research synthesis, barriers and opportunities, and research roadmap development

Through a series of workshops, conversations and document reviews, the delivery team has combined findings of previous tasks, to identify priority research questions and business opportunities, including specific identification of knowledge gaps, required enabling technologies, and desirable demonstrations and pilots. The research synthesis includes an analysis of the barriers and opportunities to SPC/H in terms of technical standards, consumer acceptance, the housing stock, and incentives, as well as an indicative quantification of achievable benefits by 2030 and 2035.

2.1.6 Industry and stakeholder engagement

The project established an IRG that engaged relevant RACE partners, peak organisations, government and industry representatives for review of the project direction and to ensure diverse industry views inform the project. Three online workshops were held with the IRG to seek their perspectives, and members were asked to review project outputs.

The intent of the three workshops were:

- An inception workshop at the beginning of the project, to provide an understanding of the project, and to seek the views of the members on where the emphasis should be;
- A review workshop midway to review progress to date and discuss details of assumptions and preliminary findings
- A stakeholder workshop towards the end of the project at draft report stage for the researchers to share knowledge and to test conclusions.

3 Current technology and market status

Even though SPC/H seem to be a narrowly focused topic, complexity arises while research proceeds due to the ever-branching questions of who, what and how, in terms of technology, control, control mechanisms, benefits, possible market response to benefits, and considerations about pricing, incentives, messaging, house quality and system integration. The review scope of current technology, market status, and consumers' perspective of this report focuses on issues related to SPC while the scenario modelling work has considered both SPC and SPH.

The matrix in Figure 3-1 illustrates the diversity of control requirements and benefits, for SPC/H depending on roles and solar power source. In all cases there are preconditions of tariffs, incentives, messaging, control technologies and house quality, for each of which there will be a range of possibilities depending on application. The vertical purple bands indicate how control may be the responsibility for one of three possible actors: the householder, the network business, or a third party that would interface with and bundle a group of households. The benefits are different for each of these roles, and will differ depending if the power is from a householder's own rooftop PV, or is from excess grid capacity, as shown in the green horizontal bands. There are also benefits that would be experienced beyond these roles in the broader community, shown in the matrix as community benefits spanning the full width. These are expected to be reduced household electricity costs particularly helping those in fuel poverty to improve their thermal comfort and thus health and well-being, and a reduction in barriers to installing rooftop PVs and feeding to the grid.

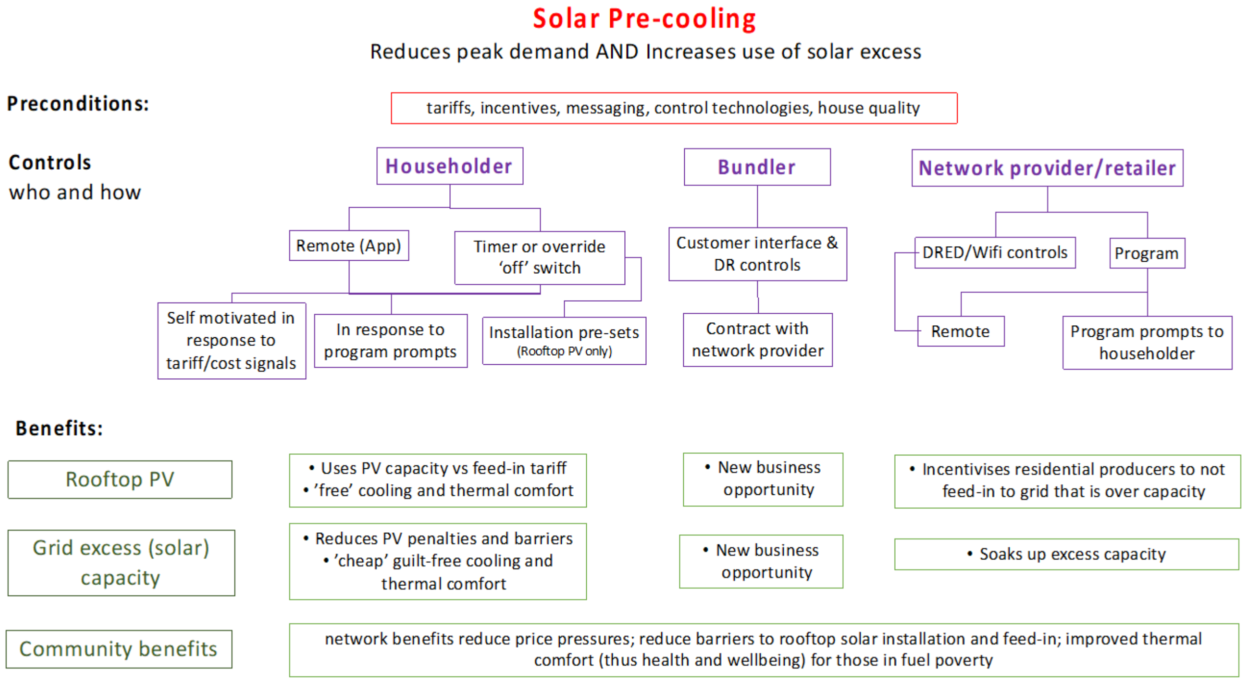

Figure 3-1. Complexity in solar pre-cooling

The alignment of solar availability with residential cooling requirements has generated large-scale interest in the development of solar assisted comfort cooling technologies across the world. The intersection of decarbonising the energy sector and rapidly increasing global cooling demand due to increased economic prosperity in tropical countries is a global driver of accelerating this technology development [14]. However, residential solar assisted cooling is still an emerging opportunity to reduce electricity demand from the grid and improve the energy footprint of the built environment. The literature scan below is focused on the status of solar pre-cooling that is suitable for residential applications and identified technology and market status in Australia.

3.1 Current scale of market

Due to the broad range of the solar cooling technologies and strategies (pre-cooling practices/ methods), assessing the market status is complex. On the one hand there are specific solar cooling technologies at different stages of market penetration, on the other hand there are solar cooling strategies and methods involving a number of technical components that have yet to be aligned and integrated for the purpose of residential pre-cooling for load shifting. The following assesses the current scale of market in terms of solar PV installations, AC systems and controls.

3.1.1 Solar PV installations

In the last decade, solar PV installers have been adding significant capacities that target applications in the built environment. Australia’s position as a world leader in rooftop solar persists: as of 31 March 2021, there are over 2.77 million PV installations in Australia, with a combined capacity of over 21.4 gigawatts[1].

A dominant trend in solar PV installations is a continued growth in average system size (see Figure 3-2).

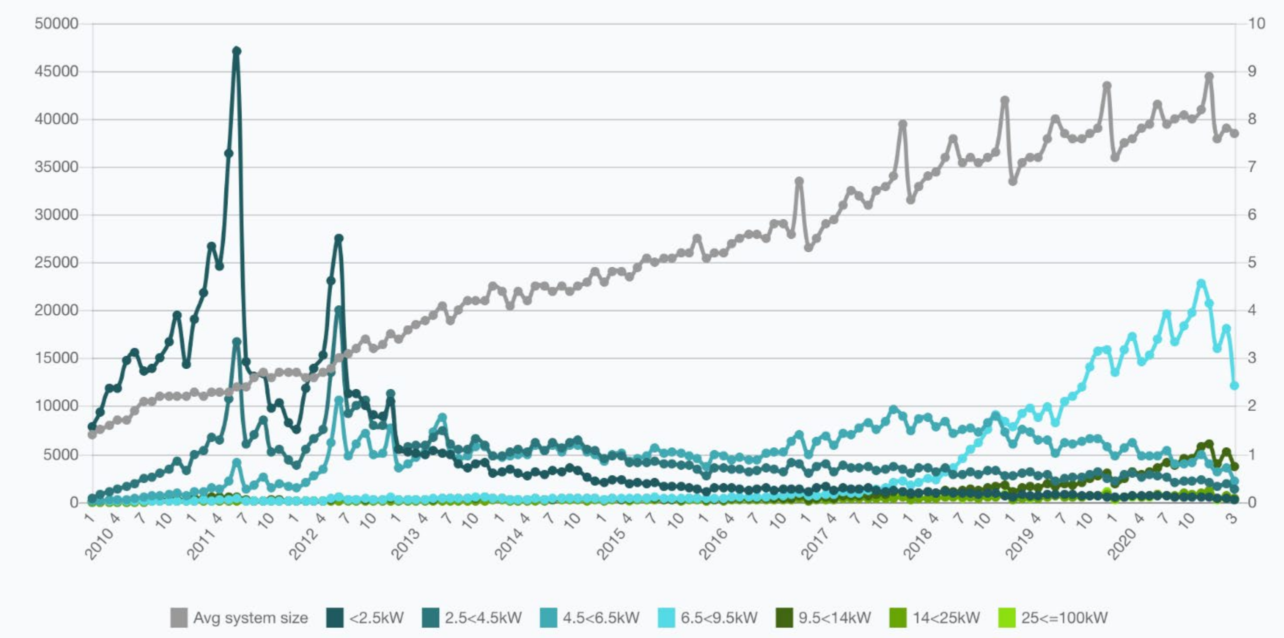

Figure 3-2. Number of solar PV installations by size category and month/ year in Australia. The left y-axis shows the number of installations; the right y-axis is the average system size (kW). Source: Australian PV Institute (APVI) Solar Map, funded by the Australian Renewable Energy Agency, accessed from pv-map.apvi.org.au on 29 July 2021.

3.1.2 AC systems and controls

The market for solar cooling methods and pre-cooling strategies could be determined by the growth of AC units and AC control systems.

In terms of AC, the most recent ABS data (2014) indicates that the penetration rate of around 75% of Australian households has stabilised. However, AC sales data and anecdotal evidence from the AC industry indicates that the total living area being cooled continues to increase. Increasing construction activities, specifically in the mid-tier building sector, are one of the factors responsible for the increase in demand for AC. There is a considerable increase in demand for smart homes across Australia. In the coming years, technologies such as IoT, automated control systems, and remote-control access are expected to transform the HVAC industry. Split air conditioners dominated the Australia AC market in 2018 and are anticipated to maintain its dominance throughout the forecast period (until 2024).

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[1] Australian PV Institute: https://pv-map.apvi.org.au/historical

Moreover, super-efficient and climate-friendly residential cooling solutions are recent developments that provide cooling while contributing much lower carbon emissions compared to regular air conditioners [15]. This is forming a new trend in light of the international moves to net zero carbon emissions, in addition to the increased awareness of the global warming potential (GWP) of the most common refrigerants. It is expected that AC technologies and systems will be different in 2030 and beyond.

The global outlook for AC controls is very positive. The market is expected to grow at a compound annual growth rate of 10.5% from 2020 to 2025, reaching USD 24.4 billion by 2025 from USD 14.8 billion in 2020 [16]. The demand for AC equipment is increasing owing to the boom in the construction sector on a global scale. Rapid urbanisation in developing countries, especially in the Asia-Pacific region, has created a huge demand for AC equipment. New constructions are proactively incorporating smart systems and automation systems in their architecture. This trend is additionally fuelled by smart home technology penetration across the globe. In addition, a growing awareness about the benefits of smart technologies coupled with the increasing willingness of consumers to spend money on connected devices are paving the way for the growth of the market.

The dominant market dynamics are:

- Consolidating trend of smart homes, accelerated further to boost AC controls market growth
- Boom in construction sector fuelling demand for AC controls
- Emergence of Internet-of-Things-enabled AC systems
- Need to achieve energy efficiency in buildings and the potential for reducing electricity bills

However, there are also challenges for adopting AC controls. These include costs and technical complexities associated with installing control systems or upgrading existing AC systems [17]. In addition, there is a lack of incentives for solar pre-cooling applications and little to no public awareness about the benefits and opportunities associated with this strategy.

In Australia, the Australian Standard AS/NZS 4755 specifies the minimum functionality and optional capabilities of demand-response-capable AC. These ACs need to be capable of responding to external command signals by switching the compressor off, or operating at a reduced load, but the standard explicitly forbids capability to remote commence operation, i.e. there can be no ‘on’ command. It is understood that there is currently a review of AS/NZS 4755 that is considering a change to the standard to allow such a mode for ACs.

The AS/NZS 4755 is not a mandatory standard, but programs such as Energex PeakSmart air-conditioning provide incentives for consumers who install air conditioners that are capable of connecting to a demand response enabled device (DRED). Air conditioner manufacturers offer compliant products due to a strong market pressure. Due to a growing market in Australia, the AS/NZS 4755 is recognised internationally as a pioneer of demand response standardisation and load management.

3.2 Current status of technology

3.2.1 Solar-assisted cooling technology

There are a number of options to deliver residential cooling using solar energy. Solar cooling technology can be broadly classified into solar thermal and solar electricity applications. Solar thermal systems have been around for over 20 years and have gone through continuous development and improvement. Cooling delivery options range from low temperature collector heat-driven absorption/adsorption/desiccant cooling systems to multi-effect chillers that use high temperature heat from concentrating collectors to solar electrical cooling systems. Such technologies are not common in Australia and tend not to be used in residential applications.

To meet the criteria for this study, this review is only concerned with solar electricity applications. The technologies are mature in the market and include compression chillers and controlled AC systems.

3.2.2 AC control technology

Using solar electricity to power AC system or thermal storage systems combines existing technologies for cooling purposes. In this context, solar pre-cooling is proposed as a strategy to shifting or reducing the peak demand and/or energy cost in residential buildings by optimal timing AC system usage. Pre-cooling is an operational strategy with potentially no up-front costs. In its simplest form, pre-cooling can be implemented by scheduling AC operation to reduce thermostat below typical comfort settings in advance of the on-peak time period, and therefore reducing the use of AC during peak times.

Hence, the key technology for solar pre-cooling strategies are controls for AC systems which have different paths of capabilities. Demand response can work in two ways, each with different technological requirements. In cases where a remote agent (electricity distributor, electricity retailer, electricity system manager, or a demand response bundler) determines when SPC/H is required, they require a contractual relationship with the customer, prior consent to any remote operation, and agreed conditions.

Manual activation has the occupant manually turning their equipment on remotely or with a pre-set timer. This could be in response to a notification from a remote agent with whom they have the prior agreement. The notification could simply come in the form of an SMS message in advance of the SPC/H requirement. Alternatively, the occupant is motivated to act by tariff or payment incentives built-in to their electricity supply agreements. The technological requirements are therefore minimal.

Automation of demand response has equipment connected to suitable control and communications devices that allow remote operation by a remote agent (electricity distributor, electricity retailer, electricity system manager, or a demand response bundler) or the occupant themselves. The Australian and international markets for air conditioners, have been anticipating demand response capabilities and gradually including this facility in their new products.

3.2.2.1 Demand Response Enabling Devices (DREDs)

A demand response system that complies with AS/NZS 4755 must include: a DRED, a means by which the DRED receives commands from a remote agent, a compliant electrical product, and a means of transmitting instructions between the DRED and the product. A DRED is the communications interface between the remote agent and the product. It can be a stand-alone element or built into the electrical product. It can be connected to individual appliances or multiple devices. It could be activated via the home area network (HAN) or a controlled load relay.

A recent report from the Institute for Energy Economics and Financial Analysis [79] is highly critical of AS4755 and advocates against it being mandated in Australia. Reasons for this include that AS4755 does not support interoperability, does not allow consumers to retain control, does not support two-way communications or verification, and has a limited range of commands that are not compatible with price-responsive distributed energy resources. These failings mean it cannot be used to calculate financial rewards for consumers offering their appliance into DR programs. Issues with AS4755 DREDs are corroborated by the findings of some of the DR trials in Australia summarised in the following section 3.3. The report suggests legislating a ‘DR capability’ instead, or if a single standard is essential then the authors suggest adopting a widely supported international solution such as IEEE 2030.5.

An Australian Standard for communication pathways is in preparation; options include powerline carrier (ripple control), broadcast wireless, and local wireless (Z-wave, Zigbee).

3.2.2.2 Ripple control

Ripple control is the most widely applied technology that utilities and demand response bundlers use to communicate with demand responsive smart appliances. In Australia, ripple control is reasonably common in the eastern states with a possibility for overall energy integration and management.

There are a few obvious drawbacks of ripple control. Firstly, it does not allow consumers to override the settings. Secondly, it does not offer the capability to be incorporated into an internet platform for an integrated flexible demand management program. Ausgrid has expressed concerns about ripple control sending signals to turn on or turn off air conditioners all at once, which would potentially exacerbate minimum demand. By contrast, internet addressable ways are capable of staging the turn-on or turn-off signals to achieve a gradual return to normal.

In application, the ripple control that is currently in use in Queensland only sends signals to turn off or turn down air conditioners to 50% or 75% of capacity to release pressure on the grid during extreme weather. It has not been used by network providers to direct control air conditioners for solar pre-cooling which requires turning-on signals.

3.2.2.3 Remote infrared control

The other commonly used technology in direct AC control DR programs is thermostat-like smart devices. These devices are Wi-Fi enabled and work by sending infrared signals (IR) to the AC unit, just like those sent from the unit's own remote control. Their development follows the general trend to remote control home services such as heating, lighting, home entertainment, security and fire alarms being integrated in more and more homes and apartment buildings. The widespread proliferation of smart controls or Internet of Things in the AC market can be witnessed by the fact that the global smart AC controller market is expected to reach a value of $8.7 billion by 2025 [18].

There are a number of products available on the market (see Table 3-1). Most of the products are compatible with almost every popular AC manufacturer brand such as residential mini-split, window AC and portable AC system. Indeed, in many cases there is no need to replace existing equipment, but simply extend the system and add new features as required. However, in some cases it can be appropriate to upgrade the control panels so that both the existing and new features are all on the same interface.

It does make a difference whether the AC system is ducted or ductless. Ducted systems usually do not have IR controls and have to be hardwired to the smart controller – these include for example thermostats. Ductless systems often come with IR functionality and can be used with smart controllers that send out IR signals to the appliance. For a ductless air conditioner, such as wall-mounted mini-splits or window air conditioners, a smart controller, like Cielo Breez Plus or Sensibo, is used. Ductless air conditioners can also be used as standalone devices with the capability of working in zones, only cooling down single, selected areas of the indoor space.

Table 3-1. Examples of smart controls for AC systems

Cielo Breez Plus	Sensibo	AC Interfaces Gateways	iZone climate control system
Available for residential users having mini splits, window ACs or even portable ACs	Sensibo supports any air conditioner that has an infrared remote control.	Not compatible with all AC models	Turns any ducted air conditioner into a smart home
			
https://www.cielowigle.com/	https://sensibo.com/products/sensibo-sky	https://www.intesis.com/products/ac-interfaces	https://izone.com.au/smart-air-conditioning/

Users can send commands to their connected devices through an app. Once a command is sent from the mobile or web app, it is sent to a cloud service. The cloud acts as a relay, sending the commands further on to the device itself. Common cloud services currently in use are Microsoft Azure and Amazon Web Services (AWS). Upon receiving a command, the device sends an infrared signal (in the case of ductless air conditioners with remote control) or through wires (in the case of ducted systems or furnaces).

Network providers have applied remote infrared control to run direct AC control DR programs, which allows them to adjust temperature settings on split system air conditioners during a peak event (see the industry practice section).

3.2.2.4 Smart thermostats

Smart thermostats are another way to control AC systems. These regulating devices sense the temperature of a physical system and perform actions so that the system's temperature is maintained near a desired set point. Smart thermostats come with Wi-Fi connection and enable remotely monitoring and controlling home temperature. An example of smart thermostats for ducted systems includes the Google Nest Smart Thermostat, the Honeywell TH9320WF5003 Wi-Fi Touchscreen Thermostat or Ecobee Smart Si Thermostat.

Some of the controls are also compatible with IFTTT (If This Then That) integration which opens up extra features from smart devices to events or scenarios (e.g. automatically switching on the AC if the temperature hits 30°C, or geofencing which allows you to provide your location to the smart device so that it can make decisions based on where you are; such as turn off when you exit the house). These controls can also be compatible with Alexa and Google Assistant.

3.2.2.5 Smart AC systems

Any new smart AC system has controls integrated and may provide much more advanced control and intelligent features than remote controls. These smart AC units do not need a separate third-party control as the Wi-Fi capabilities are built-in by the manufacturer. Downloading the smart AC’s mobile app is all that is needed to start controlling it using the mobile device.

The smart AC market has grown significantly in the last years with a great range of brands available. For example, LG Dual Inverter Smart Window Air Conditioner, Kuhl Smart Window Air Conditioner and Frigidaire Gallery 10,000 BTU Cool Connect Smart Air Conditioner.

However, these smart air conditioners require intervention by consumers on a daily basis or using ongoing settings that are difficult to understand, in comparison to a network-level controlled program.

3.3 Industry practice

Electricity distributors and retailers in Australia are currently offering a number of demand response programs, including direct control of air conditioners and more general behavioural demand response programs. These programs aim to improve the reliability of the grid, especially for extreme hot weather events. The growth of renewable energy sources, including rooftop PVs, have brought forward the idea of shifting peak demand to times when the sun is shining. These programs often offer the capacity for residential solar pre-cooling in terms of remote monitoring and controlling technicalities and business models, although their main focus is reduction of peak demand.

3.3.1 Energex/Ergon PeakSmart Air Conditioning Program (ripple control)

The PeakSmart program offered by Energy Queensland (EQ) is the largest of its kind for uptake of direct load control of air conditioners. Energex/Ergon – Queensland Government owned electricity distributors – has connected over 130,000 home and small business air conditioners, providing up to 150MW of diversified load under control during peak demand events [19]. Even though it is still a small percentage of the total number of Energex/Ergon customers, the penetration progress of this program is considered as a success. This is because participation in the program is continuing to grow compared to only 88,000 PeakSmart air conditioners rewarded in 2018, and over 80% of those surveyed participants indicated that they would recommend the program to others [20].

The AC controls use a DRED that can cap energy consumption of an AC unit to run at 75% or 50% of capacity. Note, 50% capacity can be called without householders noticing/reacting, thus providing a dispatchable resource. The DREDs are activated via audio frequency load-control (AFLC) and are randomly grouped into 1 of 5 channels that can be staggered at the start and end of the flexible demand event to prevent sudden large loss or gain of load. The DRED is supplied by EQ and is installed by industry providers and can attract a $50 incentive per device (paid by EQ) claimed upon application.

A one-off cash incentive of either $200 or $400 is provided to the home/business owner, after which the air conditioner is available to be managed by Energex/Ergon during peak demand events. Participants can leave the program by opting out and disabling the DRED device. But that must be done by an electrician or air conditioning installer at the homeowner’s expense. EQ attempts to then recover the removed device.

The key drawback of the PeakSmart program is that the AFLC DREDs are one-way communication. Therefore, it is not possible to know if the controller has responded in a given home, whether the air conditioner was operating (one can't reduce load from an air conditioner that isn't switched on), or how much flexible demand was delivered from a given home. However, metering at substation level provides an aggregated view of achieved load reduction (where sufficient PeakSmart air conditioners are on that substation). Significant trials have been conducted prior to program implementation to give a good idea of average deemed demand reductions from each PeakSmart enabled air conditioner.

Looking to the future, it would be advantageous to activate air conditioners through two-way HEMs/ IoT communications. New business models and tariff arrangements for managing AC Flexible Demand could also be explored. Investigating the role of AC demand for addressing minimum demand issues is a potential future research topic.

3.3.2 CitiPower and Powercor Energy Partner Program (remote infrared control)

Another established AC demand control program in Australia is run by CitiPower and Powercor [distribution, Victoria] during summer. Their most recent Energy Partner Program (https://www.powercor.com.au/energy-partner/) was offered between 1 December 2020 and 31 March 2021, aiming to cost-effectively manage the peaks. This demand response program provided participating households a free Sensibo unit that allowed the electricity distributors to adjust temperature settings on split system air conditioners during an event that was on days exceeding 36 degrees for up to three hours between 3pm and 8pm. Prior to each event, householders received four sequential email and/or SMS notifications detailing the start and expected finish time, and another notification when the event was over. Late notice of changes happened due to changes in weather and temperature, and the consequential electricity demand.

Sensibo is a small infrared controller that connects to split system air conditioners via home Wi-Fi. It allows householders to remotely control split system functions via a phone app for turning on/off, scheduling on/off, and monitoring home temperature and humidity. It can also react to room temperature changes and start cooling automatically till reaching a pre-set temperature.

To be eligible for the Energy Partner Program, householders who live in the target areas were required to have a split system air conditioning unit in the living room that operates via a remote control, home Wi-Fi with strong signal in the living room, and a smart phone/tablet for the Sensibo app. No other direct incentives were given to the participating households, except for a free Sensibo unit with an RRP of $159. The overall message was to empower households to "partner with CitiPower and Powercor to help reduce demand through the air conditioning unit in your home".

Notably, Powercor launched and piloted the Energy Partner Program over the 2018-2019 summer in the Bellarine Peninsula and parts of the Surf Coast. To support the launch, a $10,000 grant was offered to the school with the most families who signed up for the program. Also, every participating households received a free Sensibo unit and $20 for taking part in each event. As a result, more than a thousand households participated in the program, and 93% of them took part in the three events over the four months. Sharing a total benefit of $50,000, the participating households achieved a reduction of 474kW in electricity demand on one day alone [21].

Prior to the launched program, CitiPower and Powercor engaged CitySmart and QUT to examine household personas for an understanding of customer motivations, preferred communication channels and barriers to uptake for demand response programs [22]. The one-year long research was funded through the Australian Energy Regulator (AER) Demand Management Innovation Allowance.

3.3.3 AGL Peak Energy Rewards Program (behavioural DR)

The most extensive inquiry into demand response applications to date was administered by ARENA and the AEMO. They co-established a three-year Demand Response Short Notice Reliability and Emergency Reserve Trader (DR SN TERT) Trial in 2017 and developed 10 pilot projects with a total funding of $35.7 million. Three electricity retailers – AGL, EnergyAustralia and Powershop – participated in the trial and offered residential programs including behavioural DR programs and controlled load programs [23]. A key finding of this trial is that customers were much more interested in the behavioural DR programs, because they have a wider range of eligibility and a lower level of technology requirement, while allowing customers the full control of their energy use and participation.

Learning from the trial, AGL is offering the Peak Energy Rewards program[2] to residential customers in VIC, NSW, SA and QLD who have a digital smart meter. The demand response program aims to reduce electricity demand and power outages during peak times by prompting behavioural changes such as pre-cooling homes, turning up the air conditioning temperature, and delaying the use of large appliances. From 1 December each year, AGL notifies participants the time and duration of each peak event when the high electricity demand pressures the grid. The participants then voluntarily attend to the peak event to reduce or shift energy usage and earn bill credits and prizes for achieving individual pre-set energy reduction targets. Historical energy usage data is applied in the formula to forecast participants' normal energy usage during peak events, with normalisation of variables such as weather, time and day. The target levels of reduction are then set prior to each event and communicated to participants via SMS.

Communication is crucial. At sign-up, participants receive a welcome pack with the full program details and information about peak events. They also receive a SMS reminder on the day and an email report within seven business days of each event, stating their energy usage and rewards, as well as the energy savings of the entire program. It is anticipated that there are up to three events per year, and each event is one to three hours long. Additional peak events may be carried out to a maximum of ten in total each program year, and participants have the choice to opt out at any time.

The message is clear – to "be rewarded for reducing your energy use". Participants can earn up to $10 in bill credits per event for achieving their pre-set energy reduction targets, and $70 bonus credit for being the top 5% of savers in the state. There is also a draw to win smart home starter kits for staying below expected usage in each event. The popularity of the program is shown as registrations are currently closed due to reaching the maximum capacity.

The other two electricity retailers in ARENA's trial – EnergyAustralia and Powershop – are offering similar demand response programs. EnergyAustralia's PowerResponse program is launched for all their residential electricity customers with smart meters from November 2020, while Powershop's Curb Your Power program is only offered to their customers in Victoria. However, the popularity of this kind of program does not mean it has few barriers to program administration and customer uptake. In AGL's experience [24], it is difficult to interpret the result of saved energy as forecasted, and explain it to customers as the amount of energy they would save. Also, customers' demand response effort may be undermined due to the fluctuations of rooftop solar output. There are also challenges to improve the penetration of smart meters as the current level is low.

Notably, none of the three electricity retailers have continued to offer controlled load programs for air conditioners after the trial, as they conclude that direct load control of air conditioners is not viable due to complexity, high expenses, and erratic outcomes from controlling pre-existing air conditioners under the Australian Standard AS4755. Many AS4755-compatible air conditioners require additional hardware for direct control, while only a small portion of the interested customers had compatible air conditioning equipment. In addition, the significant shortcoming of AS4755 is that the standard does not provide remote control for customers to opt-out or override network control. This increases the administrative workload for retailers to process opt-out requests for each event via email.

3.3.4 Origin Spike platform (behavioural DR)

Partnering with a US start-up company called OhmConnect, Origin Energy [retailer] has launched a demand-response platform called Origin Spike[3] in 2020. Origin Spike enables residential consumers' participation in the NEM by improving energy efficiency and reducing grid load. It applies gamification logic and invites members who have signed up for the program to participate in energy-saving challenges called SpikeHours when electricity demand is high. Members are prompted via a weekly email or SMS to reduce their energy use through small behaviour changes such as turning off lights, adjusting heating and cooling thermostats, and shifting the use of energy-hungry appliances to solar hours etc. Origin Spike also has the capacity to connect to smart devices such as smart plugs and AC controllers to automate members' participation in

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[2] https://www.agl.com.au/newcampaigns/peakenergyrewards
[3] https://www.originenergy.com.au/spike/

SpikeHours. Eligible Origin customers must have a smart electricity meter that can be read remotely to join the program.

In return, members not only save on energy bills, but also earn points from Origin Spike once they reduce energy usage during SpikeHours to beat their baseline energy forecast of 1.2kWh or higher, depending on their average energy use over the previous 10 days. Collected points then can be used to redeem PayPal cash or gift cards. Members who manage to reduce their energy use by 60% for more than 20 consecutive SpikeHours could earn about $250 per year in rewards.

The message of “get paid for saving energy” has attracted more than 13,000 Origin customers to sign up for the program to date. Prior to entering the Australian market, OhmConnect has more than 500,000 customers in US and Canada, and has paid a total of US$12 million in rewards for a reduction of over 5.2GWh in electricity demand since the business started in 2014. In the summer of 2019 along, OhmConnect’s US customers received a total of US$3.2 million in rewards for a reduction of over 387MWh in electricity demand.

3.4 Business models

Particular potential is seen in third parties managing a cooling load shift and supporting households to manage their solar PV electricity consumption. By bundling a group of households, taking responsibility for recruiting and maintaining communications, bundlers may help to mitigate the risks and costs for networks to maintain an active SPC/H program. A successful example of a co-coordinated approach was the energy initiative of the Solar $aver program by the City of Darebin and Australian Energy Foundation (formerly Moreland Energy Foundation)[4]. This program was able to co-ordinate the installation of almost 300 solar PV installations on to the roofs of low-income households in Darebin for the Council.

3.5 Current state of research

Although residential PV-assisted cooling systems have drawn considerable interest in the last few years, most studies have investigated the energy savings and cost benefits of solar cooling systems in commercial buildings. These range from payback calculations that assume a fixed cooling load [25, 26] to detailed modelling that considers hourly variation in cooling load [27, 28]. These studies found that solar PV cooling solutions can deliver more primary energy savings compared with a single-effect thermal chiller-based solar thermal cooling system. A large reduction in the thermal chiller system cost is required for solar thermal cooling solutions to be competitive with PV cooling systems. As this technology is only incidental to solar pre-cooling, this study did not pursue this topic further.

3.5.1 Technologies

A Brisbane study has evaluated the effect of adopting cold storage on the peak demand of AC systems where it is integrated with a 5-star house thermal storage and roof-top PV system into a residential AC system [29]. The storage system uses the PV output to generate heat/coolth for the building’s thermal comfort using a vapour compression heat pump. The thermal storage coupled to the heat pump is used to utilise the PV output at the time of PV generation. The results indicate that using thermal storage coupled to a domestic heat pump and PV system greatly reduces summer grid-based energy consumption and shifts the peak load. The authors conclude that this distributed thermal storage coupled with PV system is expected to be a potential new generation of thermal comfort system for residential dwellings.

PV-assisted cooling systems can take advantage of the high cooling efficiency (energy input to cooling output) benefits offered by compressor-driven air conditioning systems. In fact, many components for PV assisted cooling systems are technically mature. However, a better integration and optimal design alignment is required for meeting end user objectives. More data is still needed to assess the viability and feasibility of these systems in the Australian context.

There has been a study on different technologies, phase change materials (PCMs) embedded in the building envelope and the potential to shift cooling energy demand away from peak hours [30]. The analysis includes

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[4] https://www.aef.com.au/projects/darebin-solar-aver/

PCM location, PCM properties, pre-cooling strategy, and an analysis of natural and forced convection models on the thermal behaviour of the house. They find the optimal combination of PCMs, convection mode, and pre-cooling schedule can completely shift cooling energy use during a three-hour demand period, producing maximum cost savings up to 29.4%, while increasing the occupant comfort.

Fewer studies and reports consider solar electricity and air conditioning for pre-cooling purposes. It is emphasised that the advent of demand response capabilities and further integration with PV time-of-use generation patterns provides for additional opportunities to flatten loads and optimise grid impacts [31].

It is highlighted the significant synergy between cooling and PV at global scale, which could considerably accelerate the growth of the global PV industry [14]. The authors note, that already today, utilising PV production for cooling could facilitate an additional installed PV capacity of approximately 540 GW, more than the global PV capacity of today. They find that without storage, PV could directly power approximately 50% of cooling demand, and that this fraction is set to increase from 49% to 56% during the 21st century, as cooling demand grows in locations where PV and cooling have a higher synergy.

3.5.2 Benefits

The literature review found a number of studies investigating the benefits of reducing cooling loads in commercial buildings [32-34]. However, there is very limited literature on pre-cooling residential buildings and the work that has been done is typically restricted in scope to the US. It is demonstrated via simulation that pre-cooling using mechanical air-conditioning could reduce annual peak period residential air-conditioner operation by between 75% and 84% in California [34]. Simulation results from a study by the Davis Energy Group for a US utility company in California suggested that, when combined with night ventilation, pre-cooling could save up to 97% of residential peak electricity consumption [35].

It is found that there is great potential for mechanical air-conditioner pre-cooling to reduce the peak electricity load and energy consumption of residential buildings [36]. A computer modelling approach was used to study the load reduction of several cooling strategies in 15 different US climates. Mechanical pre-cooling using the air conditioner can remove up to 97% of the peak cooling load at the settings tested. However, this is heavily dependent on climate zone, the length of the pre-cooling period and the pre-cooling set point.

Pre-cooling strategies in Oklahoma USA drew on a pre-cooling optimisation model that accounts for the thermal properties of a specific home, HVAC system capacity, utility rate structure, and weather conditions [37]. The authors found that a pre-cooling optimisation algorithm for homes provides a way to benchmark energy performance of the optimal pre-cooling strategy. However, the optimisation is heavily dependent on a specific set of conditions (i.e., specific thermal properties, HVAC system capacity, utility rate structure, and weather conditions). Further research is needed to investigate the impact of different sets of conditions on the energy performance of optimal pre-cooling operation.

In conclusion, although there is great opportunity to individually or collectively reduce cooling load or utilise excess solar electricity, there is a significant gap in studies or trials of pre-cooling strategies for remotely controlled AC units powered by solar PVs. More research is needed to understand the benefits of SPC strategies and the technology alignment and compatibility.

4 Consumer benefits and acceptance

Consumer attitudes play an imperative role in any demand management programs. Demand management is a demand control strategy that is associated with both network suppliers and end-users (consumers) to reduce peak network demand. It can be achieved by customers shifting their electricity use patterns or by electricity networks controlling the supply of electricity or directly managing consumer appliances [38]. Solar pre-cooling, as an emerging demand control strategy, aims to educate and incentivise consumers to participate in demand management that uses excess solar PV generation to pre-cool their homes before peak times during summer. While such a program has the potential to provide both cost and energy savings to consumers, its success depends upon attracting sufficient consumer engagement to achieve peak demand reduction targets.

The following identifies the feasibility of solar pre-cooling programs as a demand management strategy for Australian houses from the consumer's perspective. Specifically, it identifies key factors that influence consumer engagement and acceptance of solar pre-cooling, including perceived consumer benefits and motivations to participate, their housing quality and thermal comfort preferences, as well as the different attitudes between solar and non-solar households. Potential barriers and enablers to engagement from the consumer perspective and detailed in Chapter 6 of this report.

This consumer benefits and acceptance study is conducted by a comprehensive review of research literature, government publications, social media, grey literature, and is supported by stakeholder interviews conducted by the authors. Stakeholders to interview were selected from members of the project Industry Reference Group (IRG). The discussions of the consumer benefits and acceptance study are reported as a combination of the findings from the literature and the IRG interviews - each theme includes findings from both of the literature and interviews. The purpose of the interviews was to investigate whether the literature findings are in line with the experience of the stakeholders.

4.1 Perceived consumer benefits

The potential benefits for consumer engagement in solar pre-cooling programs have been identified by many studies [31, 39-42]. As solar pre-cooling aims at cooling the houses in advance during the unoccupied hours, it allows the opportunity for an 'instant' thermal comfort as soon as the occupants get home [31, 43]. Participating in such a demand management program can also help consumers to increase the awareness of their energy use, improve energy adaptability, and increase the control of energy bills [44, 45]. A number of studies also demonstrated that, under suitable operational strategies, pricing mechanisms and electricity tariffs, solar pre-cooling could help to achieve substantial energy savings and energy utility bill savings [31, 46, 47]. A Hong Kong case study showed that solar pre-cooling under suitable system settings and operations could reduce the non-solar energy demand from 19 kWh/day without pre-cooling to 5 kWh/day [48].

There are also many network benefits from solar pre-cooling, including smoothing out the residential load profile, reducing peak electricity demand, and therefore helping to maintain a more reliable and stable electricity grid [31, 49-52]. A US study shows that pre-cooling for residential homes can shift 50% to 99% of the peak cooling load with the tested settings, heavily depending on climate zones, length of the pre-cooling period and the pre-cooling set points [53]. Network benefits can also be considered as consumer benefits, according to an IRG interviewee, because a more reliable network could ultimately help communities/consumers in terms of access and use of energy.

> *"Optimised network systems could stabilise the work of electricity networks to minimise the cost of repairing and maintaining the grids/parts while delivering energy to many households."*

Solar pre-cooling can also increase the economic value of solar PVs [50]. As solar pre-cooling uses the excess of solar PV generation in the middle of the day, it increases the level of self-consumption of energy for the solar households.

Our IRG interviews point to a belief that solar pre-cooling also has potential social and community benefits, particularly if control and supply of solar pre-cooling services are handed to community aggregators.

> *"It can potentially result in cheaper electricity tariffs for the local community while improving social services within the community."*

From the environmental perspective, it was also mentioned that solar pre-cooling can have a positive effect on optimising the use of solar generation and promoting the reduction of GHG emissions.

4.2 Motivations

This section discusses reasons why consumers may decide to participate in solar pre-cooling. The review has identified a wide range of motivations for residential consumers to participate in solar pre-cooling and demand management. The following discussions are based on literature about both solar pre-cooling and about demand response in general.

Literature suggests that the two highest motivations reported by consumers for participating in solar pre-cooling are financial benefits and environmental benefits, with financial benefits typically rated the highest importance by the consumers [54]. A recent Australian study reported that 41% of participants were motivated to engage in demand response for reduced electricity bills, followed by 33% of participants motivated by sustainability [68]. In order to attract more consumers to participate in demand response, policymakers have come up with many financial incentives. A recent study in Australia reported that almost 90% respondents have a very positive attitude towards participating in a peak event product, such as peak rebate, dynamic peak pricing, seasonal time of use pricing, and top up rewards. It revealed that the incentive-based Peak Rebate product has inspired 10% higher participation rate than the tariff-based peak pricing product [44]. Another study in UK indicates that for some users, bill reductions are more appealing than rewards or other financial incentives [55].

Other identified motivations that are assumed to be important to consumers include increased control over energy use and bills [44, 56], free or reduced cost technology such as smart meters, smart control devices and solar PV [57], and thinking it may be interesting or fun to participate in demand response [54]. Some consumers are curious about the program, and want to know what they can do to make improvement (e.g., reduce energy use and energy bills, reduce peak energy use and help improve electricity grid) [58]. Research also pointed out that while financial rewards were a fantastic incentive for consumer registration, ongoing gamification was required to motivate and ensure participation in successive events [56]. Participants would also enjoy the challenge of responding to dynamic pricing and treat it like a game or project [54]. However, our IRG interview results did not find the gamification of the demand response program as a consumer motivation.

One additional social motivation identified from our IRG stakeholder interviews suggests that consumers would be motivated by their possible contribution to a stable grid.

> *"If pre-cooling was needed for reasons of system security (e.g., network breakdown, heatwaves), and to be done infrequently, people may value their participation as a social good. Consumer can be motivated to participate if they understand that their role in participating in precooling could make a good difference in the system as a whole; and thus, it may give them the satisfaction of being part of the good stuff."*

4.3 Housing quality

Housing quality is a very important factor for consumers in considering participating in solar pre-cooling, as it has significant impact on the pre-cooling performance. Research studies indicated that pre-cooling effects would be more effective in heavyweight thermal mass buildings, while lightweight thermal mass buildings would need sufficient insulation in order to make SPC/H beneficial from a physics perspective [37]. Solar pre-cooling is also considered as a very promising strategy to reduce electricity bills for moderate to well insulated houses, but considered to have limited application to poorly insulated, energy inefficient houses [40].

Some IRG stakeholder interviewees thought that consumers would be more inclined to participate in a pre-cooling or pre-heating program if they have a thermally well-performing home that would retain the heat or the coolth. People with energy inefficient houses would be less likely to participate as they may think the pre-cooling or pre-heating effect is not efficient, and therefore may result in energy and bill increases. However, other interviewees from the IRG argued that due to the better thermal performance of the houses, well-insulated houses would not need pre-cooling at all. For example, they argued that high NatHERS star rating houses have the capability to keep the building thermally comfortable during hot summers and cold winters. They argued that from the long-term perspective, improving the housing performance would be more acceptable for most consumers, because it is relatively inexpensive compared to the long term and ongoing energy efficiency benefits.

> *“It's a much better bang for your buck investment to upgrade the house because it's not that expensive, relatively speaking, and that makes a vast difference to any usage.”*

4.4 Thermal comfort preference

Thermal comfort preference is imperative in applying solar pre-cooling to residential homes as it could also act as a barrier to pre-cooling. Stakeholder interviews strongly agreed that the ability to tolerate higher temperatures by consumers would prevent their engagement in pre-cooling programs. It is very imperative to understand the thermal comfort levels of consumers as it will affect how deep and for how long solar pre-cooling should be cooled.

A comfort survey conducted by the Centre for the Built Environment (CBE) at the University of California-Berkeley for 170 office buildings across North America and Europe indicated that occupant comfort was maintained in the pre-cooling tests as long as the room temperatures were within the range of 21.1°C to 25.6°C [46]. A distribution of desired thermostat set point temperatures based on 162 homeowner surveys in Austin, Texas, USA showed 25.6°C to be the most common cooling set point when the home is occupied [59]. The survey also revealed that the occupied lower and upper bounds for the thermostat set point was 23.3°C and 25.6°C, respectively; and unoccupied hours (9:00 to 17:00) lower and upper bounds for the thermostat set point was 20°C and 27.78°C, respectively.

Some research studies in Australia demonstrated that AC was most unlikely to be switched on at around 20 to 22.5°C, 21.5 to 24°C and 23.5 to 26°C indoor temperatures in Melbourne, Adelaide and Brisbane. This temperature range around 20°C to 26°C has been argued by some as the preferred or typical temperature range for thermal comfort by the majority of the populations in buildings with heating and cooling [60, 61]. Some literature reports that people in climate controlled environments experience thermal dissatisfaction when in buildings with temperatures outside of the narrow range of temperatures suggested by standards such as ASHRAE 55 [3].

However, thermal comfort researchers have found that occupants are willing to accept a wider range of temperatures when buildings are naturally heated or cooled [63]. This is also consistent with the adaptive thermal comfort model in Australia’s house energy rating scheme (NatHERS) and the National Construction Code. It establishes different temperature bands for different climates (based on mean monthly temperatures), for different seasons (summer and winter), for different room types (living rooms vs bedrooms) and different times of day (accounting for different activity levels). For example, a study for a temperate Australian climate showed that under the adaptive thermal comfort model, the thermal comfort temperatures could be expanded to 22.7^{o}C to 29.7^{o}C in summer and 19.6^{o}C to 26.6^{o}C in winter in the Newcastle climate [77]. [63]. The NatHERS protocols would also point to a ‘comfortable’ temperature range (annual) of 18.2 – 27.9 °C for south-east Queensland, and 20.1 – 28.6 °C for Townsville. International standard BSEN15251 is based on adaptive comfort, using a running outdoor mean. ASHRAE 55 also has an adaptive comfort option, for use in natural and hybrid ventilation buildings. Our IRG interview findings also supported this argument that people may have a broader thermal comfort range that indicated in some literature.

> *“While residents may have varied thermal comfort preferences, humans in general also have ‘body plasticity’, which helps people to adapt to cold and heat, unless it is in an extreme condition (e.g., heatwaves), or people with specific condition that requires relatively stable room temperature (e.g., Multiple Sclerosis). Furthermore, ‘body plasticity’ leads to the debate that pre-cooling/pre-heating may reduce human ‘body plasticity’, and whether pre-cooling should be conducted on regular (e.g., every day in summer) or non-regular basis (e.g., only in heatwaves).”*

This is important to acknowledge because it impacts on estimations of the potential impact of precooling strategies: cooling from what to what? By whom? It would be a mistake to assume that thermal comfort bands are homogenous across all households, in all climate zones, in Australia.

4.5 Occupancy behaviours

Pre-cooling will be affected by occupancy (how homes are occupied in terms of times, days, number of occupants) and occupant behaviour (the actions of occupants), due to cultural, climatic and household differences, and different approaches to using air conditioning to meet their thermal comfort needs. Research by Daniel et al. [62] shows that in Australia, there is a dramatic difference in how consumers use AC in different states. A 2015 national survey indicated that the majority of respondents (67.1%) did not have any cooling appliances, and that a reverse cycle single-room air conditioner was the most prevalent type of cooling device. Other those with AC, a majority of consumers in four states used the AC for less than one month per year (NSW (100%), VIC (78%), SA (86%), and WA (56%)). This is in contrast to QLD (50% of residents use AC for less than one month and 50% of residents use AC for one to three months) and the NT (50% of residents use AC for one to three months and 50% of residents use AC for three to six months). In addition, a large part of these differences can be explained by the climate: northern Australia has longer summers; a large part of Australia is in temperature climate zones; and all climate zones have periods of the year where the ambient temperature is within human comfort levels without the need for additional cooling. Some of the differences could also be cultural (in the sense of reflecting local practices and acclimatisation). For example, a 2019 study showed that in Queensland, about 84% of residences have air conditioners (62% split systems; 13% ducted systems), and 78% have ceiling fans. It is quite common for Queensland residents to use ceiling fans alone, or in combination with air conditioners. Ceiling fans are also included as an energy efficiency measure in the National Construction Code and the inclusion of ceiling fans increases the NatHERS rating [78].

In tropical and subtropical climates where multiple split systems are the dominant air-conditioning type, it is reported that households may only be using the AC in the particular room/s that are occupied (i.e. not all ACs on at any one time). The most common operating times of AC in these climates is reported to be afternoons (45%) and evenings (40%) [62]. This same report indicates that some residents would be satisfied with the thermal comfort provided by good passive design (e.g. thermal mass, cross ventilation, orientation) supported by ceiling fans, removing the need for air conditioning and satisfying environmental concerns about energy associated with air conditioning [62].

This section only reports limited studies about air conditioning use in Australian homes. More information is required before generalisations can be made, across all climate zones. The key points are that homes are not generic (in terms of the building envelope to manage heat flows and store 'coolth'); that households are also not homogenous (in when homes are occupied and the activities undertaken by occupants); and that climate and local cultural practices vary significantly across Australia, impacting on the need for, and the approaches to, cooling in homes.

4.6 Solar households vs. non-solar households

Solar households and non-solar households have different attitudes towards engagement in a solar pre-cooling program. Literature shows that solar households would be more likely to use solar PV generated electricity locally rather than selling it into the electricity network [41]. Thus, they would be more likely to participate to make the best use of solar PV. Some IRG interviewees support the view that solar households would like to use their solar excess to be energy independent. These households are highly price sensitive and highly sensitive to using the output from the solar PV system. Non-solar households, however, may respond to price signals to determine whether or not they would participate.

Other IRG interviewees argue that solar households may be ready to participate in solar pre-cooling because they already have the basic devices and technology (e.g., inverter, smart appliance/AC) required to sign up. However, they can also be less inclined to participate because of changing policies and attitudes towards solar households that are considered, by them, to be inconsistent and somewhat contradictory to their initial motivation to sign up to a solar program. Solar homeowners may feel offended for the perception that electricity networks are blaming them for all network related problems. Some IRG interviewees believe that the proposed electricity market change that would enable solar households to be charged for excessive solar export would encourage them to participate in solar pre-cooling (to limit export).

On the other hand, non-solar households are probably more inclined to participate if they can get financial benefits for soaking up grid solar excess. However, they may not always have the basic technologies ready (e.g., smart meters, smart control devices, smart AC, etc.) that would be needed for external control. Thus, providing them with free or low-cost equipment would increase the potential for non-solar households to participate.

IRG interviewees also referred to challenges faced by renters. Renters are seen to be more vulnerable in terms of their energy purchase ability, control over the dwelling being rented, utilities and the pre-installed appliances. As a ‘vulnerable group’, they may be more likely to participate in the pre-cooling program if it helps to reduce their electricity bills. However, renters are often left out in the policy making, despite their number continuing to increase. For renters, it should also be made clear who would sign up to a pre-cooling program, and pay any costs incurred from participation.

4.7 Conclusions and recommendations

The perceived mismatch, by the electricity sector, between the increasing peak evening demand and excessive solar PV generation during the day draws policy attention. Solar pre-cooling, as a demand management strategy, may have the potential to alleviate peak network demand and contribute to a stable electricity grid. Although there are many potential benefits for the application of solar pre-cooling for residential households, considerable variations in consumer engagement and acceptance could impact on solar pre-cooling program as a means to manage electricity network. 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. Based on a comprehensive review of academic and grey literature and stakeholder interviews, findings about the social factors influencing the consumer acceptance and engagement in solar pre-cooling are summarised below.

Perceived consumer benefits: Reducing peak demand and reducing energy bills are identified as the most significant benefits for consumers to engage in solar pre-cooling. Consumers contribute to a more reliable and stable electricity network by switching their peak load and benefit from a resulting lower electricity price. Other benefits include reduced carbon emissions, allowing for an ‘instant’ thermal comfort, and increased awareness of their energy use and energy bills.

Motivations to participate: Financial incentives are typically the most common and important motivation for residential consumers to participate in solar pre-cooling, especially for non-solar households. Other motivations include increased control over energy use and energy bills, social good from participation, and reduced technology costs such as solar PV, smart control and smart meter devices.

Housing quality: Pre-cooling is thought to be more effective when the building mass is relatively heavy and the home is well insulated. Houses need sufficient internal thermal mass to be able to act like a battery, and sufficient insulation and air tightness to ensure minimal heat transfer. Determining the sufficient levels of thermal mass and insulation and ideal thermal performance of homes for SPC/H is a research gap.

Thermal comfort preferences: Consumers have a diversity of thermal comfort preferences and can and do exhibit adaptive behaviours in response to climate, cultural and social practices and their individual circumstances. This means that there is no ‘set point’ for cooling, on which to base any evaluation of the potential benefits of a pre-cooling program at a national level.

Based on the findings, possible policy implications and recommendations for residential demand response in solar pre-cooling, are summarised in below:

- Improving understanding and trust between the consumers and electricity suppliers by providing more apparent feedback technologies
- Allowing interactive control by consumers to override external control
- Keep it simple: reducing the complexity for consumer engagement

- For solar PV households, ensure the policy that requires their participation in the program aims to support the network performance and does not contradict their initial motivation to participate in renewable energy (solar panel program)
- Give incentives for improving home-energy performances (e.g., from 6 to 8 stars, etc.)
- Two-way pricing for demand response program (e.g., additional cost for injecting solar excess)

5 Scenario modelling

Solar pre-cooling/heating (SPC/H) is a form of demand side management (DSM) where surplus solar energy is used to power the air conditioning (AC) unit in the home instead of being exported to the grid. The SPC/H energy is stored in the thermal mass of the home. Under conditions where SPC/H is appropriately controlled, following SPC/H the energy stored in the thermal mass slowly decays over time until the indoor temperature of the home converges with non-SPC/H temperature. When the energy stored in the thermal mass persists into the evening, resulting in the home being cooler or warmer than it otherwise would have been had SPC/H not occurred, this equates to an increase in thermal comfort for the occupants, reducing their need to cool or heat their home in the evening during the peak demand period.

5.1 Benefits

The potential, direct, consumer benefits of solar pre-cooling/heating include:

- Increased thermal comfort. The homeowner is able to maintain a greater level of thermal comfort in the home throughout the day, and into the evening
- Reduction in energy bills. SPC/H can reduce the amount of cooling/heating energy required to maintain comfort levels in the evening when the electricity tariffs can be high. If the tariff is suitable, savings from the reduction in evening AC consumption can exceed the revenue lost from not exporting solar energy to the grid

Importantly, SPC/H smooths out the residential load profile by reducing both peak solar export during the day and peak demand from AC in the evening. Smoothing out the residential load profile provides the following network benefits:

- Reducing peak solar export increases solar hosting capacity, allowing for more homes to install solar. It also helps mitigate voltage rise, reducing curtailment of solar export.
- Reduces power (normal and peak) flows through transformers and cables, prolonging the life of these assets. Peak reduction defers expensive network upgrades.
- Modulates voltage variability from solar and voltage excursion generally, making voltage management easier
- Reduces reliance for PV inverters to engage Volt-VAr response voltage control, which in aggregate can exchange large amounts of reactive power from the grid, increasing losses and reducing power factor (pf)

The grid wide benefits which come from smoothing out the residential load profile include:

- Reduced load variation, increasing load forecast accuracy, and allowing for a more accurate allocation of generation and reserves
- Less peak demand means less need for peaking plants (which sell electricity at orders of magnitude higher price than baseload plants) and less capacity upgrades, resulting in an overall reduction in the cost of electricity

The scenario analysis below builds a foundation for the quantifiable economic benefits of solar pre-cooling and solar pre-heating for households and network providers. It indicates the options for network providers to manage load profile.

5.2 Characteristics of a suitable home

In supporting Theme H1: Residential Solar Pre-Cooling in the RACE for 2030 Opportunity Assessment Project, this sub-project is aimed at developing a sample house design to be used to assess the potential benefits of solar pre-cooling in Australian residential buildings. It is understood that although using one house design to represent the entire Australian housing stock or even a city is restrictive, this approach is suitable for assessing the feasibility of solar pre-cooling, and for estimating the opportunities to reduce peak load and energy costs.

Considering that the solar PV information available to this research team (from SolarAnalytics) only covers Sydney, Adelaide, Brisbane and Melbourne, we have limited our study to these four cities. In this study, a sample house plan was developed based on the information in the Australian Housing Data (AHD) Portal[5]. At the same time, houses with different constructions such as external wall, floor and ceiling were developed (using the same house plan) to represent light-weight, medium-weight and heavy-weight houses and existing, new and future housing stock. These sample houses were then used for building thermal performance simulations and pre-cooling opportunity assessment.

5.2.1 The sample home floor plan

In this study, the information in the AHD Portal was used to guide the sample house design. The AHD portal collects the design information for residential dwellings using NatHERS rating scheme from May 2016 to March 2021 with a total of around 870,000 dwelling designs in Australia including old dwellings (~10,000), renovations (~20,000), and new dwellings (~840,000). The collection of renovation and new dwelling designs in the AHD portal covers approximately 85% of all the dwelling approvals listed in the Australian Bureau of Statistics (ABS, 2021) during the same period which totals 1,013,000 dwellings. Thus, the AHD portal collection gives a good representation of the relatively new building stock in Australia and at the same time provides some representation of the old housing stock.

Figure 5-1 shows the average floor area of houses in the eight States and Territories. As shown in Figure 5-1, the average house floor areas in the four relevant states, i.e., NSW, SA, QLD and VIC are in general close to the national average of around 180-190 m2 (including a garage area of around 28 m^2) with an average of 3.5 bedrooms. Considering the overall house information, the four-bedroom single storey house currently used as a sample house for NatHERS software accreditation was selected as the sample house in this study. Figure 5-2 shows the floor plan of this house. In order to match the national average house size, the original double garage area of 32 m^2 has been modified to be 28 m2, which gives a total house floor area of 188 m^2.

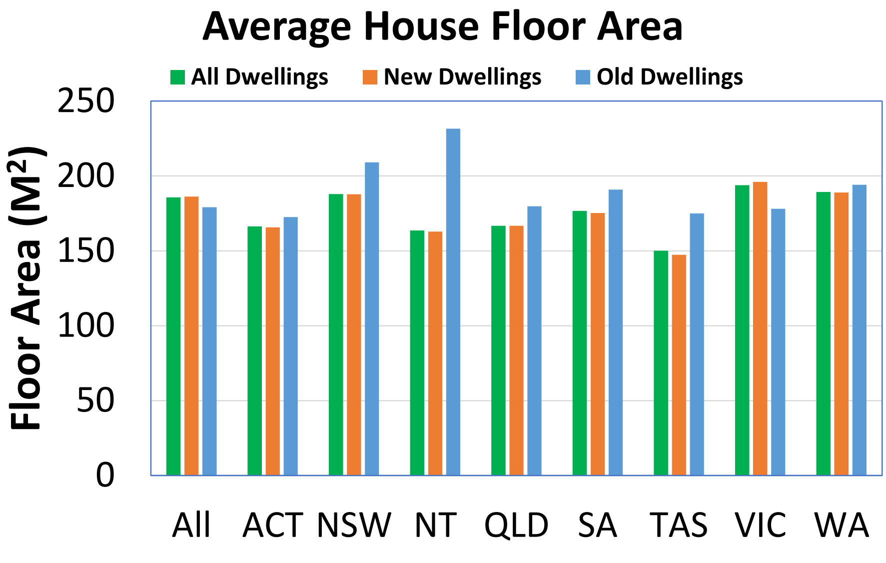

Figure 5-1. Average house floor areas in different states and territories. Source: AHD

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[5] https://ahd.csiro.au/

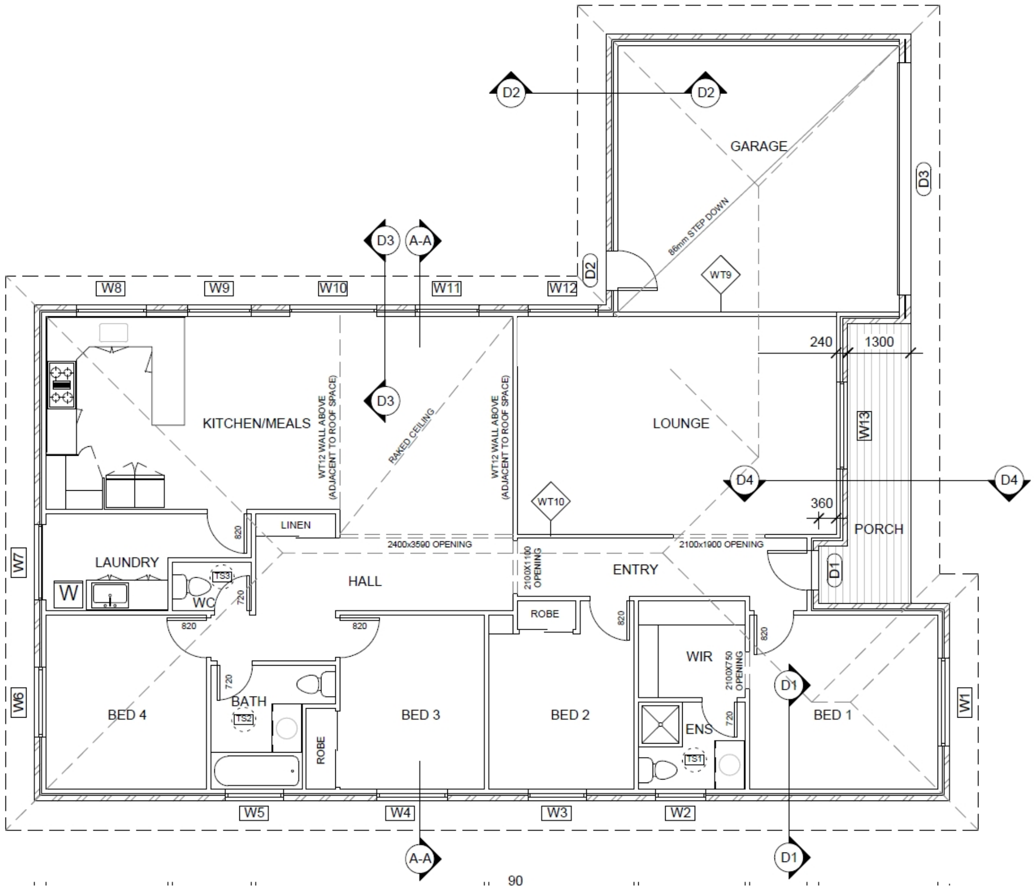

Figure 5-2. Sample house floor plan. Source: NatHERS

5.2.2 Local climates

In each city, a representative NatHERS climate zone region was selected based on the number of recent house designs from May 2016 to March 2021. As shown in Table 5-1, the selected four NatHERS climate zones are within three NCC climate zones, i.e., NCC climate zones 2, 5 and 6.

Table 5-1. Representative NatHERS climate zones and the number of recent house designs from May 2016 to March 2021. Source: AHD

City Name	NatHERS Climate Zone	NCC Climate Zone	Weather Station	No. of house constructions
Melbourne	62	6	Moorabbin	80890
Adelaide	16	5	Adelaide	14946
Sydney	56	5	Mascot (Sydney Airport)	33990
Brisbane	10	2	Brisbane	47615

5.2.3 Construction types of the sample houses

According to AHD, the average star ratings for existing, renovated and new houses are 2.2 stars, 4.9 stars and 6.2 stars respectively. In this study, we chose 2-star, 6 star and 8-star houses to approximately represent the old housing stock, the new housing stock and the high-end energy efficient housing stock respectively.

Figures 5-3, 4 and 5 show the distributions of external wall, floor and roof construction types for houses rated below 7 stars and equal/above 7 stars in the four relevant states. New house designs represent around 95% of the house designs in the AHD and their star ratings are around 6 stars or above. Consequently, the 6 star and 8-star houses may be designed based on the construction types for below 7 star and equal/above 7 stars respectively. From Figures 5-3, 5-4 and 5-5, houses below 7 stars have very similar construction types as those equal/above 7 stars. In this study, as shown in Table 5-2, the wall, floor and roof constructions for 6 and 8 stars are assumed to be the same.

For light-weight houses, fibre cement cladding is the main external wall construction type. Suspended timber floor and metal roof are used for the floor and roof constructions respectively considering their low thermal mass.

For medium-weight houses, brick veneer is the main external wall construction type. The most frequently used waffled pod floor construction is selected for the floor constructions in Sydney and Melbourne, while in Adelaide and Brisbane, concrete slab is the choice. The most frequently used metal roof is selected for the roof constructions except in Melbourne where tile roof is selected.

For heavy-weight houses, cavity double brick is selected as the external wall construction, while tile roof and concrete slab are the obvious roof and floor constructions. It should be noted that for houses with star rating around or above 6 stars, the autoclaved aerated concrete (AAC) external wall is constructed similar to a brick veneer external wall with air gap and insulation between the external AAC skin and the inner plaster board. So, AAC external wall is not considered as a heavy construction for houses with star rating around or above 6 stars.

The construction types for old existing houses are occasionally different from those of new houses. For example, timber-clad (weather board) is often used for old light-weight houses in Melbourne, while fibre-cement board is used for light-weight new houses in Melbourne. Waffle-pod floor constructions were generally not available in old houses. In Brisbane, double layered AAC external wall construction is used as the external wall construction for heavy weight houses. Based on the construction type information in AHD, the constructions of the 2-star sample houses, which represent old housing stock were developed and listed in Table 5-3.

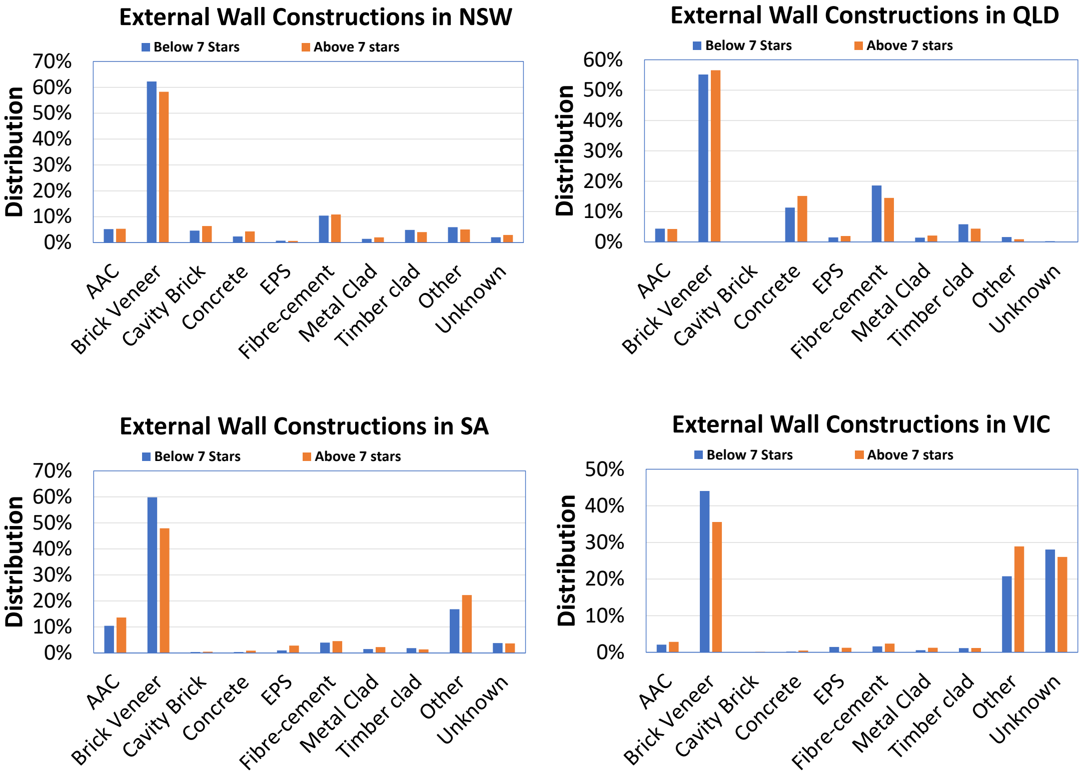

Figure 5-3. Distribution of external wall construction types in the four relevant states. Source: CSIRO

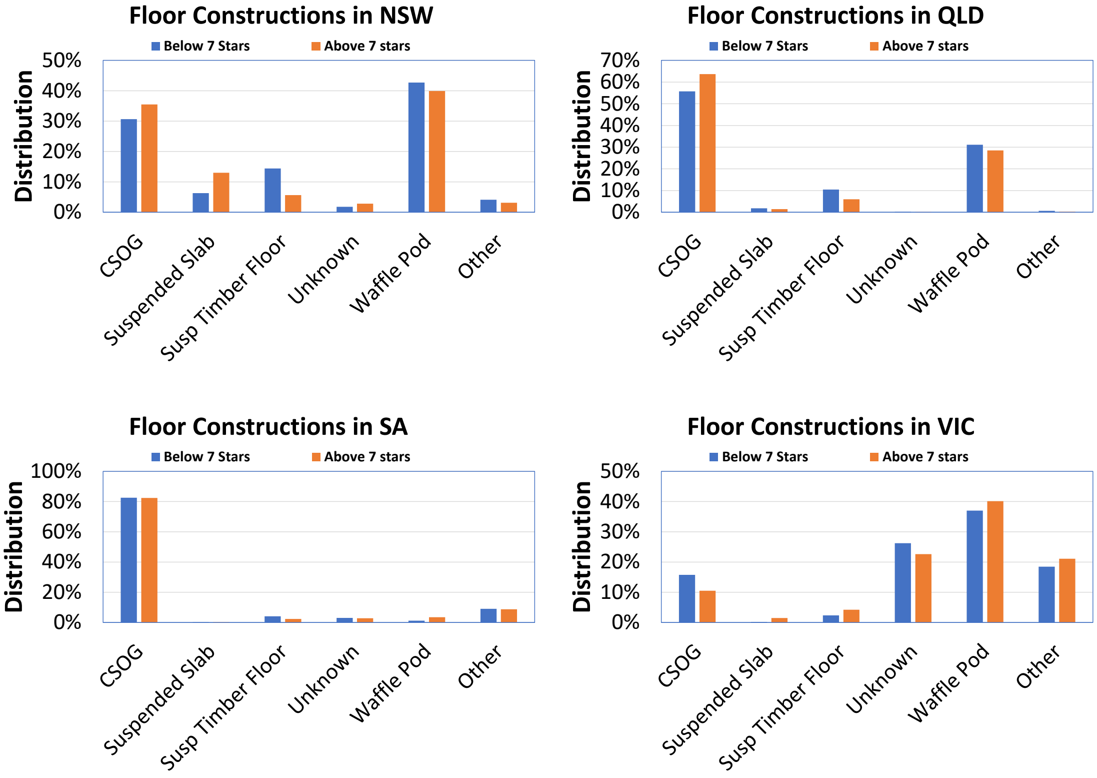

Figure 5-4. Distribution of floor construction types in the four relevant states. Source: CSIRO

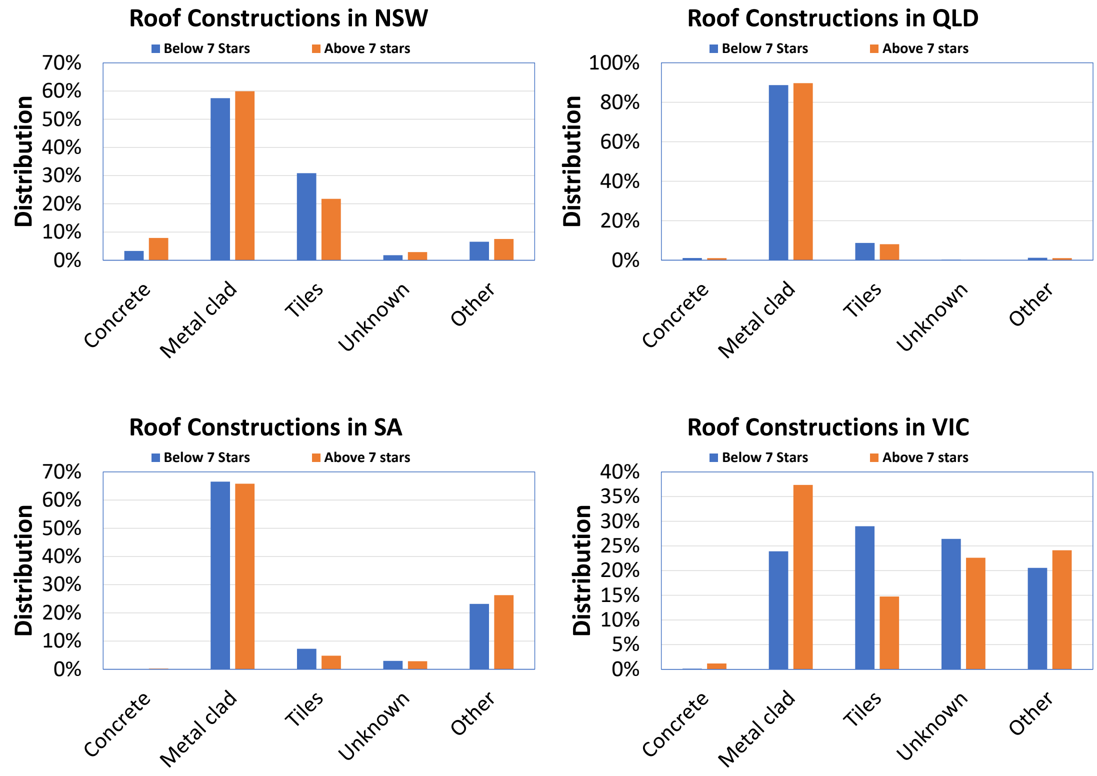

Figure 5-5. Distribution of roof types in the four relevant states. Source: CSIRO

Table 5-2. Construction types for 6- and 8-star sample houses. Source: CSIRO

Light-weight Construction			
	External wall	**Floor**	**Roof**
Melbourne (CZ62)	Fibre-cement	Susp Timber Floor	Metal clad
Adelaide (CZ16)	Fibre-cement	Susp Timber Floor	Metal clad
Sydney (CZ56)	Fibre-cement	Susp Timber Floor	Metal clad
Brisbane (CZ10)	Fibre-cement	Susp Timber Floor	Metal clad

Medium-weight Construction			
	External wall	Floor	Roof
Melbourne (CZ62)	Brick Veneer	Waffle Pod	Tiles
Adelaide (CZ16)	Brick Veneer	CSOG	Metal clad
Sydney (CZ56)	Brick Veneer	Waffle Pod	Metal clad
Brisbane (CZ10)	Brick Veneer	CSOG	Metal clad

Heavy-weight Construction			
	External wall	**Floor**	**Roof**
Melbourne (CZ62)	Cavity Brick	CSOG	Tiles
Adelaide (CZ16)	Cavity Brick	CSOG	Tiles
Sydney (CZ56)	Cavity Brick	CSOG	Tiles
Brisbane (CZ10)	Cavity Brick	CSOG	Tiles

Table 5-3. Construction types for 2-star sample houses. Source: CSIRO

Light-weight Construction			
	External wall	**Floor**	**Roof**
Melbourne (CZ62)	Timber clad	Susp Timber Floor	Metal clad
Adelaide (CZ16)	Fibre-cement	Susp Timber Floor	Metal clad
Sydney (CZ56)	Fibre-cement	Susp Timber Floor	Metal clad
Brisbane (CZ10)	Fibre-cement	Susp Timber Floor	Metal clad

Medium-weight Construction			
	External wall	**Floor**	**Roof**
Melbourne (CZ62)	Brick Veneer	CSOG	Metal clad
Adelaide (CZ16)	Brick Veneer	CSOG	Metal clad
Sydney (CZ56)	Brick Veneer	CSOG	Metal clad
Brisbane (CZ10)	Brick Veneer	CSOG	Metal clad

Heavy-weight Construction			
	External wall	**Floor**	**Roof**
Melbourne (CZ62)	Cavity Brick	CSOG	Tiles
Adelaide (CZ16)	Cavity Brick	CSOG	Tiles
Sydney (CZ56)	Cavity Brick	CSOG	Tiles
Brisbane (CZ10)	AAC	CSOG	Tiles

5.2.4 Building thermal performance simulations

5.2.4.1 Thermostat settings

Heating and cooling energy required for keeping indoor thermal comfort was calculated using AccuRate Sustainability v2.4.3.21, a residential house energy rating software used in Australia [63]. AccuRate calculates hourly heating and cooling energy demands of a house to satisfy occupant thermal comfort over a period of one year. The heating and cooling thermostat settings used in AccuRate for house energy rating are based on the Protocol for House Energy Rating Software published by Australian Building Codes Board (ABCB):

- For living spaces (kitchens and other spaces typically used during the waking hours): a heating thermostat setting of 20°C is used. For sleeping spaces (including bedrooms, bathrooms and dressing rooms, or other spaces closely associated with bedrooms): a heating thermostat setting of 18°C from 0700 to 0900 and from 1600 to 2400; and a heating thermostat setting of 15°C from 2400 to 0700.
- The cooling thermostat setting varies according to the local climate which was, to some extent, consistent with the adaptive thermal comfort in ASHRAE 55-2017 (ASHRAE, 2017). They are 24.0ºC, 25.0ºC, 24.5ºC and 25.5ºC and for Melbourne (CZ62), Adelaide (CZ16), Sydney (CZ56) and Brisbane (CZ10) respectively.

It should be noted that for cooling, a 2.5ºC cooling leeway is assumed with the current NatHERS software, which means cooling will only start when the room air temperature is 2.5ºC above the thermostat setting. This 2.5ºC cooling leeway is assumed for each air-conditioned zone and for each hour. Research has indicated that this cooling operation scheme may be too optimistic and that after cooling is started occupants will generally maintain cooling operation, with a cooling leeway of 0.5ºC is more realistic [64]. Therefore, in this study, we have also carried out simulations using this modified cooling operation scheme for the pre-cooling opportunity assessment.

5.2.4.2 Weather files used in this study

The existing weather files for NatHERS climate zones were Reference Meteorological Year (RMY) weather files developed based on local weather data from 1967 to 2004. Recently, future weather files from 2030 to 2100 under RCP2.6, RCP4.5 and RCP8.5 (Representative Concentration Pathway protocols) for building thermal performance simulations were developed [65]. In the current study, simulations were thus carried out using the existing weather files, as well as the projected future weather files in 2030 and 2050 under RCP2.6, RCP4.5.

5.2.4.3 Building thermal performance simulations

Building thermal performance simulations were carried out using AccuRate Sustainability V2.4.3.21. For achieving different star ratings, changes were made in the insulation levels in walls, floors, ceilings and roofs, the thermal performance of windows, the colour of the external walls and roofs, the depth of eaves and the shading factor of shading devices. For 2-star houses, increased air infiltration by large door or window leakage gaps may be used in order to achieve the required the thermal performances. For all the 8-star houses, the orientation has been optimized by facing the bedrooms to the south, while the bedrooms are facing east with the original design.

In this study, after the sample house design achieved the required NatHERS star rating, internal thermal mass was added 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 was used for representing the internal thermal mass relating to furniture and other household contents in residential dwellings [66]. It is understood that such an internal thermal mass implementation is rough. However, this approach provides a slight improved representation of real dwellings in comparison with the current NatHERS approach which does not include furniture thermal mass.

For pre-cooling, the sample houses should generally be operated with windows closed to avoid heat gains due to ventilation. Consequently, simulations were carried out for sample houses with all the windows closed.

Simulations were carried for all the sample house designs for the four locations with the existing weather files as well as future weather files based on RCP2.6 and RCP4.5 using the NatHERS thermostat settings as discussed in following. To investigate the impact of cooling thermostat on the solar pre-cooling potential, simulations using the variation of the NatHERS thermostat settings were also carried out.

5.2.5 Results and discussion

5.2.5.1 Designing houses with different star ratings

Tables 5-4, 5-5 and 5-6 show the details of the insulation levels that the building thermal performance simulations showed are required for external wall, floor and roof/ceiling constructions as well as the window types for 2-, 6- and 8-star sample houses with light-weight, medium-weight and heavy-weight constructions respectively. As shown in Tables 5-4, 5-5 and 5-6, with the increase in the thermal mass of the constructions, it is generally easier to achieve the same star levels at these four locations due to the buffering effect of the thermal mass.

As shown in Table 5-6, it was found that 8 stars is difficult to achieve with light-weight constructions due to their suspended floors, especially in Sydney and Brisbane, where extremely high-performance windows and high-level wall, floor and roof/ceiling insulations are required to achieve eight stars. Although only one sample house plan was investigated in this study, the finding here does suggest that some light-weight house designs could be very difficult to achieve eight stars in some climates.

Table 5-4. Constructions used for achieving 2 stars for light-weight/medium-weight/heavy-weight houses. Source: CSIRO

City	External Wall	Window	Floor	Roof/Ceiling
Melbourne (CZ62)	R0/R0/R0	Single-glazing/ Single-glazing/ Single-glazing	R0/R0/R0	R0/R0.1/R0.1
Adelaide (CZ16)	R0/R0/R0	Single-glazing/ Single-glazing/ Single-glazing	R0/R0/R0	R0.3/R0.1/R0
Sydney (CZ56)	R0/R0/R0	Single-glazing/ Single-glazing/ Single-glazing	R0/R0/R0	R0.5/R0/R0
Brisbane (CZ10)	R0/R0/R0	Single-glazing/ Single-glazing/ Single-glazing	R0/R0/R0	R0.4/R0.1/R0

Note: insulation values or window types are in the order of light-weight/medium-weight/heavy-weight houses.

Table 5-5. Constructions used for achieving 6 stars for light-weight/medium-weight/heavy-weight houses. Source: CSIRO

City	External Wall	Window	Floor	Roof/Ceiling
Melbourne (CZ62)	R1.4/R1.1/R2.0	Double-glazing/ Double-glazing/ Single-glazing	R3.0/R0/R0	R4/R4/R4
Adelaide (CZ16)	R2.0/R0.7/R0.4	Double-glazing/ Double-glazing/ Single-glazing	R3.0/R0/R0	R4/R4/R2.5
Sydney (CZ56)	R2.5/R0.9/R1.3	Double-glazing/ Double-glazing/ Single-glazing	R3/R0/R0	R5/R4/R4
Brisbane (CZ10)	R2.3/R0.7/R0	Double-glazing/ Single-glazing/ Single-glazing	R2.5/R0/R0	R5/R4/R4

Note: insulation values or window types are in the order of light-weight/medium-weight/heavy-weight houses.

Table 5-6. Constructions used for achieving 8 stars for light-weight/medium-weight/heavy-weight houses. Source: CSIRO

City	External Wall	Window	Floor	Roof/Ceiling
Melbourne (CZ62)	R3/R3/R2.5	Double-glazing/ Double-glazing/ Double-glazing	R5.8/R0/R0	R7/R6.5/R6.5
Adelaide (CZ16)	R3.8/R2.0/R0.5	Triple-glazing/ Double-glazing/ Double-glazing	R5.0/R0/R0	R8/R5.5/R4
Sydney (CZ56)	R3.8/R3/R1.5	Triple-glazing/ Double-glazing/ Double-glazing	R10/R0/R0	R10/R5.5/R4
Brisbane (CZ10)	R5.0/R2.0/R0.5	Triple-glazing/ Double-glazing/Single-glazing	R10/R0/R0	R10/R5.0/R5.0

Note: insulation values or window types are in the order of light-weight/medium-weight/heavy-weight houses.

5.2.5.2 Cooling energy requirements

As detailed in Section 5.2.4, building thermal performance simulations were carried out using AccuRate Sustainability V2.4.3.21. Tables 5-7, 5-8 and 5-9 list the heating, cooling, total heating and cooling energy requirement and star ratings of the sample houses using the current weather files for the sample houses with all the windows closed and with windows operated to achieve thermal comfort whenever possible (the NatHERS protocol). It is noted that these results are for sample houses with the internal thermal mass included. Consequently, the star ratings may be different from the corresponding rated star levels using the NatHERS protocols which does not consider the internal thermal mass of furniture and allow window operation.

As expected, with windows closed, the heating energy requirement is slightly reduced, while the cooling energy can be significantly increased since heat is trapped in the house during the warm season.

From Tables 5-7,8 and 9, it is seen that in general, the heating energy requirement increases from light-weight, medium-weight to heavy-weight constructions at the same star rating, while the cooling energy requirement decreases from light-weight, medium-weight to heavy-weight constructions. This means that in these four climates, the thermal mass buffering effect during summer period results in more hours within thermal comfort indoor air temperature range.

It was also found that for 8-star houses, the cooling energy requirement is generally low, especially for cases with window operation. Therefore, pre-cooling of high energy efficient houses may be not effective in terms of electricity cost savings. This will be further investigated during the pre-cooling benefit analysis.

Table 5-7. Heating, cooling, total heating and cooling energy requirement and star ratings of 2-star sample houses (window closed/window operated)

Light-weight Construction				
	Heating (MJ/m2)	**Cooling (MJ/m2)**	**Total (MJ/m2)**	**Star Rating**
Melbourne (CZ62)	418.3/425.3	67.5/43.0	485.9/468.3	1.9/1.9
Adelaide (CZ16)	191.0/198.7	167.6/135.2	358.6/333.9	1.9/2.2
Sydney (CZ56)	114.1/119.1	121.5/64.6	235.6/183.8	1.7/2.3
Brisbane (CZ10)	70.4/71.9	101.1/64.6	171.6/136.5	1.6/2.3
Medium-weight Construction				
Melbourne (CZ62)	460.4/462.7	26.6/21.3	487.0/484.1	1.9/1.9
Adelaide (CZ16)	257.5/260.6	94.5/85.9	352.1/346.5	2.0/2.0
Sydney (CZ56)	166.6/167.9	56.1/34.7	222.6/202.7	1.8/1.9
Brisbane (CZ10)	80.6/81.5	93.7/63.7	174.4/145.2	1.6/2.1
Heavy-weight Construction				
Melbourne (CZ62)	464.5/465.9	12.0/9.7	476.6/475.7	1.9/1.9
Adelaide (CZ16)	285.7/288.1	67.5/59.8	353.1/347.9	1.9/2.0
Sydney (CZ56)	185.5/186.1	35.2/20.0	220.7/206.0	1.8/1.9
Brisbane (CZ10)	90.1/90.5	79.0/57.4	169.1/147.9	1.7/2.0

Table 5-8. Heating, cooling, total heating and cooling energy requirement and star ratings of 6-star sample houses (window closed/window operated)

Light-weight Construction				
	Heating (MJ/m2)	**Cooling (MJ/m2)**	**Total (MJ/m2)**	**Star Rating**
Melbourne (CZ62)	110.6/115.8	38.2/16.7	148.7/132.4	5.7/6.1
Adelaide (CZ16)	38.7/42.4	71.4/44.7	110.1/87.1	5.8/6.6
Sydney (CZ56)	18.3/22.1	72.7/25.6	91.0/47.7	4.2/6.6
Brisbane (CZ10)	10.0/10.4	64.3/28.5	74.3/39.0	4.1/6.7

Medium-weight Construction				
Melbourne (CZ62)	128.2/130.4	17.3/8.3	145.5/138.8	5.8/5.9
Adelaide (CZ16)	69.1/70.8	40.3/28.3	109.3/99.1	5.8/6.2
Sydney (CZ56)	31.1/32.6	51.7/21.1	82.9/53.7	4.4/6.1
Brisbane (CZ10)	13.5/14.0	57.6/30.7	71.1/44.7	4.3/6.2
Heavy-weight Construction				
Melbourne (CZ62)	132.6/134.0	11.4/3.9	144.0/137.9	5.8/5.9
Adelaide (CZ16)	69.7/71.5	51.2/28.8	121.0/100.2	5.4/6.1
Sydney (CZ56)	34.2/35.3	53.9/20.6	88.1/55.9	4.3/5.9
Brisbane (CZ10)	20.3/20.7	51.4/26.8	71.7/47.5	4.3/5.9

Table 5-9. Heating, cooling, total heating and cooling energy requirement and star ratings of 8-star sample houses (window closed/window operated)

Light-weight Construction				
	Heating (MJ/m2)	**Cooling (MJ/m2)**	**Total (MJ/m2)**	**Star Rating**
Melbourne (CZ62)	40.1/46.0	28.2/9.8	68.2/55.8	7.9/8.2
Adelaide (CZ16)	18.6/19.9	34.1/20.0	52.7/39.9	7.9/8.4
Sydney (CZ56)	8.2/9.5	35.8/13.6	44.1/23.1	6.9/8.4
Brisbane (CZ10)	2.1/2.3	51.8/19.0	53.9/21.3	5.4/8.7
Medium-weight Construction				
Melbourne (CZ62)	51.7/56.3	18.2/5.6	69.9/61.9	7.8/8.0
Adelaide (CZ16)	22.4/27.2	28.3/16.2	50.7/43.4	7.9/8.2
Sydney (CZ56)	2.7/6.8	57.8/18.6	60.5/25.3	5.7/8.0
Brisbane (CZ10)	6.5/6.9	31.7/17.1	38.2/23.9	6.8/8.4
Heavy-weight Construction				
Melbourne (CZ62)	60.3/61.8	5.9/1.0	66.2/62.8	7.9/8.0
Adelaide (CZ16)	36.3/37.7	22.5/12.1	58.8/49.7	7.7/8.0
Sydney (CZ56)	12.6/13.7	36.9/14.8	49.5/28.6	6.4/7.9
Brisbane (CZ10)	8.7/9.1	37.4/17.4	46.2/26.5	6.0/8.1

5.2.6 Conclusion

A representative four-bedroom, single storey sample house plan was selected as a basis for an assessment of solar pre-cooling. This representative home was selected based on the Australian Housing Data (AHD) Portal, which has a total of around 10,000 existing old dwelling designs, 20,000 renovated dwelling designs, and 840,000 new dwelling designs from May 2016 to March 2021.

Based on this sample house plan, 2-star, 6-star and 8-star (NatHERS star) house designs with light-weight, medium-weight and heavy-weight constructions were developed for Sydney, Adelaide, Brisbane and Melbourne climates. These sample houses represent old, new and high-end energy efficient housing stock with different thermal mass constructions respectively.

Building performance simulations were then carried out with both air-conditioning and free-run operations for pre-cooling benefit analysis using current weather files as well as future projected weather files under RCP2.6 and RCP4.5 in 2030 and 2050 respectively.

Simulation results show that in general, the heating energy requirement increases from light-weight, medium-weight to heavy-weight constructions at the same star rating, while the cooling energy requirement decreases from light-weight, medium-weight to heavy-weight constructions.

For 8-star houses, the cooling energy requirement is generally low. Therefore, pre-cooling of high energy efficient houses may be not effective in terms of electricity cost savings. This will be further investigated during the pre-cooling benefit analysis.

5.3 Scenario modelling

The following quantifies the potential of SPC/H to reduce household energy bills and smooth out the residential load profile for the cities of Brisbane, Sydney, Melbourne, and Adelaide. This chapter consists of the following sections:

- The first section gives a summary version of the method used to estimate the SPC/H process and calculate the change in household load profiles,
- The second presents the results for three types of analysis; the first examines the efficiency of SPC/H, the second the financial viability of SPC/H, and the third how SPC/H changes the residential load profile,
- The third presents the key findings, and
- The final presents future work.

5.4 Method

This section gives an overview of the method used to simulate the SPC/H process and therefore calculate the change in household load profile due to the reduction in solar export and evening AC consumption. A more detailed description of the method is given in Appendix I-a. Figure 5-6 illustrates the SPC/H process.

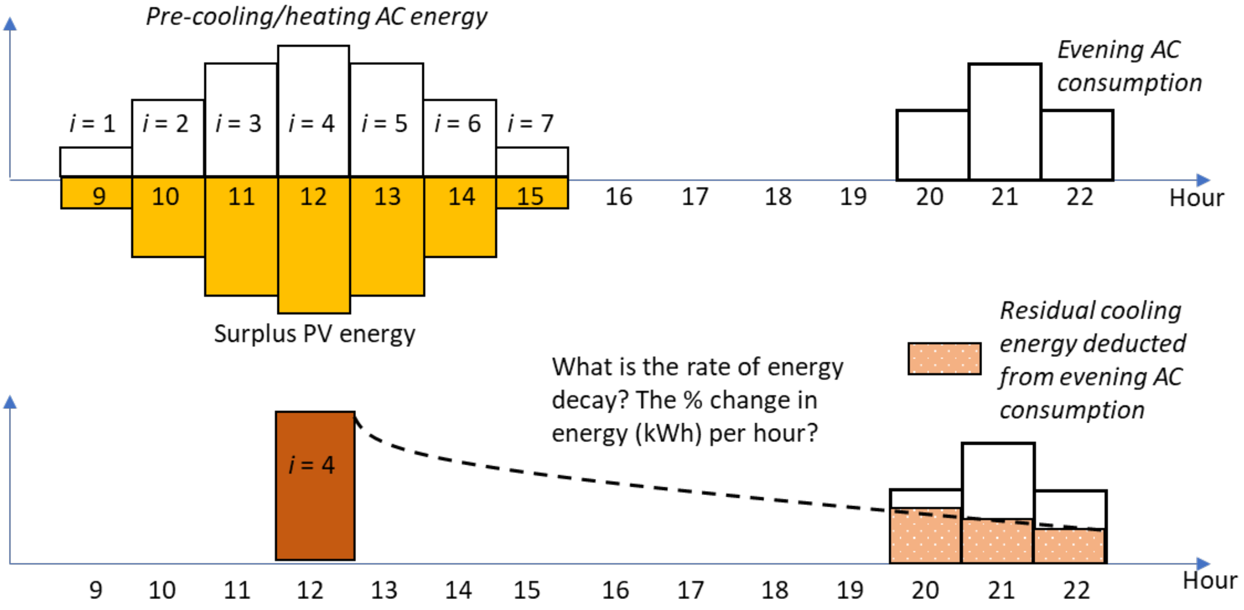

Figure 5-6. Schematic illustrating the SPC/H process

**The x-axis represents the time of day, with each bar representing one hour. The y-axis represents energy*

To be able to simulate the above process the following data and inputs are required:

- The cooling and heating energy decay rates for the home,
- Hourly data of household solar generation and AC consumption, and
- Forecasting strategy

5.4.1 Scenarios

The scenarios modelled were for 2021 and 2030 for each of a business as usual (BaU) and accelerated scenarios.

An accelerated scenario presumed improvements to technologies and building materials. As these factors affect the house star rating, for the purpose of this analysis the accelerated scenario has been defined as an improvement in star-rating across the housing sector. The method and calculations showing the change in mix of ratings for each house types and development of future scenarios are provided in the Appendices.

5.4.2 Cooling and heating decay rates

Thermal modelling utilising AccuRate was used to provide the hourly temperature (in degrees Celsius) and AC consumption (kWh) data required to derive the cooling and heating decay rates. The data provided consisted of two indoor temperature measurements, one termed T_{SP} and the other T_{FR}, or the free-running temperature. T_{SP} is the indoor temperature following an SPC/H event and T_{FR} is the indoor temperature in the case where no SPC/H event occurred. This data was provided for nine types of home for each city. The nine types of home are categorised according to build weight (heavy, medium, light) and NatHERS star rating (2, 6, 8). The two indoor temperatures T_{SP} and T_{FR} were used to derive the present model for estimating the cooling/heating energy decay rate following SPC/H for the nine types of home for each city. The unit of measurement for the decay rate is percentage change in energy (kWh) per hour, written as % change in energy per hour. A detailed description of how the model is derived is given in Appendix A.1.

Figure 5-7 plots the cooling and heating decay rates for each city, build weight, and star rating. The figure shows that heavy builds have the lowest decay rates, followed by light then medium, with light builds having similar decay rates for all cities. Interestingly, medium builds (aside from Melbourne) for SPH have much higher decay rates compared to SPC. Importantly, in general, the decay rates are sufficiently low (approximately between 4-12% per hour on average) such that pre-cooling or pre-heating can influence temperatures a significant number of hours into the future.

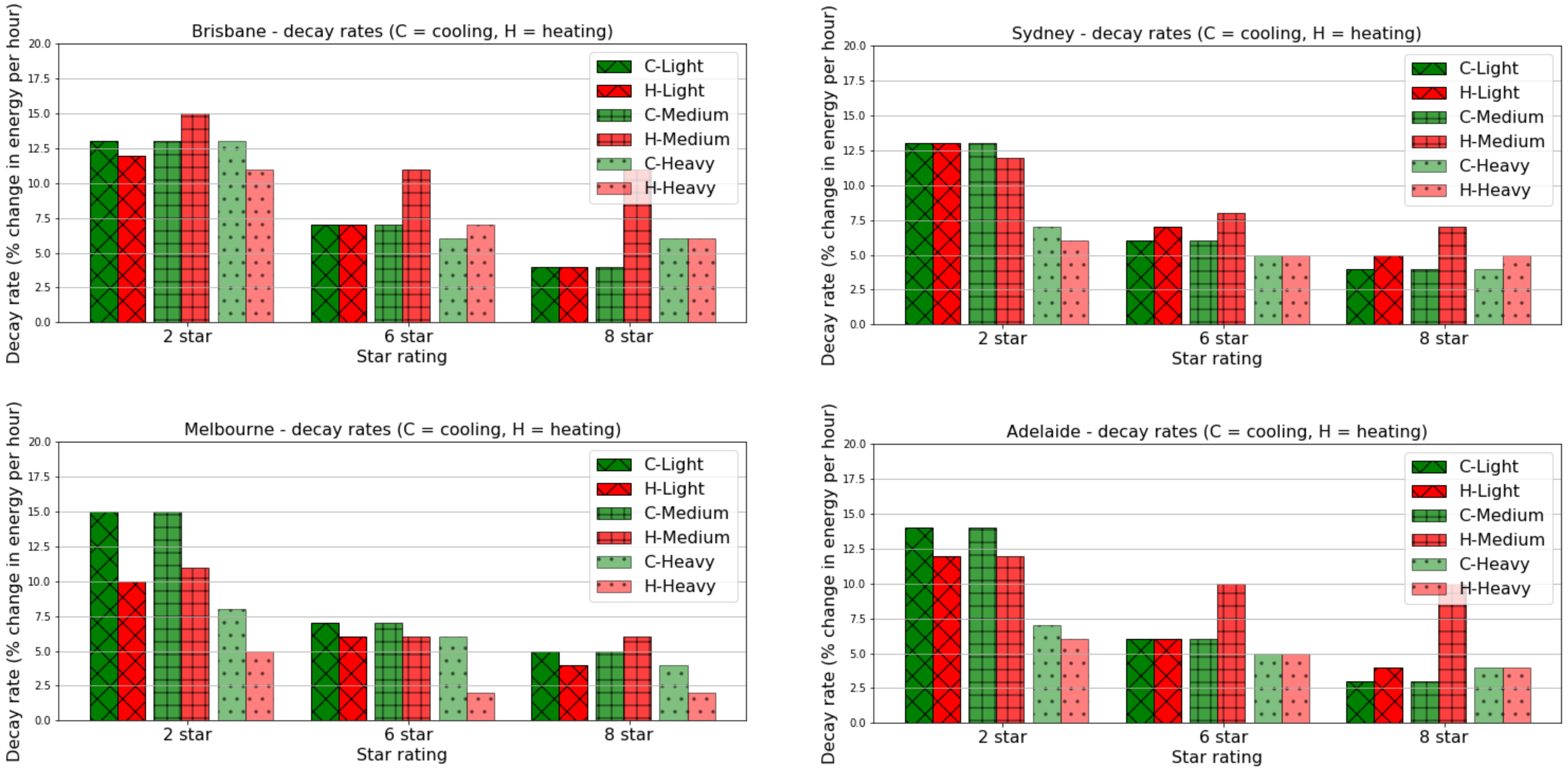

Figure 5-7. Plot of cooling and heating decay rates for each city, build weight and star rating

5.4.3 Hourly household PV and AC data

The hourly data of household solar generation (gross and exported) and AC consumption used in this study is provided by Solar Analytics. The data set consists of 12 months' worth of measurements for 400 residential homes located in Brisbane, Sydney, Melbourne, and Adelaide.

5.4.4 Forecasting strategies

When calculating the change in load profile two forecasting strategies, F1 and F2, were simulated.

F1, basic forecasting, represents the scenario where the occupants know they are going to use their AC unit in the evening but do not know how much. It is assumed that the occupants set their controller to divert all excess solar energy to the AC unit during the day. For F1, all potential revenue from the solar feed in tariff (FiT) is lost, and the home may also be cooled or heated to levels greater than would normally be required to meet comfort levels, as indicated by the historical AC consumption data provided by Solar Analytics.

F2 assumes a perfect forecast of both solar generation and evening AC consumption. It is assumed that the controller optimises the amount of excess solar energy diverted to the AC unit during the day, never diverting more than is required to cover the (known) evening AC consumption.

F1 and F2 could be considered to represent the two control scenario extremes, F1 being the least efficient and F2 being the most (but unlikely to be achievable in practice). In reality, sophisticated forecasting and optimisation strategies will be required to minimise energy waste during SPC/H while still meeting thermal comfort requirements.

5.4.5 Method steps

The steps used to simulate the SPC/H process and calculate the change in household load profile are described by the flowchart below.

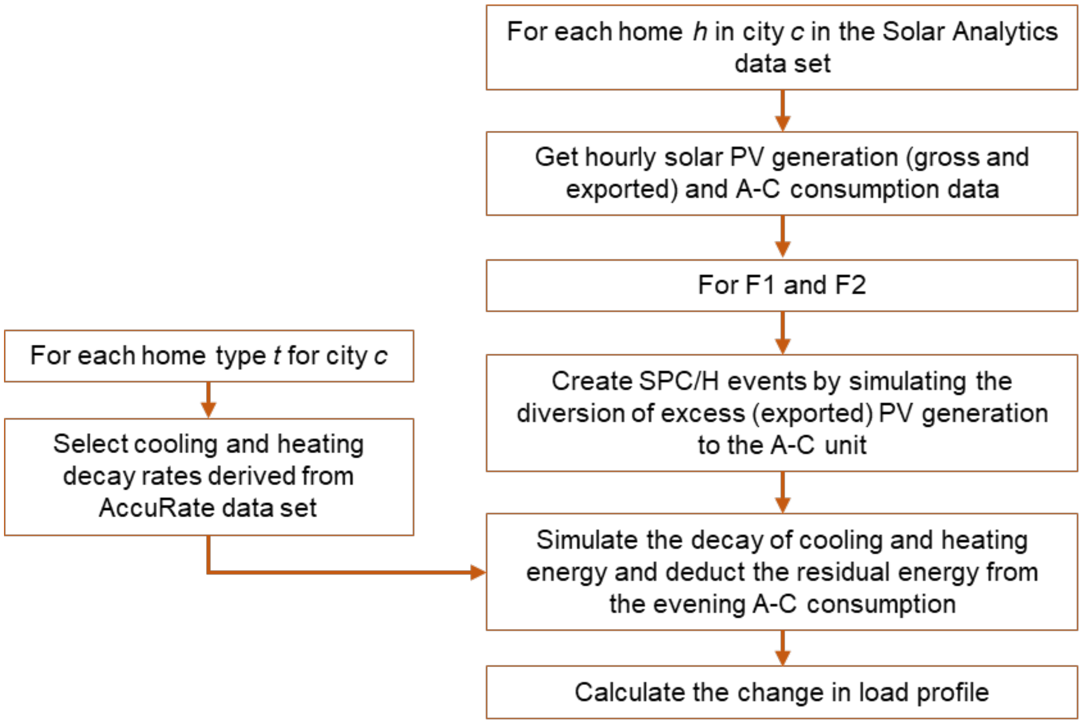

Figure 5-8. Flowchart showing the method steps to simulate the SPC/H process and calculate the change in household load profile

5.4.6 Assumptions

- AC units are assumed to be appropriately sized (i.e., not over, or undersized) to meet the cooling/heating needs of each room

- Each home is assumed to have the star rating (and therefore rate of cooling and heating decay) associated with the assigned building type
- The process of diverting solar energy does not consider thermal comfort and is only limited by the power rating of the AC unit. Even F2 may at times cool or heat the home outside comfort levels if it's required to meet evening AC consumption requirements.
- The diversion of excess PV generation to the AC unit is assumed to be lossless

5.5 Analysis

The results for three types of analysis are presented in this section; the first examines the efficiency of SPC/H, the second the financial viability of SPC/H, and the third how SPC/H changes the residential load profile.

5.5.1 SPC/H efficiency

The efficiency of SPC/H is a measure of how much energy is lost in the conversion of excess solar energy (diverted to the AC unit) to a reduction in evening AC consumption. SPC/H efficiency for a household depends on three factors:

- Thermal efficiency of the home, represented by the cooling and heating decay rate (i.e., the lower the decay rate, the more savings can be expected)
- Typical time difference between when there is excess solar generation and when the household normally uses their AC unit. If excess solar generation is normally available earlier in the day, or the household normally uses their AC later in the evening, then the SPC/H energy will experience more decay, which in turn will reduce SPC/H efficiency
- Forecasting accuracy, represented in this study by F1 and F2.

The efficiency of SPC/H can therefore be defined as the ratio of the reduction in evening AC energy consumption due to SPC/H, AC_{red}, to the total amount of solar energy diverted to the AC unit during SPC/H, PV_{toAC}, i.e.:

$$SPC/H\ efficiency\ = {}^{AC_{red}}/_{PV_{toAC}} \tag{1}$$

A graphical description of AC_{red} and PV_{toAC} is presented in Figure 5-6.

Figure 5-9 below gives the spread of SPC/H efficiency for each household, for each city, for each build type, and for forecasting strategies F1 and F2. The box and whiskers values are 5% (bottom whisker), 25% (lower quartile), median, 75% (upper quartile), and 90% (upper whisker). The SPC/H efficiency is calculated daily, using data from all homes located within their respective city. Each box and whisker therefore consist of ~ 90 data points, i.e., the total number of days in summer and winter. Key observations on Figure 5-9 are listed below.

A significant difference in SPC/H efficiency is seen between the two different forecasting strategies, with F2 generally being twice as efficient. This indicates that up to twice the savings (in terms of energy) can be realised through appropriate control and forecasting. This is consistent across all cities and home types, and for both SPC and SPH.

Efficiency tends to be higher for SPH than for SPC, especially for forecasting strategy F1. This is likely due to there being more solar generation, and therefore more PV_AC energy, during summer than is required to meet evening AC consumption requirements. SPH may therefore offer larger potential savings than SPC.

As the star rating of the home increases, efficiency increases, as expected. That is, SPC/H offers potentially higher savings (i.e., more efficient utilisation of solar energy for evening cooling/heating) as star rating increases. However, the difference in efficiency between 6-star and 8-star homes is relatively small (compared to the difference between 2-star and 6-star homes), suggesting diminishing returns as the star rating increases.

The difference in efficiency between light, medium and heavy-weight construction material is relatively small, particularly for 6-star and 8-star homes. This implies that once a home has achieved a 6-star or higher rating, the effect of construction material on SPC/H performance is negligible.

There is significant spread in the data for each star rating and construction type (as indicated by the error bars). This is due to the large variation in household consumption behaviour, implying that occupancy behaviour has a significant impact on the efficiency of SPC/H.

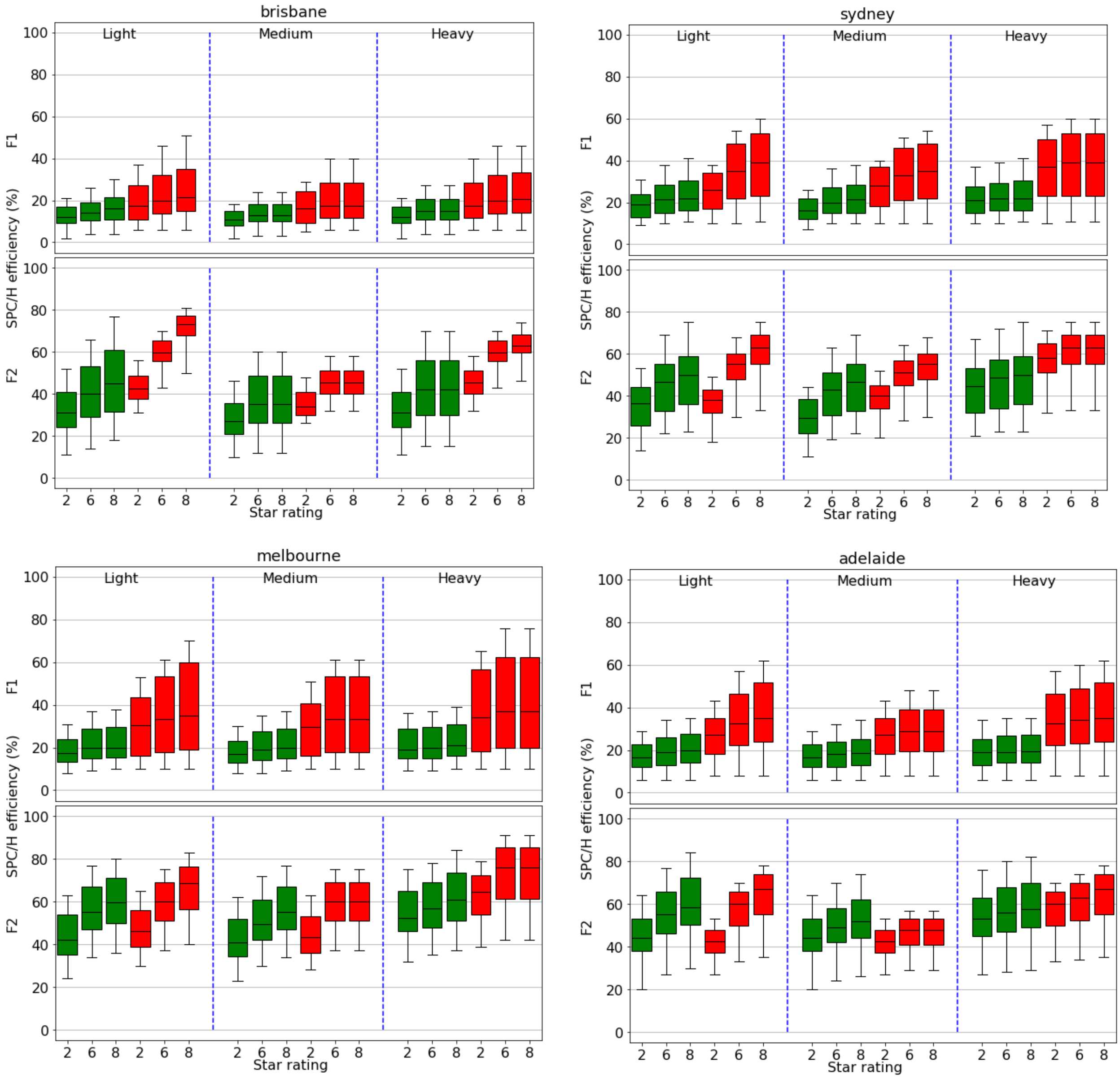

Figure 5-9. Spread of SPC/H efficiency for each household in each city, for each build type, and forecasting strategies F1 and F2.

**The green bars indicate SPC, while the red bars indicate SPH.*

5.5.2 Financial viability of SPC/H

The financial viability of SPC/H for a home is dependent upon its efficiency and tariff. The key aspect of the tariff is the difference between the solar feed-in tariff (t_{sFiT}) and the evening consumption tariff (t_{eve}). Essentially, for SPC/H to be financially viable, the SPC/H efficiency for a home needs to be greater than the ratio of t_{sFiT}/t_{eve}. This relationship can be defined as:

$$SPC/H\ efficiency > {}^{t_{sFiT}}/_{t_{eve}} \tag{2}$$

A derivation of the above equation and an explanation on how it determines the financial viability of SPC/H is given in Appendix I-c. Table 5-10 compares the average existing retail tariff for each city versus SPC/H efficiency for each home type. Cells highlighted in green indicate that the SPC/H efficiency for a home type is greater than t_{sFiT}/t_{eve} and therefore SPC/H is financially viable, red indicates that SPC/H efficiency for a home type is less than t_{sFiT}/t_{eve} and not financially viable.

Table 5-10 shows that under forecast strategy F1, SPC is not financially viable for any of the 4 cities regardless of building star rating or build weight. Furthermore, under F1, SPH is only viable for Sydney (6 stars and above) and Adelaide (all house types). By contrast, under forecast strategy F2, both SPC and SPH are financially viable for all cities for homes that are 6-star and above, regardless of build weight. This highlights the need for appropriate forecasting and control to enable SPC/H to be financially viable. The results also show that even under sub-optimal control strategies (i.e., F1), SPH can have financial merit under certain conditions, particularly in cities such as Adelaide and Sydney.

Table 5-10. Average tariffs together with SPC/H efficiencies for each city

City	t_eve (c/kWh)	t_sFiT (c/kWh)	t_sFiT/t_eve (%)	Forecasting strategy	SPC effiency (%)									SPH effiency (%)								
					Light			Medium			Heavy			Light			Medium			Heavy		
					2	6	8	2	6	8	2	6	8	2	6	8	2	6	8	2	6	8
Brisbane	**21.34**	**6.60**	**30.93**	**F1**	12	14	16	11	13	13	12	15	15	17	20	22	16	18	18	18	20	20
				F2	31	41	46	27	36	36	31	42	42	43	59	73	34	46	46	46	59	63
Sydney	**24.66**	**6.80**	**27.58**	**F1**	19	22	22	16	20	22	21	22	22	26	35	39	28	33	35	37	39	39
				F2	37	47	52	29	43	47	45	50	52	38	55	63	40	51	55	58	63	63
Melbourne	**20.96**	**10.20**	**48.66**	**F1**	17	20	20	17	19	20	19	20	21	30	34	35	29	34	34	34	37	37
				F2	42	55	60	41	49	55	53	57	61	46	60	68	43	60	60	65	75	75
Adelaide	**34.24**	**8.20**	**23.95**	**F1**	17	19	20	17	18	19	19	20	20	27	33	35	27	29	29	33	34	35
				F2	44	55	59	44	49	53	54	56	58	42	60	67	42	48	48	60	63	67

**Green cells indicate that SPC/H is financially viable (i.e., positive savings can be realised) while red cells indicate that SPC/H is not financially viable under current conditions.*

Figure 5-10 illustrates how much a household can save annually through participating in SPC/H. Results use the average existing tariff rates in Table 5-10 and applied them to a heavy 8-star home with forecasting strategy F2 for each city. This represents a best case scenario in terms of annual savings from SPC/H as it has the highest SPC/H efficiency for all cities for both SPC and SPH. Figure 5-10 shows that savings are extremely modest, with the majority of homes in all cities except Adelaide saving less than $10/year for both SPC and SPH, respectively. The most savings can be made in Adelaide with an average of around $12/year for SPC and SPH, respectively, or a total average annual savings from both SPC and SPH of $24/year.

So, while the majority of tariffs are financially viable, the savings are modest and unlikely sufficient to incentivise households to participate in SPC/H. If a tariff was offered which made SPC/H more worthwhile, households may be more inclined to participate. Going by historical AC consumption behaviour of the households in the Solar Analytics, a key reason for low savings is that household AC consumption (kWh) is low over the course of the year, thus there is not large amounts of evening AC consumption to be reduced through SPC/H. But when AC is used, on days of extreme temperatures, it is used by a large number of households, causing a spike in peak demand. It may be that a temporary tariff be offered during these times to incentivise SPC/H. Future work on this would benefit from analysis using a larger data set, ~400 homes is not sufficient to be considered representative AC consumption behaviour for the majority of Australian homes. But even so, if say AC consumption were to double, savings for Adelaide would still only be ~ $50/year under current tariffs.

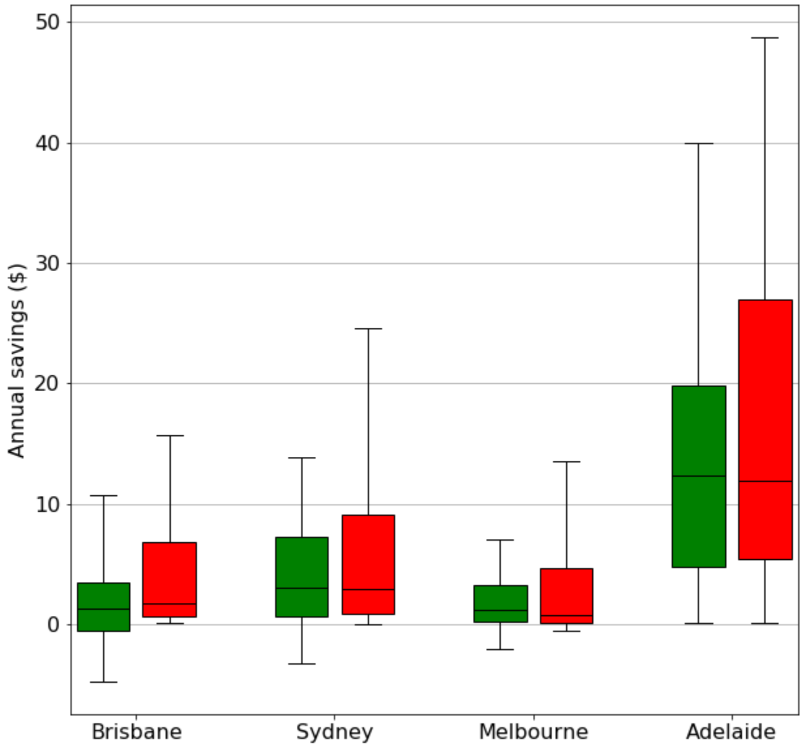

Figure 5-10. Annual household savings from SPC/H for a heavy 8-star home using the average tariff from Table 5-10 for each city

It should be noted that the above tariffs are highly averaged and do not reflect the very high cost of supply at times of peak demand. For example, wholesale spot price can rise to as much as $15 per kWh in the National Electricity Market for short periods, (compared to the $0.21 to $0.34 shown above). The cost of providing network peaking capacity may be added to this cost. If electricity prices or incentive payments more closely reflect these costs in future, then the financial benefits of SPC/H are may be significantly more attractive.

5.5.3 Change in load profile due to SPC/H

This section presents results on the impact of SPC/H on the residential load profile. The change in load profile can be represented by the daily reduction in solar export and evening AC consumption as a result of the SPC/H process. Evening AC consumption is defined as occurring after 4 pm.

Three metrics are used to quantify the daily reduction in evening AC consumption under SPC/H relative to the case where no SPC/H is utilised. Note that all results related to evening AC consumption are the same for both forecasting strategies F1 and F2. The three metrics are:

- Daily reduction in evening AC energy consumption % (kWh)
- Daily reduction in peak evening AC power % (kW). This metric is calculated by comparing the peak evening AC kW value with and without SPC/H.
- Daily reduction in evening AC energy consumption (kWh).

The same type of metrics is used to quantify the daily reduction in solar export under SPC/H relative to the case where no SPC/H is utilised. The three metrics are:

- Daily reduction in solar energy export % (kWh)
- Daily reduction in peak solar power export % (kW). This metric is calculated by comparing the peak solar export kW value with and without SPC/H.

- Daily reduction in solar energy export (kWh).

The first step of the analysis calculates the change in the above metrics at a household level, the second step then scales up these values to estimate the potential change in load profile aggregated by city. The second step is calculated for the present day, as well as a BaU and accelerated scenario for the year 2030.

5.5.3.1 Daily change in load profile per household

This section presents the results for the change in daily load profile per household. Results are presented and discussed for four of the metrics:

- daily reduction in evening AC energy consumption % (kWh),
- daily reduction in peak evening AC power % (kW),
- daily reduction in solar energy export % (kWh), and
- daily reduction in peak solar power export % (kW).

The tables of results for all six metrics are provided in Appendix A.5

Results are presented as boxplots; for each city, build type, star rating, and for both SPC and SPH. SPC is analysed over summer, and SPH over winter. As the metrics are a daily calculation, aggregating data from all homes located within each city, each individual box and whisker therefore consist of ~90 data points, equal to the number of days in summer (for SPC) and winter (for SPH).

Daily reduction in evening AC consumption

Figure 5-11 gives the spread for both the daily reduction in evening AC consumption % (kWh), first and third columns, and the daily reduction in peak evening AC consumption % (kW), given in the second and fourth columns. Key observations are given below.

Generally, the peak (% kW) reduction is greater than the energy (% kWh) reduction for SPC, indicating that the hour of peak evening AC consumption (prior to SPC) occurs earlier in the evening during summer. The opposite is the case for SPH, indicating that peak evening AC consumption (prior to SPH) occurs later in the evening during winter.

The most noticeable feature of the results is the significant difference between SPH and SPC for Brisbane. This is because for Brisbane’s generally warmer climate (relative to other cities), the energy consumption for evening cooling during summer is significantly (by approximately a factor of 5) higher than the evening heating energy required during winter. By contrast, the amount of solar energy absorbed during summer is only approximately a factor of 1.5 times that during winter. This means that during winter there is far more excess solar energy available for SPH, and there is much less evening AC consumption to reduce. Therefore, the climate of Brisbane is more suitable for SPH

The opposite behaviour to Brisbane (just less pronounced) is demonstrated for Melbourne and Adelaide, where due to their relatively cool climates, SPC is more effective than SPH. The reasons for this are the same as for Brisbane except inverted. Therefore, the climates of Melbourne and Adelaide look to be more suitable for SPC.

Sydney does not demonstrate any strong tendencies for either SPC or SPH, probably due to its generally moderate climate, with SPH only slightly more effective than SPC.

It can also be observed that as the home star ratings increase, the amount of evening AC energy reduction increases, particular between 2-star and 6-star homes. The reduction between 6-star and 8-star homes is marginal.

Aside from SPH for Brisbane, the differences in energy reduction between light, medium and heavy construction is small.

It should be noted that a reduction of ~40% in peak AC consumption, as anticipated for Melbourne and Adelaide from SPC, is significant. As evening AC consumption is a major contributor to peak electricity demand during summer, these results show that SPC can potentially significantly reduce peak loads on the electricity grid if utilised properly.

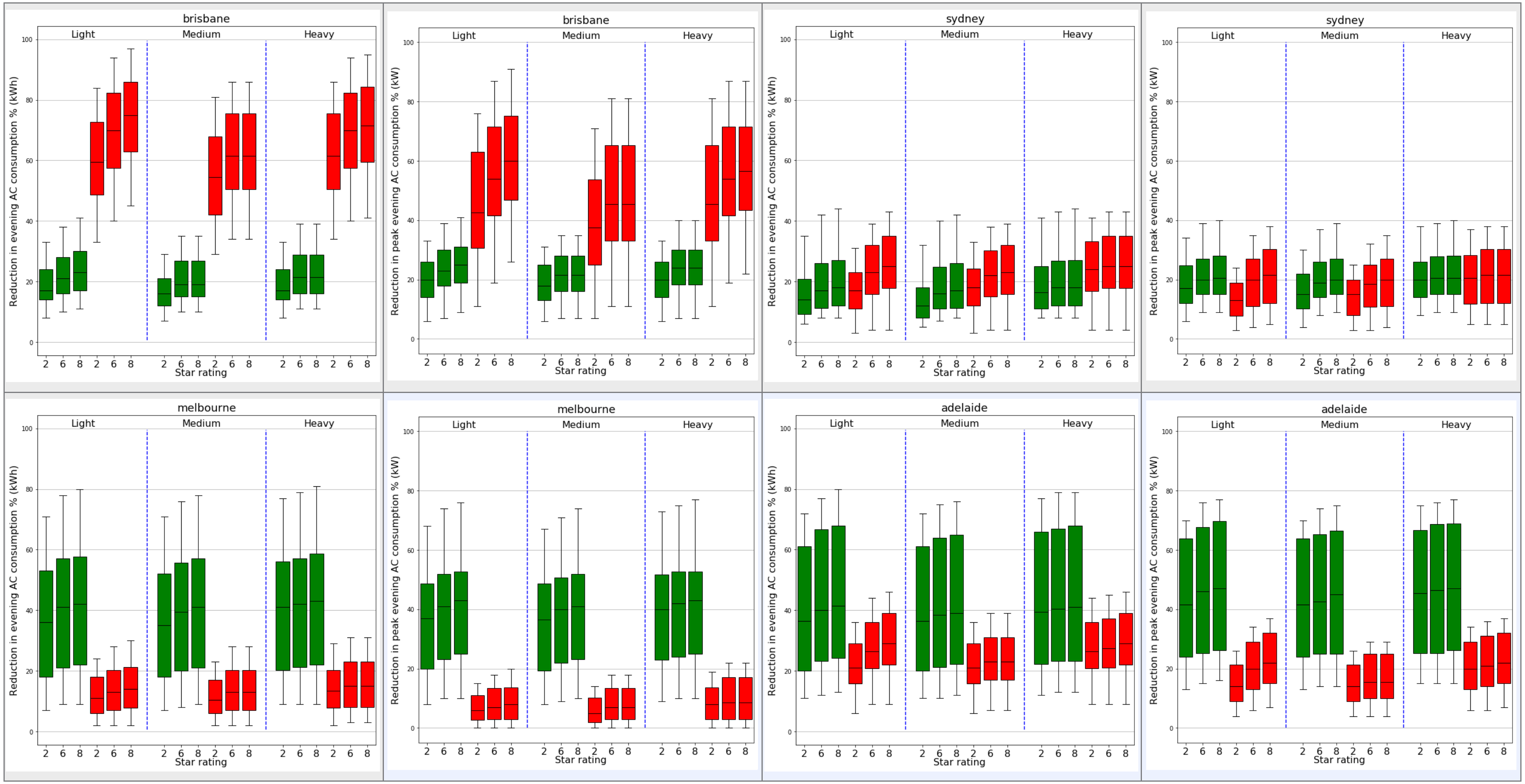

Figure 5-11. Spread in the daily reduction of evening AC consumption % (kWh), first and third columns, and daily reduction in peak evening AC consumption % (kW), second and fourth columns

*The green bars indicate SPC, while the red bars indicate SPH.

Daily reduction in solar export

Figure 5-12 gives the spread for both the daily reduction in solar export % (kWh), first and third columns, and the daily reduction in peak solar export % (kW), given in the second and fourth columns, for forecasting strategy F2. Results for forecasting strategy F1 are not presented in this section, as they can be directly extrapolated from the SPC/H efficiency results presented in Figure 5-9. F2 is typically 1.5 to 2 times more efficient than F1, this translates to a 1.5 to 2 times greater reduction in solar export for F1 compared to F2. Key observations are given below.

The most obvious observation in Figure 5-12 is that the peak reduction % (kW) in solar export is always greater than the reduction in energy % (kWh). This may be because the solar peak occurs later in the day (relative to the solar export profile), but further investigation is required to confirm this.

For all cities, SPH reduces solar export significantly more than SPC, over 50% more in some instances. This is due to there being significantly more solar export available during summer than winter, without an equivalent increase in evening AC consumption. Thus, percentage wise, the reduction in solar export required to service SPH will be higher.

The other key observation is that the reduction in solar export does not vary much according to building star rating or weight, or for each city.

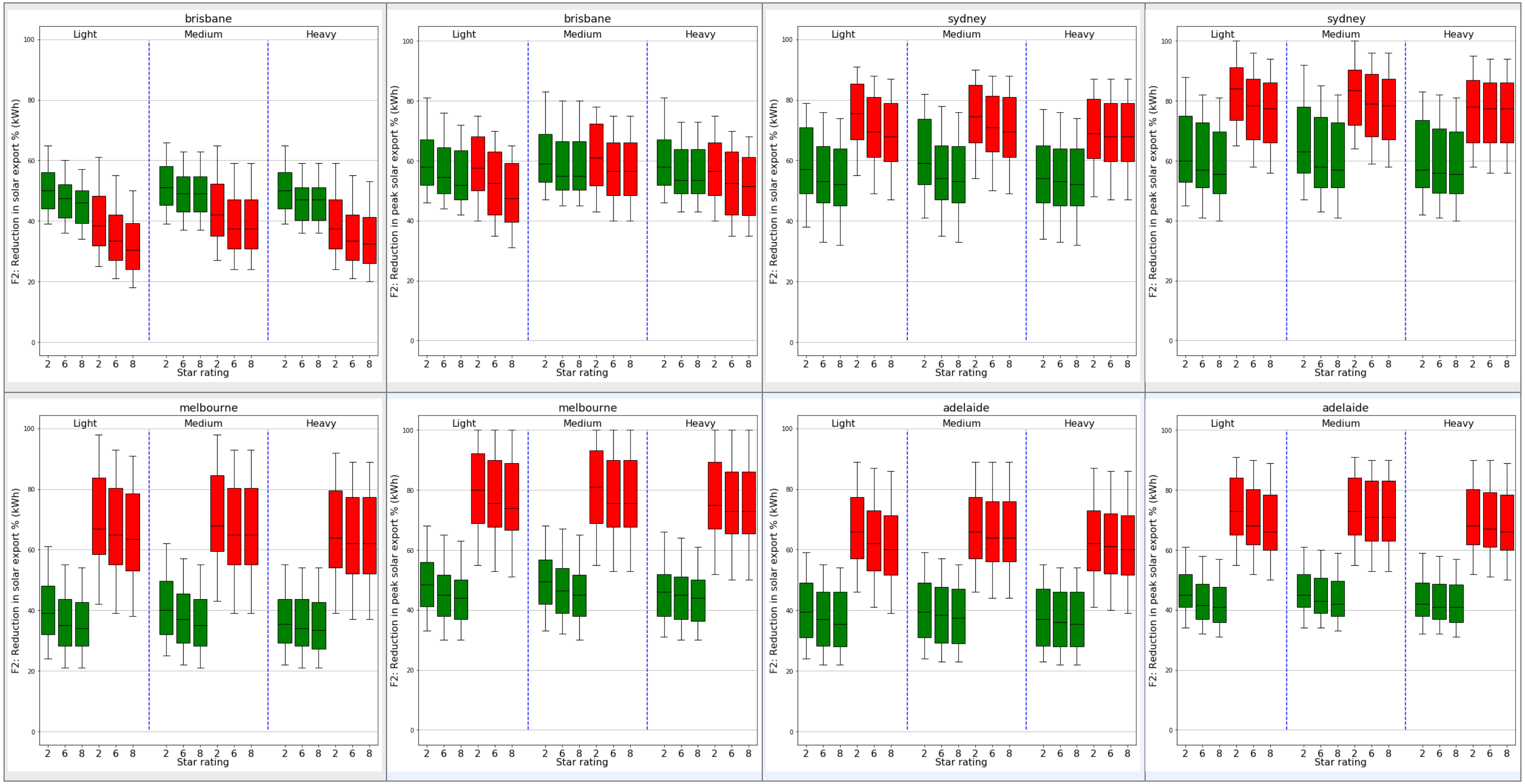

Figure 5-12. Spread in the daily reduction of solar export % (kWh), first and third columns, and daily reduction in peak solar export % (kW), second and fourth columns, for forecasting strategy F2

**The green bars indicate SPC (analysed over summer), while the red bars indicate SPH (analysed over winter).*

5.5.3.2 Daily aggregated change in load profile

The two metrics, daily reduction in evening AC consumption % (kWh) and daily reduction in solar export % (kWh), calculated in the previous section, were converted to absolute values (kWh) and scaled up to estimate the potential daily change in load profile aggregated by city.

To get aggregated values for each city, the absolute per household kWh values are scaled up by the estimated number of solar installs in each city, for the present day, the year 2030 BaU and for the accelerated 2030 scenario. This method of scaling therefore assumes that all homes with solar installed are participating in SPC/H.

Solar installs

Solar install numbers for 2016 for each city are taken from the Clean Energy Council (CEC)[6] website. These values were then scaled up using solar install data available from the Australian PV Institute (APVI)[7] website to get solar install numbers for the year 2016 and 2021. According to APVI data, residential solar installs have increased at approximately 7.8% per year. Assuming this uptake rate remains constant for the next decade, this value is used to extrapolate solar install numbers up to the year 2030. The table below shows the estimated number of solar installs for each city for years 2016, 2021, and 2030.

Table 5-11. Estimated number of solar installs for each city for years 2016, 2021, and 2030

Year	Brisbane	Sydney	Melbourne	Adelaide
2016	207,008	127,875	182,993	176,976
2021	300,659	185,726	265,779	257,040
2030	588,612	363,603	520,327	503,218

Housing stock allocation

To estimate the aggregated metrics, it is also necessary to estimate the allocation of housing stock, according to weight and star rating, for each city. To give an example of housing stock allocation, the housing allocation percentages for Brisbane for 2021 and 2030 BaU are given in Table 5-12 and Table 5-13, respectively. The housing allocation percentage tables for all cities are given in Appendix I-f. The process for estimating housing stock allocation is also given in Appendix II.

The final allocation percentages are applied to the solar install numbers to get an estimation of the number of homes for each build type within each city with solar installed. The number of homes for each build type is then multiplied by the per household metrics (i.e., reduction in evening AC consumption (kWh) and reduction in solar export (kWh)) to get the aggregated value. The 2030 accelerated scenario assumes that all old homes have been upgraded from 2-star to 6-star.

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[6] https://www.cleanenergycouncil.org.au/

[7] https://pv-map.apvi.org.au/analyses

Table 5-12. Percentage housing allocation for 2021 for Brisbane. Non-zero percentages are highlighted in green

Year	2021	City	Brisbane			
Age	Age % allocation	Weight	Weight % allocation	Star rating	Star rating % allocation	Final % allocation
Old	72	Light	43	2	100	31.0
				6	0	0.0
				8	0	0.0
		Medium	48	2	100	34.6
				6	0	0.0
				8	0	0.0
		Heavy	9	2	100	6.5
				6	0	0.0
				8	0	0.0
New	28	Light	27	2	0	0.0
				6	91	6.9
				8	9	0.7
		Medium	73	2	0	0.0
				6	91	18.6
				8	9	1.8
		Heavy	0	2	0	0.0
				6	91	0.0
				8	9	0.0
Sum	100					100

Table 5-13. Percentage housing allocation for 2030 BaU for Brisbane. Accelerated 2030 scenario assumes that all old homes have been upgraded from 2-star to 6-star

Year	2030 (BaU)	City	Brisbane			
Age	Age % allocation	Weight	Weight % allocation	Star rating	Star rating % allocation	Final % allocation
Old	58	Light	43	2	100	24.9
				6	0	0.0
				8	0	0.0
		Medium	48	2	100	27.8
				6	0	0.0
				8	0	0.0
		Heavy	9	2	100	5.2
				6	0	0.0
				8	0	0.0
New	42	Light	27	2	0	0.0
				6	75	8.5
				8	25	2.8
		Medium	73	2	0	0.0
				6	75	23.0
				8	25	7.7
		Heavy	0	2	0	0.0
				6	75	0.0
				8	25	0.0
Sum	100					100

**Non-zero percentages are highlighted in green.*

Daily aggregated reduction in evening AC reduction (Figure 5-13)

Figure 5-13 gives the daily reduction in evening AC consumption aggregated by city for 2021 (current), 2030 (BaU), and the 2030 accelerated scenario. Key observations are listed below.

Comparing 2021 to 2030 (BaU), the increase in reduction is approximately equivalent to the increase in solar installs (double), as expected.

For the 2030 accelerated scenario, all old homes are upgraded from 2-star to 6-star, representing more than 50% of the housing stock, but despite this the increase in reduction in evening AC consumption relative to the 2030 scenario is marginal, only up to around 10%. This warrants further investigation but may be due to the available evening AC consumption gradually becoming exhausted. The difference in reduction in evening consumption between the BaU and accelerated scenarios (for 2030) is greatest for Brisbane, with an increase in reduction of approximately 100 MWh for both SPC and SPH, respectively.

Of importance is the daily aggregated reduction in evening AC consumption as a percentage of estimated total daily evening AC consumption for each city, this analysis is provided in Section 3.3.3.

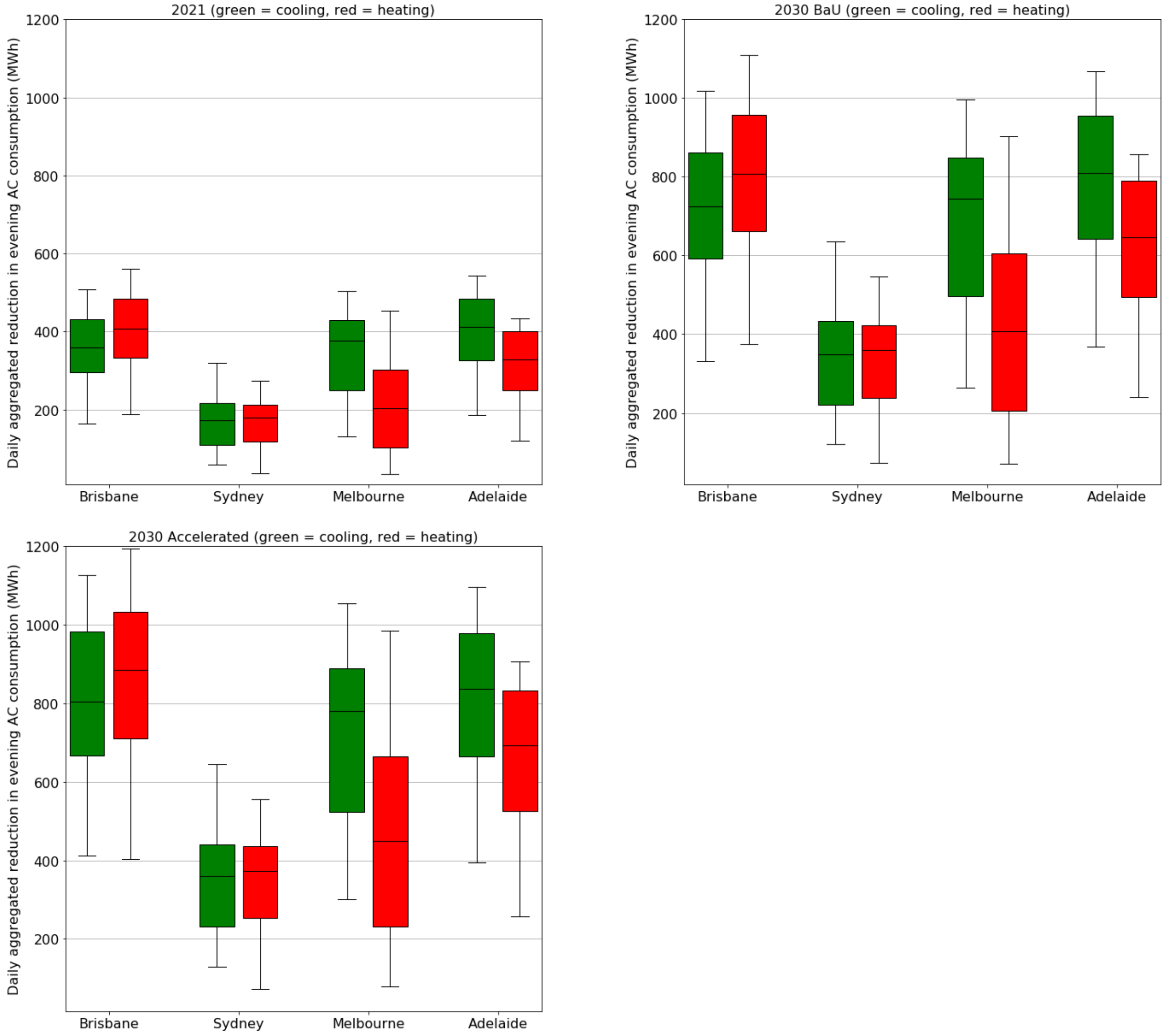


Figure 5-13. Reduction in evening AC consumption aggregated by city for 2021, 2030 (BaU), and 2030 accelerated

**The green bars indicate SPC (analysed over summer), while the red bars indicate SPH (analysed over winter).*

<u>Daily aggregated reduction in solar export (Figure 5-14)</u>

Figure 5-14 below gives the daily reduction in solar export aggregated by city for 2021, 2030 BaU, and the 2030 accelerated scenario. Key observations are listed below.

As per Figure 5-13, the increase in reduction from 2021 to 2030 BaU is approximately equivalent to the increase in solar installs (double), as expected

Again, as per Figure 5-13, there is only a subtle difference between the 2030 BaU and 2030 accelerated scenario, where solar export reduces slightly. The 2030 accelerated scenario results in a decrease in the reduction in solar export. That is, under the accelerated scenario, more solar is exported to the grid compared to the BaU scenario. This is due to the increased star rating of the homes, requiring less solar energy to meet evening AC demand. Brisbane exhibits the largest decrease in reduction in solar export between 2030 BaU and the 2030 accelerated scenario, indicating the SPC/H efficiency of Brisbane homes increases the most with an increase in home star rating. This is more beneficial to homeowners, but not necessarily to networks.

Again, of importance is the daily aggregated reduction in solar export as a percentage of estimated total daily solar export for each city, this analysis is provided in Section 3.3.3.

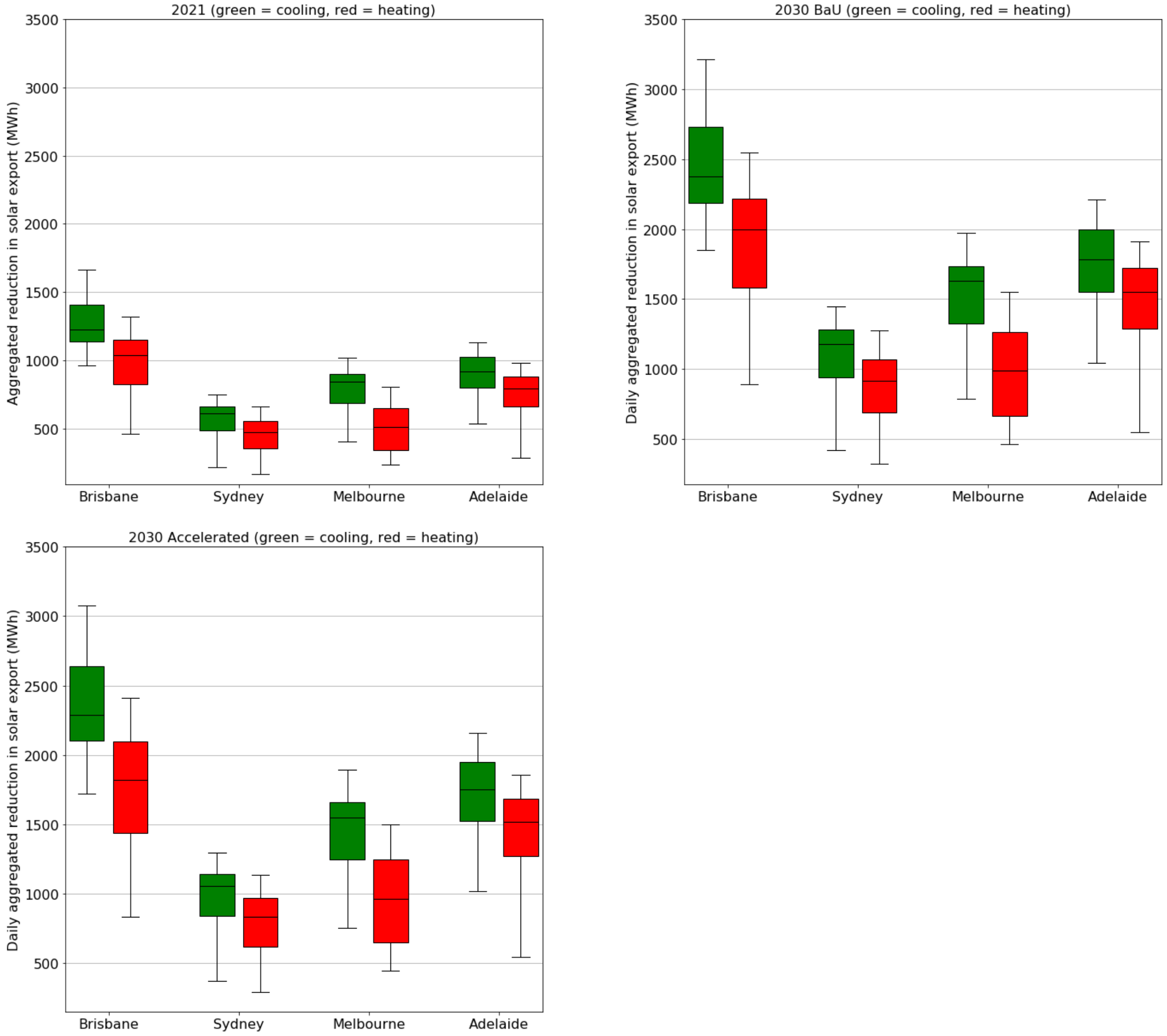


Figure 5-14. Reduction in solar export aggregated by city for 2021, 2030 BaU, and 2030 accelerated

**The green bars indicate SPC (analysed over summer), while the red bars indicate SPH (analysed over winter).*

5.5.3.3 Aggregated metrics relative to total demand

Substation level A-C consumption and solar export measurements from CSIRO's NEAR data set from 2015 were used to estimate aggregated A-C consumption and solar export values for each city. Unfortunately, initial analysis (restricted by time and scope) of the NEAR data set resulted in unexpected MWh values for each city and didn't allow for a meaningful comparison against the estimated aggregated values for reduction in evening AC (Figure 5-13) consumption and solar export (Figure 5-14) for year 2021. It is recommended that a more in-depth analysis in this area be undertaken as future work

5.6 Key findings

Decay rates

Heavy builds, for all cities and star ratings aside from 8 star homes in Brisbane and Adelaide, were shown to have the lowest decay rates, followed by light then medium. Light builds for all cities have similar decay rates. Medium builds (aside from Melbourne) for SPH have much higher decay rates compared to SPC.

In general, decay rates are sufficiently low (approximately between 4-12% per hour on average) such that SPC/H can influence temperatures a significant number of hours into the future.

Efficiency

Using forecasting of both AC consumption and solar export to optimise SPC/H significantly improves SPC/H efficiency. SPC/H efficiency using perfect forecasting (F2) was shown to be twice as efficient when compared with basic forecasting (F1).

Efficiency tends to be higher for SPH compared to SPC, especially for forecasting strategy F1. This is likely due to there being more solar generation, and therefore more PV_AC energy, during summer than is required to meet evening AC consumption requirements. SPH may therefore offer larger potential savings than SPC.

As the star rating of the home increases, efficiency increases, as expected. That is, SPC/H offers potentially higher savings (in terms of energy wasted) as star rating increases. However, the difference in efficiency between 6-star and 8-star homes is relatively small (compared to the difference between 2-star and 6-star homes), suggesting diminishing returns as the star rating increases

The difference in efficiency between light, medium and heavy is relatively small, particularly for 6-star and 8-star homes. This implies that once a home has achieved a 6-star or higher rating, the effect of construction material on SPC/H performance is negligible.

There is significant spread in the data for each star rating and construction type (as indicated by the error bars). This is due to the large variation in household consumption behaviour, implying that occupancy behaviour has a significant impact on the efficiency of SPC/H.

Financial viability

For SPC/H to be financially viable for a household, the SPC/H efficiency of the home needs to be greater than ratio of the evening tariff to the solar feed-in tariff.

The difference in SPC/H efficiency due to forecasting strategy has a big impact on the financial viability of SPC/H. For homes assumed to operate using basic forecasting (F1), using current typical evening and solar feed-in tariffs, only SPH for homes in Sydney and Adelaide was found to be financially viable. For F2, the majority of tariffs were found to be financially viable.

Household savings from SPC/H under current tariffs are modest. Adelaide demonstrated the most savings from SPC/H, using F2, and only saved households ~$25/year on average. Tariffs will need to change, and/or customer-based incentives offered to incentivise households to participate in SPC/H.

Reduction in evening AC consumption

Generally, the reduction in peak evening AC consumption (% kW) is greater than the reduction in energy (% kWh) for SPC, indicating that the hour of peak evening AC consumption (prior to SPC) occurs earlier in the evening during summer. The opposite is the case for SPH, indicating that peak evening AC consumption (prior to SPH) occurs later in the evening during winter.

There is an extreme difference in the reduction in evening AC consumption between SPH and SPC for Brisbane.

This is because for Brisbane’s generally warmer climate (relative to other cities), the energy consumption for evening cooling during summer is significantly (by approximately a factor of 5) higher than the evening heating energy required during winter. By contrast, the amount of solar energy absorbed during summer is only approximately a factor of 1.5 times that during winter. This means that during winter there is far more excess solar energy available for SPH, and there is much less evening AC consumption to reduce. Therefore, the climate of Brisbane is more suitable for SPH. The opposite behaviour to Brisbane (just less pronounced) is demonstrated for Melbourne and Adelaide, where SPC is obviously more effective than SPH. The reasons for this are the same as for Brisbane except inverted.

The climate of Brisbane looks to be suitable for SPH, while the climates of Melbourne and Adelaide look to be more suitable for SPC. Sydney doesn’t demonstrate any strong tendencies for either SPC or SPH, with SPH only slightly more effective than SPC.

As home star ratings increase, the amount of evening AC energy reduction increases, particular between 2-star and 6-star homes. The reduction between 6-star and 8-star homes is marginal.

Aside from SPH for Brisbane, the differences in the reduction in evening AC consumption between light, medium and heavy construction is small.

A reduction of ~40% in peak AC consumption (Melbourne and Adelaide) from SPC is significant. Evening AC consumption is a major contributor to peak electricity demand during summer, these results show that SPC can potentially significantly reduce peak loads on the electricity grid if utilised properly.

There is a large difference in the spread of reduction in evening AC consumption between the cities, with Melbourne (closely followed by Adelaide) demonstrating the larger spread for both SPC and SPH. This is most likely due to a large spread in temperatures across each season (summer and winter).

Reduction in solar export

Peak reduction % (kW) in solar export is always greater than the reduction in energy % (kWh). This may be because the solar peak occurs later in the day (relative to the solar export profile), but further investigation is required to confirm this.

For all cities, SPH reduces solar export significantly more than SPC, over 50% more in some instances. This is due to there being significantly more solar export available during summer than winter, without an equivalent increase in evening AC consumption. Thus, percentage wise, the reduction in solar export required to service SPH will be higher.

The reduction in solar export doesn’t vary much according to building type, either star rating or weight, for each city

Aggregated reductions in evening AC consumption and solar export

Upgrading all old homes from 2-star to 6-star (2030 accelerated scenario), representing more than 50% of the housing stock, only marginally increases the reduction in evening AC consumption relative to the 2030 BaU scenario. This may be due to the available evening AC consumption gradually becoming exhausted. Brisbane shows the greatest benefit, largest increase in reduction in evening AC consumption, from an increase in home star rating.

As per reduction in evening AC consumption, there is only a minor difference between the 2030 BaU and 2030 accelerated scenario, where solar export is reduced only slightly. Brisbane exhibits the largest decrease in reduction in solar export between 2030 BaU and the 2030 accelerated scenario, indicating the SPC/H efficiency of Brisbane homes increases the most with an increase in home star rating. This is more beneficial to homeowners, but not necessarily to networks.

5.7 Future work

Note that the purpose of the findings for this section is to identify where follow up research is needed.

The current model does not take into account thermal comfort – more work is required to determine the effect of SPC/H on thermal comfort. This modelling may require the development of a method for estimating the indoor temperature of a home using only outdoor temperature.

Peak reduction % (kW) in solar export is always greater than the reduction in energy % (kWh). This may be because the solar peak occurs later in the day (relative to the solar export profile), further investigation is required to confirm this.

A comprehensive analysis of the CSIRO NEAR data set, combined with robust projections of solar PV uptake and evening AC consumption, to calculate the potential aggregated reduction in evening AC consumption and solar export according to zone substation, suburb, city, state, and DNSP jurisdiction.

An investigation into the benefit SPC/H may bring to the network. Power flow analysis, using the adjusted load profiles from SPC/H, could be undertaken to determine the impact on voltage and loading levels of transformers and cables.

6 Barriers and solutions

6.1 Barrier analysis

The barriers outlined in this section are derived from a review of the literature and interpretation of the modelling analysis undertaken in this study. The barriers affecting consumers are supplemented or validated by interviews with stakeholders representing consumer perspectives, drawn from the project IRG (refer Methodology section 2.1.2.1).

The barriers are divided into categories of social, technical, and economic.

6.1.1 Social barriers

6.1.1.1 Consumer knowledge and understanding of energy supply

Some consumers consider that the supply of energy is not important to them and monitoring their real time energy usage is not a priority [67]. They may only think about their energy consumption when they receive a bill and may not be aware how their energy consumption and costs compare with other households. Consumers may also be unaware of what behaviours they can change to reduce their consumption, meaning they are not necessarily incentivised to change their energy consumption behaviour. Where consumers do not feel they have any control over the size of their energy bill [67], there is a sense that retailers determine costs, and consumers just need to pay. Research indicated that access to energy consumption products and services (e.g. mobile apps, in-home display monitoring, messaging from retailers) increased customer awareness of their energy use [44] although it is not clear whether the products and services increased their awareness, or whether households chose to use them because they were already more conscious of their energy consumption.

Different features of electricity plans and electricity rates are found to be difficult for consumers to understand [38, 54]. In many cases, there are multiple electricity providers, each with multiple plans that are often difficult to compare on an equitable basis [67]. People are found to have a status quo bias and are reluctant to adapt to change (such as changing their electricity plan and electricity providers). They are strongly motivated to stay with the default or current option; thus, they may prefer to stay with their existing retailer even if there is potential economic benefit from switching [67, 70].

Some consumers think it is the network's responsibility to keep a stable and reliable electricity grid and that consumers play no role in this [38]. This is also supported by our IRG stakeholder interviews that in most cases, people pay little attention to how energy is supplied, priced, and regulated. Our IRG stakeholder interviews suggest that some consumers confuse 'networks' and 'retailers' although they tend to trust networks more than retailers. Participants in demand management programs were found to be more concerned about the stability and reliability of the electricity supply [54].

6.1.1.2 Consumer knowledge and understanding of SPC/H

The literature and our IRG stakeholder interviews indicate that consumer's understanding of SPC/H, and demand response in general, is very low. This is a worldwide situation in which Australia lags behind other continents such as Europe and Asia [1].

Consumers are unfamiliar with how consumers and energy companies each benefit from demand response, and may perceive it to be disadvantageous to themselves [68]. Our IRG stakeholder interviews suggested that there may be a perception (correctly or otherwise) that SPC/H is an additional and wasteful energy use when the house is unoccupied. There is a lack of understanding about how SPC/H would impact the network, especially since modern air conditioners are considered quite efficient.

Poor understanding of strategies for SPC/H operation leads to consumer questions regarding the proper temperature range for pre-cooling, for how long it should pre-cool their houses (to achieve a thermal comfort level without being over cooled or under cooled), and whether it should be operated from a thermal comfort or energy bill savings perspective [37, 43].

Our IRG stakeholder interviews in Queensland highlighted the importance of tailoring promotional strategies for SPC/H to different household characteristics, as the barriers vary between specific categories of householders. For example, solar households might have already signed up for a demand response control program and understood the infrastructure and technologies to some extent, as opposed to the non-solar households who have limited access to those technologies. Different approaches should also be adopted between homeowners and renters. Homeowners have absolute control of their homes, whereas renters may not be sure about who is paying for what and whose responsibilities it is to sign off relevant contracts.

Interviewees suggested that consumers should be able to choose which appliances they time shift the use of to maximise the uptake of solar generation, rather than being constrained to only AC. To mitigate the concern with the excessive rooftop solar PV export, consumers could be encouraged to include other solutions such as electric vehicle charging, electrical space heating, solar hot water heating, and pool pumps.

Consumer messaging and incentive measures will influence the success of SPC/H as an intervention to avoid possible misunderstandings. Economic incentives may attract people to do daytime cooling for the sake of a pricing reward, even when they do not usually use evening cooling or heating. Non-solar households may think the extra energy consumption is unjustified to cool or heat an unoccupied home, which may be resolved through appropriate tariff structures and awareness.

6.1.1.3 Trust

The levels of trust in the energy industry in Australia are suggested to be as low as 54% compared to the global average of 68% [45]. Our IRG interview findings indicated that consumers would not be familiar with what is involved in a solar precooling program, how solar precooling works, and how to operate it, causing mistrust between the consumers and stakeholders such as electricity distributors, retailers, the government and the policy makers. Mistrust is often linked either to technology or technical issues, or to a lack of transparency around demand response in general. For example, unfamiliarity with the principle of demand management can cause mistrust of electricity supplier motivations. Ever-changing regulations without proper communications can also affect consumer’s trust of the network and policy makers.

Some consumers find contracts misleading when signing up to a plan/program where savings are highlighted but there is less transparency about what is involved for the pro/consumer (e.g. curtailment, limited use of device in a certain time/condition). As a consequence, this may lead consumers to mistrust network/retailers and be cautious about any new program that is offered. A recent study identified general mistrust of electricity retailers with participants suggesting they were sceptical about the information provided to them [76]. Therefore, any program messaging and contracts should make clear the benefits and impacts for each party, and how SPC/H will be controlled, in order to improve trust between consumers and retailers/network operators.

Perceived risk may also be associated with the level of complexity and effort for consumers to participate [38] regarding contracts, costs and control technologies.

6.1.1.4 Control strategies

A review of the literature and feedback from our IRG interviews revealed that most consumers are not very accepting of third party control over their appliances. They perceive risks in giving up control (like house getting too cold/hot, damaged appliances or electricity disconnection to their homes) [54]. A US trial relating to consumer acceptance of demand response indicated that consumers strongly preferred to programme their AC thermostats themselves as they were reluctant to allow direct load control [54].

A review of the literature, also supported by our IRG interviews, found that consumers are more likely to participate in demand side management (DSM) initiatives if they have more control [38], particularly preferring automated or programmed AC thermostat control over third party direct load control, to allow for manual override. Our IRG interviews suggested that appropriate incentives and better communication from the networks would encourage greater acceptance of a level of external control. Research also reported that most users relaxed concerns about external control after gaining familiarity with the programmable thermostats and experience of direct load control by their utility [54].

Our IRG interview findings indicated that giving consumers options over how their appliances were controlled, allowing them to select and trial different types/levels of control, did encourage participation. However not all consumers want to maintain full control with a survey reviewed from the literature showing that whilst 49% of consumers preferred to retain control in the household side, 28% of consumers would like the network to take control [38].

Finally, networks also admit to preferring DSM schemes where they have more control, as it makes DSM outcomes more predictable.

6.1.1.5 Safety

A recent study reported that safety, affordability, security, and sustainability are the priorities for customer engagement in demand response programs [68]. Maintaining a reliable electricity supply and safety concerns (e.g. smart meters) are considered to be as important as economic concerns [44]. It was estimated that 64% customers were willing to support additional investment in demand response if potential safety issues could be solved [68].

6.1.1.6 Data control

Our IRG interviews indicated that consumers may fear that third party control infringes their privacy through sharing energy use information that identifies their household, occupancy patterns and energy behaviours. Research also showed that 40% of households were uncomfortable about sharing their data to third-party providers or retailers [44]. Additionally, the potential risk of leaking personal information (e.g. email, mobile, address, etc.) makes some consumers cautious about signing up to programs.

6.1.1.7 Occupancy impacts

Stakeholders in our IRG interviews were concerned that SPC/H may have thermal comfort disadvantages for some households, such as those with unpredictable household activity patterns, (guests visiting or a change of daily routine). People with particular illnesses or disabilities may have particular thermal comfort needs that could be disrupted by SPC/H. Bigger households may be less adaptive to the program due to having to negotiate different preferences in thermal comfort levels between more occupants.

Consumer preferences in how AC is operated may affect uptake. Interviews noted that some consumers prefer running their AC all the time, at a constant temperature. Others limit their use to very hot (or cold) periods to maintain a basic level of thermal comfort.

6.1.2 Technical barriers

6.1.2.1 Reasonable control/operation strategies

Research indicated that energy consumption increases almost linearly when the pre-cooling time increases. Lower pre-cooling temperatures had a larger energy increase rate [43]. Literature studies showed that current solar pre-cooling strategies are mostly rule-based using temperature setting schedules. This usually involves modifying the HVAC control by setting proper setback period, and changing the set points/setback temperatures guided by intuition [37]. Research indicated that the energy saving potential was highly dependent on climate zone, selected pre-cooling strategies, energy prices, and thermal properties of the houses [42, 71], so rule-based strategies may not be optimal. Therefore, developing model-based pre-cooling strategies that consider the complexity of climates, housing features, and residents' diversities are necessary to improve the efficacy of SPC/H.

6.1.2.2 Technological limitations

Although there are no major technical barriers to the implementation of solar PV and solar AC, there are acknowledged technical issues that limit the performance of SPC/H. Firstly, as stated above, a key limitation is consumers' lack of understanding of the effect of different SPC/H control strategies on the efficacy of SPC/H, in terms of energy savings, peak load reduction and thermal comfort. Secondly, there are currently no standards regarding integrating the different technologies (e.g. air-conditioning systems, control protocols, etc.) relevant to SPC/H. Engineering design and quality installation of cooling systems would influence the performance of solar pre-cooling [1]. Stakeholder interviews suggested that smart metering and smart control technology is also critical.

To avoid another obstacle for consumers to participate, the cost and complexity of required technology needs to be limited.

In terms of government policy and regulation, the DREDs standard of AC control has too many limitations to be suitable for SPC/H in its current form and needs to address these and at least permit commands to turn ACs on or up.

6.1.3 Economic barriers

A significant barrier for consumer engagement in solar pre-cooling is undoubtedly economic [1].

It will be important that network providers share the network benefits of demand response programs through the design of tariffs and additional financial incentives to make it financially worthwhile for householders to participate in SPC/H.

Household incomes may affect user engagement. Research indicated that many low to middle income households withstood wider temperature ranges instead of using AC in order to avoid energy costs [72].

If consumers need additional equipment such as smart meters and smart devices for remote control in order to participate in SPC/H programs, there is a question of whether the network providers or the consumers should pay for the equipment as the advantage of SPC/H is management of the network. Network providers have indicated concerns about their eligibility of claiming “behind the meter” investment (providing in-home technologies), as the current practice seems to only allow investment claims for pilots and trials. Efforts are in place to push for a change to be able to claim large-scale “behind the meter” investments.

Another barrier for retailers is their lack of understanding of consumer behaviour after the uptake of solar pre-cooling, which could impact the benefits to the network if misjudged. This becomes a risk to revenue if the pricing incentives assume a level of network benefit. This risk can be mitigated through a pilot program to understand the impact of solar pre-cooling on load shift in terms of magnitude and timing.

Powerlink has advised that low demand during the day due to excess solar export is of greater concern to them than peak demand. This is when more investment, such as network reactors, synchronous condensers and pumped hydro is required to manage the symptoms of low demand during the day than managing evening peak demand. It is worth noting that peak demand within the NEM connected states is forecast to maintain relatively flat growth over the next ten years [73]. Low demand during the day is also forcing more synchronous generation to turn-off or reduce their generation output during the day, reducing spinning reserve and system stability.

Reducing solar export through cost-reflective tariffs may incentivise households to solar soak but evidence shows [74] these types of tariffs, more complicated than flat, are not well received by consumers. While consumers (through excess roof-top PV export) are the reason for the grid issues which come from low demand, cost-reflective tariffs do place all the responsibility on addressing these grid issues on to the consumer. A household changing their behaviour as desired (by networks) due to a cost-reflective tariff may only result in a household NOT paying more for their electricity, but a household will likely be worse off (paying more for their electricity in the evening and receiving less for their solar export during the day) if they do not change their consumption behaviour. However, Powerlink has advised that while network companies can continue to address the symptoms which come from excess roof-top PV export, the solutions are becoming more expensive and investment costs would be passed onto all electricity consumers, irrespective of whether they have roof-top PV.

Incentivising households to change their behaviour to avoid being worse off, is different to incentivising households to change their behaviour in order to be better off. To implement the latter consumers may need to be paid to change their behaviour, possibly an amount according to how ‘smooth’ their load profile is. Paying the consumer can be justified by an offsetting of network costs due to a ‘smoothing’ of the load profile. Residential load smoothing results in a reduction in network costs across a variety of value streams [75], and relieving the need to install synchronous condensers is just one example. However, Powerlink has advised that since utilities have fixed revenues, unless additional funding is provided by another external source, the cost of funding incentives for some customers ultimately needs to be recovered from other consumers.

6.2 Solution analysis

6.2.1 Enablers to consumer uptake

There are many economic and technical enablers for consumers to engage in solar pre-cooling demand response. To reduce peak electricity demand and curb greenhouse gas emissions, policy makers introduced a series of pricing regimes, tariffs mechanisms, and financial incentives to encourage household participation in demand response [70]. In particular, it has been found that time varying electricity price is very effective in attracting consumer responses [70]. A study in New Zealand showed that low off-peak prices encouraged consumers to spend more electricity energy during the off-peak times, while reducing the electricity energy use during high on-peak prices, which resulted in at least a 10% reduction in total annual electricity consumption [70]. Dynamic peak pricing engages households as co-managers through a series of notification signals (e.g., SMS, phone, email, in-home display, etc.) [3]. Rebates or rewards for peak load switch proved to be a great trigger for consumers to participate in demand response [54, 58]. GoodGrid program provided by the AusNet Services achieved a high rate of successful participation, with 75% earning rewards across all events [56]. In addition, social media reported that lower solar feed-in tariffs give households an inclination to shift consumption to the day time to take more advantage of their rooftop solar electricity generation [39].

As mentioned previously, one barrier for consumer engagement in demand response is the complexity and effort for consumers to participate. Technologies such as automation, programmable thermostat, and direct load control are designed to reduce the complexity and effort of participation by facilitating demand shifting without the need for manual behaviour change. Research found that remote network control can reduce perceived complexity, effort, and risk associated with residential demand response, which acts as another enabler for consumers to participate [54]. Feedback technologies such as home energy monitors and in-home display were found to strongly increase customer engagement [44, 45]. This is because they have greater awareness of their electricity use from participation, especially understand their consumption during events [56].

Other technology enablers include smart metering and control infrastructures, and communication infrastructures. Advanced metering infrastructure and smart meters are vital for implementing demand response strategies. Smart meters are capable of bi-directional communication between the consumer and the network. Incentive-based energy management systems in consumer areas are critical components to provide automated control for effective participation. Additionally, an appropriate communication infrastructure is an essential prerequisite to implement effective demand response programs [58].

Protocols and standards could also encourage consumers to participate in demand response programs. For example, IEEE has a number of standards relevant to the smart grid operations. Australia and New Zealand have a common AS/NZS 4755.3.2 standard titled ‘Demand response capabilities supporting technologies for electrical products’ [58], although attention is drawn to its limitations (refer section 3.2.2.1). In addition, the stakeholder interview demonstrated that familiarising consumers with previous demand management programs helped to reduce mistrust.

In summary, rebates or rewards for peak load switch is a fantastic economic enabler to encourage consumers to participate. Feedback technologies, remote control, smart metering and automation technologies could also reduce the perceived risk associated with consumer engagement in demand response.

6.3 Barriers and solutions summary

The following table summarises barriers raised in this study, paired with possible solutions.

Table 6-1 Barriers and solutions

Barriers	**Solutions**
Social	
Poor public perception, trust and awareness	Improve understanding and trust between the consumers and electricity suppliers by providing more transparent feedback technologies and contracts
Consumers' knowledge, experience, and familiarity with demand control/solar pre-cooling technology is very low	Education; Pilot programs to build familiarity; information about optimal operation strategies
Conflicting needs for level of control by consumers and networks – predictability, ease of use, lack of understanding or care, losing control	Balance network control with a degree of freedom for householders; allow consumers to select control types & times; to test & get feedback from selected control, allow for consumer opt out or override Convenience also plays a key role for consumers, particularly when technology is cheap and management is app-based
Consumer perception of risk regarding safety, affordability, security, and sustainability	Keep it simple: reducing the complexity for consumer engagement Clear incentives; positive messaging For solar PVs household, ensure the policy that requires their participation in the program aims to support the network performance and does not contradict to their initial motivation to participate in renewables energy (solar panel program)
Lack of understanding of consumer behaviour after the uptake of solar pre-cooling	A pilot program to understand the impact of solar pre-cooling on load shift in terms of quantum and timing
Consumers may prefer activating alternative appliances to shift load to solar power instead of cooling or heating	Not a problem; can be an extension of any program or approach
Technical	
Technical complexity and effort for consumers to participate	Automation, programmable thermostat, and direct load control are designed to reduce the complexity and effort; smart metering and control infrastructures, and communication infrastructures are base requirements
AS4755 forbids ACs from having the capability to be turned on or turned up remotely	Amend AS4755, taking into account all concerns that resulted in the original standard barring remote control of AC units in the first place; or mandate compliance with 'DR capabilities' or with an international standard without the limitations of AS4755.
Lack of storage and direct coupling between solar PV and the cooling energy demand may deliver limited benefit in terms of reducing peak demand	New technologies to directly couple either through storage or smart controllers is required between onsite PV generation, and heating/cooling loads and storage to maximise the benefits of solar PV-driven heating and cooling solutions. More data is still needed to assess the viability and feasibility of these systems in the Australian context

Barriers	Solutions
Sub-optimal control of SPC/H may result in SPC/H having a detrimental effect on energy consumption, running cost and thermal comfort	Improve understanding of the influence of SPC/H control strategies and forecasting on the thermal, economic and grid benefits of SPC/H through a combination of modelling and demonstration/pilot projects
Control modifications to existing residential air conditioners may be costly and carry some risk as modifications are not supported by the AC manufacturer potentially voiding warranties	Using demand response ready ACs means that the manufacturer's warranty remains valid and the AC is designed to operate in these modes
Ducted systems require hardwiring from the thermostat to the smart controller	Technology development opportunity
Pre-cooling of highly energy efficient homes is not effective	Increase the number of homes that are energy efficient to mitigate the need for cooling overall Give incentives for improving home-energy performances (e.g., from 6 to 8, etc.)
Economic	
SPC/H may increase total household energy use and reduce thermal comfort	Determine and provide public information on optimal temperature and time settings for different climate zones and house types; develop model-based pre-cooling strategies that consider the complexity of climates, housing features, and residents' diversities
High costs and risk demonstrated by earlier trials indicated that air conditioning load control did not offer a cost-effective demand management solution under certain program models	Keep it simple. Use price signals.
Consumers need incentives to participate	Lower solar feed-in tariffs - if self-use of solar for pre-cooling is more valuable than grid-export, then the value of solar increases with the volume of self-use Implement appropriately structured time of use tariffs or dynamic peak pricing. Network providers need to provide additional financial incentives (rebates or rewards) to share the network benefits of SPC/H
Consumers may need additional equipment such as smart meters and smart devices for the remote control. Networks concerned they are ineligible to claim "behind the meter" investment (providing in-home technologies)	Clarify situation; policy/regulatory change may be needed
Energy costs are a disincentive for AC use by low to middle income households	Positive messages about free, cheap or guilt-free thermal comfort combined with appropriate tariffs
Current measure of AC penetration rates may be insufficient to forecast future electricity demand	A new measure may be required to adequately track the influence of air conditioners on peak electricity demand

7 Path to impact

7.1 Impact analysis

The diagram below (Figure 7-1) describes a process of the impact framework, flowing between the desired impact and the required research activities. The impact framework is a tool for the research theme to strategically plan how it seeks its desired impact and articulates the various impact pathways projects may take. The framework is also a tool for projects to help identify and plan for impact over and beyond their lifecycle. While the representation of the impact logic is linear for ease of communication, it is important to note the feedback loop, from the desired impact to planned activities, while designing the research program.

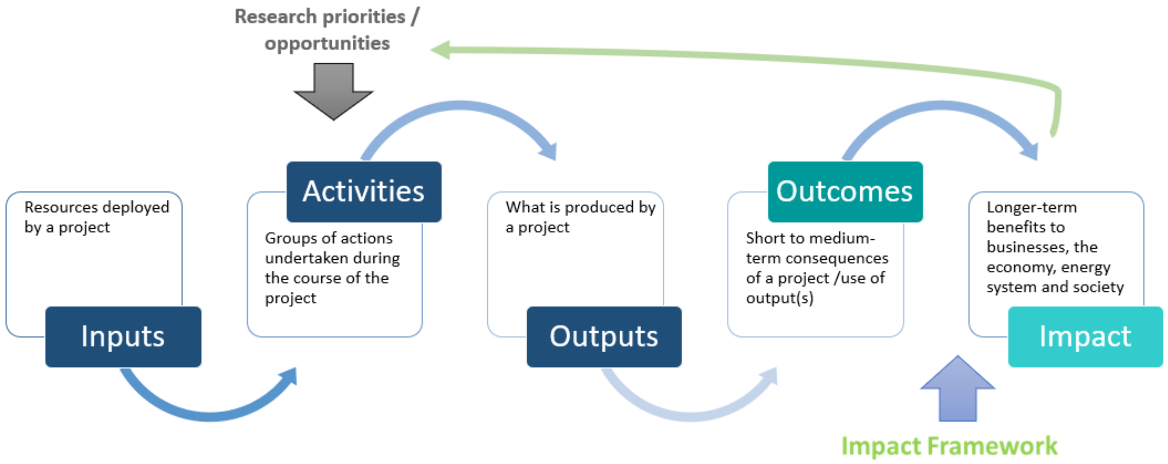


Figure 7-1. Activities to impact

The path to impact for the H1 Theme follows a common ‘program logic’ moving from inputs (time, funds, people etc.) and activities to outputs to outcomes and impacts. For projects funded by RACE for 2030, resources (grant funds, time) are used as **inputs** to support various project **activities** (market design, feasibility studies, etc.). The effectiveness of these activities depends on **knowledge and technology diffusion** – the reach of the knowledge sharing activities or the uptake of the newly developed product/outputs. This diffusion will seed new ideas among the stakeholders and this will be used to **develop the market**, such as implementing new industry practices or reducing barriers to SPC/H. This, in turn, can lead to wider **societal impacts**, such as reduced greenhouse gas emissions.

As shown in Figure 7-2, the control over the outcomes and ability to attribute them to project activities generally decreases along this chain. Projects funded under the H1 Theme can contribute to the identified outcomes. The role of RACE for 2030 will be ensuring that the outputs and outcomes integrate with other relevant industry processes in order to deliver their full impact.

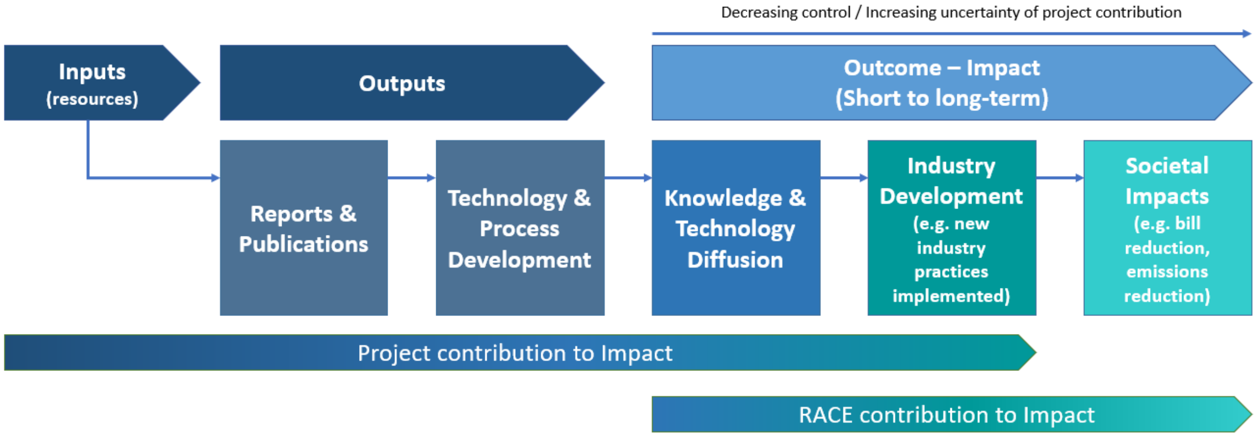
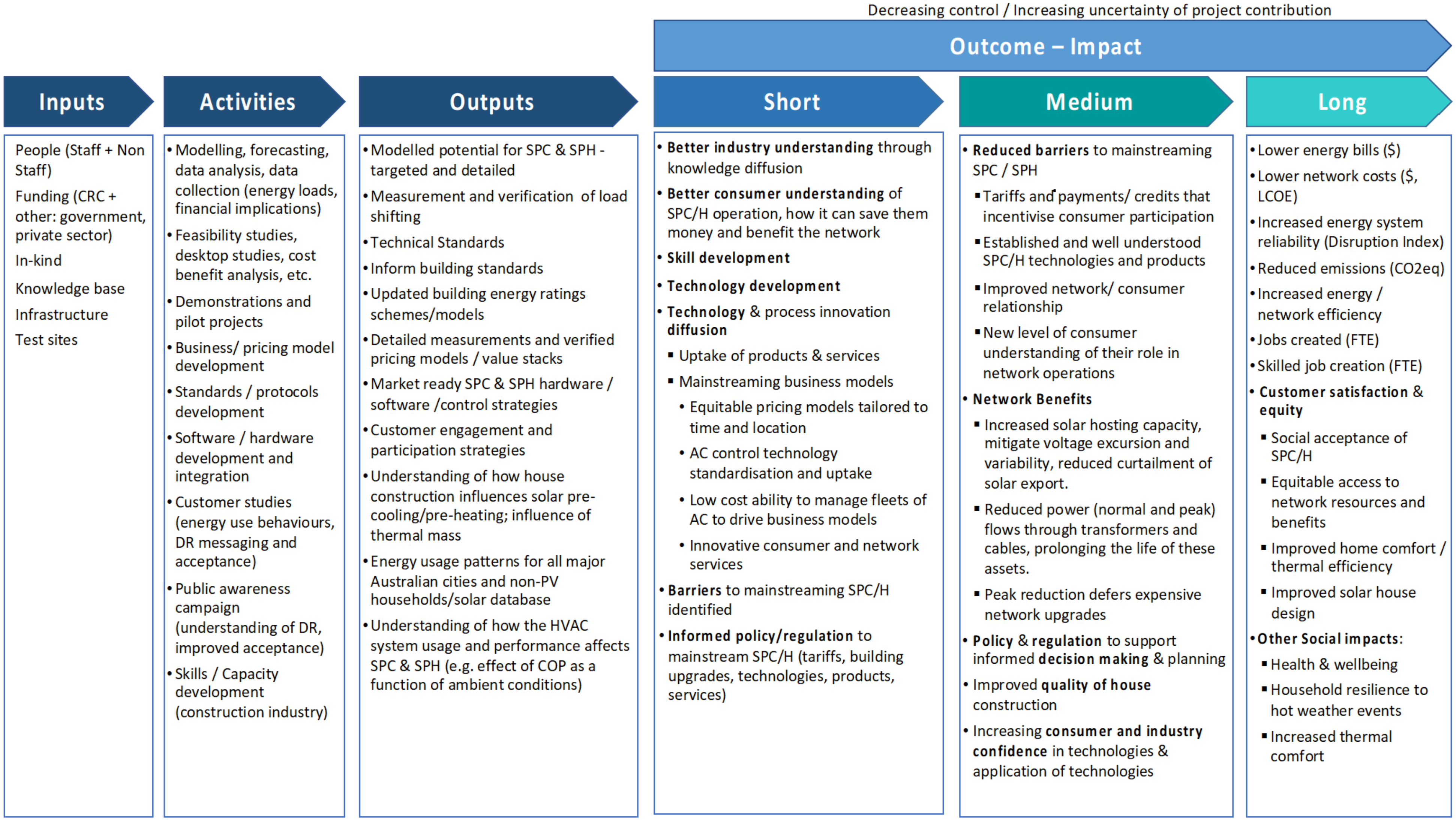


Figure 7-2. High-level impact framework



Decreasing control / Increasing uncertainty of project contribution

Outcome – Impact

Inputs

People (Staff + Non Staff)

Funding (CRC + other: government, private sector)

In-kind

Knowledge base

Infrastructure

Test sites

Activities

- Modelling, forecasting, data analysis, data collection (energy loads, financial implications)
- Feasibility studies, desktop studies, cost benefit analysis, etc.
- Demonstrations and pilot projects
- Business/ pricing model development
- Standards / protocols development
- Software / hardware development and integration
- Customer studies (energy use behaviours, DR messaging and acceptance)
- Public awareness campaign (understanding of DR, improved acceptance)
- Skills / Capacity development (construction industry)

Outputs

- Modelled potential for SPC & SPH - targeted and detailed
- Measurement and verification of load shifting
- Technical Standards
- Inform building standards
- Updated building energy ratings schemes/models
- Detailed measurements and verified pricing models / value stacks
- Market ready SPC & SPH hardware / software /control strategies
- Customer engagement and participation strategies
- Understanding of how house construction influences solar pre-cooling/pre-heating; influence of thermal mass
- Energy usage patterns for all major Australian cities and non-PV households/solar database
- Understanding of how the HVAC system usage and performance affects SPC & SPH (e.g. effect of COP as a function of ambient conditions)

Short

- **Better industry understanding** through knowledge diffusion
- **Better consumer understanding** of SPC/H operation, how it can save them money and benefit the network
- **Skill development**
- **Technology development**
- **Technology** & process innovation **diffusion**
  - Uptake of products & services
  - Mainstreaming business models
    - Equitable pricing models tailored to time and location
    - AC control technology standardisation and uptake
    - Low cost ability to manage fleets of AC to drive business models
    - Innovative consumer and network services
- **Barriers** to mainstreaming SPC/H identified
- **Informed policy/regulation** to mainstream SPC/H (tariffs, building upgrades, technologies, products, services)

Medium

- **Reduced barriers** to mainstreaming SPC / SPH
  - Tariffs and payments/ credits that incentivise consumer participation
  - Established and well understood SPC/H technologies and products
  - Improved network/ consumer relationship
  - New level of consumer understanding of their role in network operations
- **Network Benefits**
  - Increased solar hosting capacity, mitigate voltage excursion and variability, reduced curtailment of solar export.
  - Reduced power (normal and peak) flows through transformers and cables, prolonging the life of these assets.
  - Peak reduction defers expensive network upgrades
- **Policy** & **regulation** to support informed **decision making** & planning
- Improved **quality of house** construction
- Increasing **consumer and industry confidence** in technologies & application of technologies

Long

- Lower energy bills ($)
- Lower network costs ($, LCOE)
- Increased energy system reliability (Disruption Index)
- Reduced emissions (CO2eq)
- Increased energy / network efficiency
- Jobs created (FTE)
- Skilled job creation (FTE)
- **Customer satisfaction** & **equity**
  - Social acceptance of SPC/H
  - Equitable access to network resources and benefits
  - Improved home comfort / thermal efficiency
  - Improved solar house design
- **Other Social impacts:**
  - Health & wellbeing
  - Household resilience to hot weather events
  - Increased thermal comfort

Figure 7-3. Detailed impact framework

Figure 7-3 above provides additional detail on the impact framework specifically for the H1 Theme of SPC/H. It repeats the logic of the previous figures, with additional detail at each step.

7.2 Key metrics for research impact

Indicators and metrics are identified below in the aspects of knowledge and technology diffusion, industry development and social impact. These indicators and metrics can assemble a set of criteria to assess the potential impact of future proposed projects. Note, the metrics below are specified as quantifiable as possible.

7.2.1 Knowledge and technology diffusion

Table 7-1. KPIs & Metrics - Knowledge and Technology Diffusion

Category	Indicators	Metrics
Knowledge, Awareness & Skills	Better understanding through knowledge diffusion	Self-reported change by industry stakeholders.
	Specialised skill development	# of people trained. # of skill sets identified.
Attitudes	Social acceptance of SPC/H Customer participation in wholesale markets / network support	# of networks buying non-network support services[8]. # of retailers buying non-network support services[9] Change in connection agreements. MW of non-network support traded
Technology & process innovation diffusion	Increased uptake of products & services (e.g. DREDs, DRED enabled equipment, control apps/equipment, smart meters)	Product /services sales # # of Retailers / aggregators offering services.
	Increased uptake of tools & methodologies for better network planning in existing network and retail businesses (predictive tools for costs/tariffs)	# of businesses adopting tools.
	Mainstreamed business models: Equitable pricing models tailored to time and location Wholesale price data for consumer manual response	# of businesses adopting models.
	Improved quality of house construction[10]	Average % new home star rating above code

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[8] Non-network support services, meaning instead of buying pools and wires, network providers adopt flexible demand solutions to reduce the pressure on the grid at a lower cost.

[9] Retailers invest in non-network support services to release pressure on pricing, as the increasing amount of solar PV sourced energy has led to low-price or negative-price events in the wholesale electricity market.

[10] Small improvements that are not recorded in NatHERS can be documented through white certificates schemes such as the NSW Energy Savings Scheme (ESS), the Victorian Energy Upgrades (VEU) program, and the South Australia Retailer Energy Productivity Scheme (REPS) etc.

7.2.2 Industry development

Table 7-2. KPIs & Metrics - Industry Development

Category	Indicators	Metrics
Reducing barriers to mainstreaming SPC/H	Alleviate export to grid constraints.	Export limits (static vs dynamic) Average solar installation size
	Optimal PV penetration / Increased Hosting Capacity.	Grid decentralization ratio % rooftop solar on LV feeders
Network Operations	Improved network utilisation.	% Utilisation Annual load variation curve within a PV loaded area
	Network operates within limits of all applicable quality standards.	Power quality metrics : Occurrences of overvoltage and undervoltage events. Phase imbalance Voltage fluctuations
Policy & Regulation to support informed decision making	Influenced decision making / decision-makers.	Evidence of policy change – reports, guidelines, etc. Citations in key industry decision-making forums
	Informed changes in industry policy, market rules, legislation, regulations or guidelines.	
Customer Satisfaction & Equity	Equitable access to network resources.	Network connection agreements Customer complaint rates Solar spillage
	Improved home comfort	Thermal efficiency Self-reported change by customers

7.2.3 Societal impacts

Table 7-3. KPIs & Metrics – Social Impacts

Category	Indicators	Metric
Economic	Lower household energy bills	$ (bill reduction)
	Lower network costs	Network LCOE
Economic / Environmental	Increased energy system reliability	Change in Disruption Index
Environmental	Reduced emissions	CO2 equivalent emissions
Economic / Social	New jobs created	FTE
Social	Health & Wellbeing	# of Weather related hospital visits Self reported change by customers
	Household resilience	Self reported change by customers Extreme weather related expenses

7.3 Solar pre-cooling and pre-heating impact

This section summarises the findings from the scenario modelling to determine the possible impacts for both consumers and networks in terms of changes to energy and costs.

7.3.1.1 Effect of house quality on impact

Heavy builds, for all cities and star ratings, were shown to have the highest thermal inertia (the lowest decay rates), followed by light then medium. Light builds for all cities performed similarly. Medium builds (aside from Melbourne) lost heat much more quickly than they did coolth. In general, decay rates are sufficiently low such that SPC/H can influence temperatures a significant number of hours into the future.

As expected, as the star rating of the home increases, the amount of energy used for SPC/H during the day more closely matches the reduction of energy needed in the peak, that is, its efficiency increases. However, the difference in efficiency between 6-star and 8-star homes is relatively small (compared to the difference between 2-star and 6-star homes), suggesting diminishing returns as the star rating increases.

The difference in efficiency between light, medium and heavy is relatively small, particularly for 6-star and 8-star homes. This implies that once a home has achieved a 6-star or higher rating, the effect of construction material on SPC/H performance is negligible.

As home star ratings increase, the amount of evening AC energy use decreases, particularly between 2-star and 6-star homes. The difference in decrease between 6-star and 8-star homes is marginal. Aside from SPH for Brisbane, the differences in energy reduction between light, medium and heavy construction is small.

The reduction in solar export does not vary much according to building star rating or weight, or for each city.

Upgrading all old homes, representing more than 50% of the housing stock, from 2-star to 6-star (2030 accelerated scenario), only marginally increases the reduction in evening AC consumption relative to the 2030 BAU scenario. This may be due to the available evening AC consumption gradually becoming exhausted. Brisbane shows the greatest benefit, largest reduction in evening AC consumption, from an increase in home star rating. Similarly, there is only a slight reduction in solar export between the 2030 BAU and 2030 accelerated scenario. Brisbane exhibits the largest reduction, indicating the SPC/H efficiency of Brisbane homes increases the most with an increase in home star rating.

Modelling of 8 star homes was constrained by the small dataset due to these homes having fewer cooling events. Whilst this is unhelpful for analysis of load shifting, it clearly shows that well designed, efficient homes in Australia have little need of any AC. Upgrading homes can remove the heating/cooling load altogether.

7.3.1.2 Effect of climate on impact

The climate of Brisbane looks to be suitable for SPH, while the climates of Melbourne and Adelaide look to be more suitable for SPC. Sydney does not demonstrate any strong tendencies for either SPC or SPH, with SPH only slightly more effective than SPC.

7.3.1.3 Effect of occupancy on impact

There is significant spread in the data for each star rating and construction type (as indicated by the error bars in the graphs). This is due to the large variation in household consumption behaviour, implying that occupancy behaviour has a significant impact on the efficiency of SPC/H.

7.3.1.4 Effect of tariffs on impact

For SPC/H to be financially viable for a household the evening tariff needs to be higher than the solar feed-in tariff. The difference needs to be by a proportion greater than the amount of evening energy saved compared to the solar PV used.

Using forecasting of both AC consumption and solar export to optimise SPC/H significantly improves SPC/H the ability to match the two, that is it improves efficiency. SPC/H efficiency using perfect forecasting was shown to be twice as efficient when compared with basic forecasting. This impacts the financial viability for consumers because forecasting means the amount of solar power used for SPC/H is only what is helpful, and as much as possible is still fed to the grid to earn a return.

Household savings from SPC/H under current tariffs are modest. Adelaide demonstrated the most savings from SPC/H, using forecasting, and only saved households ~$25/year on average. Tariffs will need to change, and/or customer-based incentives offered to incentivise households to participate in SPC/H.

7.3.1.5 Impact of SPC/H on the grid

It should be noted that a reduction of ~40% in peak AC consumption, as anticipated for Melbourne and Adelaide from SPC, is significant. As evening AC consumption is a major contributor to peak electricity demand during summer, these results show that SPC can potentially significantly reduce peak loads on the electricity grid if utilised properly

7.3.1.6 Impact of SPC/H on CO2 emissions

SPC can potentially significantly reduce peak electricity demand, particularly in Adelaide and Melbourne; however, SPC/H increases energy consumption and potentially CO2 emissions if excess solar export used for SPC/H would otherwise have been used elsewhere in the network.

8 Research Roadmap

8.1 Research priorities discussion

8.1.1 Program design

Given the understanding of consumer perspectives, a useful SPC/H program strategy would start from the general behavioural demand response programs, (such as those following the ARENA trials, refer section 3.3.3), that are already popular and require less “behind the meter” investment compared to a direct AC control program [23]. Pilot programs can introduce consumers to the benefits and impact of SPC/H and provide access to an understanding of peak events and energy saving activities. While pilot programs may help to overcome the barriers due to a lack of knowledge and awareness of demand response programs and SPC/H in particular, they can also be used to monitor and verify technology settings, thermal inertia, human factors, different levels of transparency for information (such as display of electricity use and live electricity prices) etc. As the consumer benefits and acceptance study of this research suggests, consumer levels of trust may be an issue, and household characteristics would significantly influence consumers’ uptake of SPC/H programs. Consumer education will be needed to overcome lack of understanding of their role in SPC/H.

In designing a suitable SPC/H program there are key considerations to overcome technical limitations, consumer reticence, and the risks and costs for networks of running a program.

- Control methods and strategies –remote control by a distributor, retailer or bundler; provide notifications and prompts for consumers to act; or remote control based on consumer setting preferences and allowing overrides or opt-out?
- Customer incentives – tariffs, rewards, bill credits, sign-on payments, free equipment? If incentives are awarded per event or pro-rata for savings how is load shifting measured or verified?
- Program management including participant recruitment and communications – use of a bundler to manage this; different messaging for different customer types and concerns; management of contracts or agreements; ongoing education and reassurance.

In terms of incentives, an equitable pricing model is needed for behavioural demand response programs where participants are notified for each event and can opt in and out as they wish. Participation in each event needs to be incentivised through bill credit and prizes. If implementing SPC/H as part of a behavioural demand response program, there is a question about how much less the feed-in tariff needs to be compared to the evening tariff to incentivise people to shift their evening AC consumption – as addressed in the scenario modelling of this study. For prosumers, there is an option to reduce solar feed-in tariffs or to increase the evening peak tariff to motivate the use of SPC/H. In the latter case, this increase will need to be met by additional financial incentives to the consumer (e.g. discounts). However, the novelty may run out, then there is a question about how to keep consumers and prosumers actively and continuously responding to peak events and SPC/H notifications in the long term.

For direct AC control, the incentive could be a one-off payment, with the system in place with minimum interruption/engagement with householders. The control devices become part of the built-in service of the house, even when selling or leasing. This incentive approach aligns with the principle of first cost sensitive, or first rebate sensitive in this case, to lock consumers in the program. In the case of Energex/Ergon PeakSmart AC program, participants still have the option to leave the program by disabling the control device, however, it must be done by an electrician or AC installer at the homeowner’s expense.

Any program must ensure that sure that there is a quantifiable value to the electricity network from the effort to implement a SPC/H program, with its additional requirements to improve control technologies, design cost-effective tariffs and incentive programs, messaging with customers, and market penetration. This value should be shared with consumers, especially the non-solar households, to encourage consumers’ uptake, so they would not need to pay more for pre-cooling/heating since network load problems are not their direct concern. This raises the question of the scale of grid management impacts from different approaches. Is excess capacity a sufficient problem to warrant the cost and effort of implementing a program?

An alternative approach that overcomes the issues raised above is to use price signals to incentivise consumers to act without further involvement by the networks or any additional technologies. Differential tariff settings that reduce the value of solar feed-in, and reduce daytime grid supply costs substantially compared to peak supply establish the conditions. An information campaign to advise ways to take advantage of the tariff structure would increase take up. The simplest form of this arrangement would be to remove all supply costs during the excess capacity hours. Free power to everyone for any purpose during this time (say, 11am to 3pm) would attract attention and incur no or few administrative costs. Similarly, no payment is made for solar feed-in during the same period.

Any approach should avoid creating the perception that SPC/H is something that reduces service in any form. It can be promoted variously in positive ways such as guilt-free thermal comfort, cooling luxury, or free cooling.

It could be an option to build on an established demand response program and explicitly target the impact of SPC/H by providing information about when to turn on and turn off air conditioners and monitoring householders' AC consumption. The program could be run as direct control by the network providers, or as a behavioural demand response program where householders voluntarily participate. A comparison could be drawn between the two types of programs with regard to participant uptake, change of load profile and change of evening AC consumption. However, the ideal setting is a direct control program by default while giving the option for householders to opt-in and out remotely at any time. Given the lack of well-established control technologies for household SPC/H, some pilot projects could be set up as a demonstration of the ideal technologies in purposely built demonstration houses.

8.1.2 Thermal comfort

For a thorough understanding of effective SPC/H, thermal comfort needs to be considered in terms of the residual temperature at the time the occupants return home. Consideration needs to be given to ensuring the home is not over-cooled or over-heated, and the consequences if it were. Further research on this is required.

8.1.3 Data

A more detailed analysis of future scenarios requires additional data, such as energy usage patterns for all major Australian cities and a solar database of PV and non-PV households. It would also be useful to be able to estimate the existing house thermal mass conditions more accurately for a simulation of future housing stock and therefore future scenarios of SPC/H.

The current coefficient of performance (COP) of HVAC system is calculated on standardised/average conditions. Information on COP under different weather conditions for both heating and cooling would allow us to operate time of day through a control system and to reduce energy consumption further and maximise the quantifiable benefits of SPC/H.

Demonstration projects could be implemented to validate the predictive modelling and measure the impact for SPC/SPH in the real world. These projects should not only test well-designed new development, but also test the potential for SPC/SPH in old houses where energy use and time of use are not currently metered and/or rooftop PVs are not installed. Data collected from demonstration projects could be compared with historical data at the network level in terms of peak demand and solar capacity with normalisation for the severity of the season.

Real household data collected from demonstration projects could reveal human factors that are out of the scope of the predictive modelling in terms of occupancy patterns, occupant behaviour and comfort parameters. It could help to validate the scale of benefits and other general findings from the model, and inform the predictive modelling for more detailed analysis regarding modelling for different climate zones, COPs of HVAC system, tariff structure and incentives etc.

8.1.4 Load management and verification

Regarding the market readiness for DRED application, on the one hand Energy QLD's successful program has achieved up to 150MW of diversified AC load under control during peak demand events. On the other hand, electricity distributors such as Ausgrid have raised concern over the uncertainty of individual households' response to the frequency signals when they are deployed, and hence the overall aggregated load settlement for the network. If an air conditioner was not on when the signal went out, there would be no flexible demand obtained from it. There is a question as to whether the networks have to know every individual household's AC consumption. The network providers generally take a weighted mean/average maximum demand and design everything around averages for demand load management. In the case of remotely controlled loads, it could be assumed that participating air conditioners would collectively behave at a certain level of performance, rather than monitoring individual AC consumption for a general demand response program. Performance reviews by networks of their programs may help to understand the nuances of individual household actions in order to improve the program effectiveness.

For SPC/H, the design of business models to communicate automated actions needs to take account of behavioural factors. Householders might prefer to be notified prior to each 'on' event or prompted to turn on the AC. They could be incentivised after each event with bill credits and/or prizes. In this case, it is necessary to monitor individual AC consumption to ensure the effectiveness of incentives. The question then is how much control a householder is given, versus the benefits an automated system can create, in particular where installation of a dedicated billing meter may be required to monitor individual AC consumption under a targeted incentivised program.

The Australian standard AS/NZS 4755 does not allow air conditioners to have remote turning on capacity, for loads and commands to be verified, or for consumer override, among other limitations for SPC/H. A change to the standard is suggested so that DRED devices and DRED enabled equipment would be available to facilitate SPC/H, or an alternative international standard be adopted.

Further research is needed to investigate technical feasibility, while demonstration projects could be set up to measure and verify the least capacity that is required to cost-effectively implement SPC/H with a level of billing certainty.

8.2 Research Roadmap

The RACE H1 Residential Solar Pre-cooling and Pre-heating Research Roadmap is presented in Table 8-1 on the following pages. The matrix structure helps to identify where and when the effort is needed.

The columns are indicative of the expected time frame for activities: short, medium, and long term.

The rows show the priority areas of activity, with sub-categories:

- Knowledge – effectiveness, housing, and financial
- Industry – technology, network impacts and market development
- Customer – Program design and customer incentives, and data ownership, use and privacy

Colour coding has been used to indicate the type of activity:

- Information – includes data, modelling, pilot and trial projects to gather data
- Incentives, pricing – includes determining possibilities, and program design and pilots
- Regulatory reform, policy and standards
- Facilitation – supporting implementation, including demonstration projects.

In summary, the key priorities of the Research Roadmap including modelling, pilot programs, and demonstration projects, should address the following:

Design of a SPC/H program

- What are the key considerations to overcome technical limitations, consumer reticence, and the risks and costs for networks of running a program? Determine:
    - Control methods and strategies

    - Customer incentives and messaging
    - Program management including participant recruitment and communications
- What is an equitable pricing model?
- Quantify the value to the electricity network
- Quantify the grid management impacts

Impact of SPC/H on thermal comfort

Collect/create additional data such as

- Residential energy usage patterns for all Australian climate zones for PV and non-PV homes
- Existing house thermal mass conditions
- Information on HVAC COP under different weather conditions

Load management and verification

- If, and how to remotely verify load response
- Appropriate standard and capabilities for control devices

Table 8-1. Research Roadmap

Research priorities Information Incentives Policy & standards Facilitation		**Short**	**Medium**	**Long**
Knowledge	**Effectiveness**	Conduct an hourly analysis on how SPC/H impacts the residential load profile. This will reveal the effectiveness of SPC/H at different times of the day		
		Model different SPC/H strategies that have been implemented in either demonstration projects or at a larger consumer scale and validate using real data.		
		Deeper modelling on the effect of SPC/H control/forecasting strategy sophistication on SPC/H efficiency, energy consumption, peak solar export reduction and peak load reduction	Trial project to test the effect of SPC/H control/forecasting strategy sophistication on SPC/H efficiency, energy consumption, peak solar export reduction and peak load reduction	
		Deeper modelling to include comfort parameters, different climate zones, more representative occupancy usage profiles, broader range of household types (included non-PV households)	Develop a consistent method/process to evaluate the benefits of SPC/H to both customers and to the network, examining all value streams.	
		Survey existing pilot/demonstration projects implementing SPC/H, including their findings. Disseminate findings to scientific community and industry		
		Model solar generation and A-C consumption data from a larger data set. The ~400 homes from the Solar Analytics used for this study may not be representative of the consumption behaviour for the majority of homes in Australia	Model how consumption behaviour impacts on SPC/H efficiency, energy consumption, peak solar export reduction and peak load reduction	
	Housing	Analyse the influence of the characteristics of the home (underlying a star rating) - thermal mass and building materials - on SPC/H efficacy	A sensitivity study utilising energy modelling to determine the impacts (positive or negative) of building construction and/or operation (including occupancy profiles)	Training and skills development for construction trades

Research priorities 🟩 Information 🟨 Incentives 🟧 Policy & standards 🟦 Facilitation		**Short**	**Medium**	**Long**
	Housing (cont.)	🟩 Modelling/trial project to determine what upgrade (retrofit) work should be undertaken to improve homes to a suitable standard for SPC/H		🟦 SPC/H suitable display homes with displays of energy data for skills development of construction trades/builders/designer and education for public
		🟩 Determine the number and thermal rating (quality) of homes in each climate zone across Australia's housing stock (with and without PVs; size of PV installations)		🟧 Development of minimum construction quality/material guidelines for SPC/H. Recommend changes to building performance and verification standards
		🟦 Determine if a home's thermal rating can be determined by its AC energy consumption. Validate the analysis against a nationalised RES rating	🟧 Investigate upgrading energy rating tools to take into account the amount of electricity imported from the grid, so that SC/H homes are not unfairly penalised for using more energy to reduce peak load..	🟧 Updated energy ratings tools (e.g. NatHERS) to account for SPH/C savings
				🟦 Methods of assessing homes for upgrades/rating homes, training for assessors, business development support. development of accreditation scheme for SPC/H installers and assessors (including ratings assessments)
	Financial	🟩 Undertake a thorough cost benefit analysis of residential load smoothing due to SPC/H for networks. The expected savings to network operational and capital costs could inform the pricing structure used to incentivise households to participate in SPC/H. This study is to include a variety of tariff structures and network to customer incentive payments.	🟧 NSW Peak Demand Reduction Scheme and SA REPS provide rewards for demand management actions. RACE could develop methodologies for deeming peak demand reductions from solar precooling/ preheating	
Industry	**Technology development**	🟩 Investigate/identify barriers to SPC/H technology and service development. Especially the impact of poor/inappropriate/non-existent equipment standards	🟨 Investigate/identify initiatives to incentivise SPC/H technology and service development	

Research priorities 🟩 Information 🟨 Incentives 🟧 Policy & standards 🟦 Facilitation		**Short**	**Medium**	**Long**
	Technology development (cont.)	🟩 Investigate the benefits and development possibilities of more sophisticated control technologies (smart thermostats, APIs) to control diversion of power from solar to air conditioners compared with DRM/DREDs (AS4755)	🟧 Develop, with broad industry consultation, device level standards, communication standards, and APIs. for equipment associated with SPC/H.	
			🟨 Support development of control mechanisms identified in the earlier investigation	
			🟧 Investigate benefits to improving control resolution/sophistication of DRED control signals (AS 4755).	
		🟩 Measurement and monitoring of the COPs of different household HVAC systems under different outside conditions and indoor temperature setpoints. This will better inform the development of optimal control strategies to reduce energy consumption and improve indoor thermal comfort.	🟩 Trial project to test/demonstrate new technologies and control mechanisms that may facilitate solar pre-cooling & pre-heating (e.g. Paladin control)	🟦 Develop and construct a display home accessible to public and industry that demonstrates the different technologies and control mechanisms. This may be integrated with the SPC/H display home proposed above
	Network impacts	🟩 Conduct power flow analysis to determine the impact of the change in residential load profile on voltage levels and mean and peak load flows through transformers and cabling. Determine how problematic excess capacity really is. This will require access to accurate load flow data (substation level) and LV feeder models from networks	🟧 Develop policies or regulation around SPC/H as a network service that can be purchased from customer by networks.	
	Market development	🟨 Improve the process for calculating the change in consumption for a household that is due to program participation. Improvement refers to the method of baseline calculation (improve on CAISO 10-by-10) and method of measurement, which may need a dedicated (A-C for example) circuit, not just for the household	🟧 Development of and support for new business models offering household bundling (aggregators) for SPC/H participation	

Research priorities Information Incentives Policy & standards Facilitation		**Short**	**Medium**	**Long**
Customer	**Program design/customer incentives**	Behavioural studies (control strategies, incentives, benefits) to better understand consumer motivations	Develop customer engagement and participation strategies including feedback of temperatures and energy costs to consumers	Program implementation: explaining the benefits for consumers; bigger picture about benefits; gaining trust regarding changing tariffs and remote control
			Trials to test most effective consumer engagement messaging, awareness campaigns, and event prompts for action.	Knowledge sharing – Development of guides, other publications
		Trials or models to understand customer consumption behaviour, and how it varies according to climate, seasons, temperature, build type (weight and star rating) etc.	Trial project on thermal comfort preferences vs energy consumption and temperatures (i.e. rebound effect)	
			Trial project to engage customers to test incentive options (tariff alternatives; payments etc.)	
			Assess options for consumer and network controls e.g. transparency of information on impacts and benefits, division of responsibility, opt-out, manual over-ride	
			Trial project to engage customers over a year to prove and quantify the benefits of pre-cooling and heating; feedback from customers on their perceived thermal comfort; data collection on temperature and peak energy consumption. Obtain data to validate computational models (particularly the assumptions used).	
	Data ownership, use and privacy		Data policies and regulations need to be developed regarding data ownership; and customer data protection	

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Appendix A Scenario modelling details

A.1 Method

The aim of this work is to determine how much SPC/H reduces evening AC consumption. A simple overview of this process, also illustrated in Figure 5-6, is as follows:

1. Divert excess solar energy to the A-C unit, this constitutes an SPC/H event. This energy is then used to cool or heat the home
2. Decay the cooling/heating energy over time until the evening
3. Deduct the residual cooling/heating energy from evening A-C consumption

To perform the above process, it is necessary to know the cooling/heating energy decay rate following an SPC/H event. Analysis of the AccuRate data revealed two important relationships which were used to derive the cooling/heating energy decay rate.

The first is the linear relationship between the A-C cooling/heating energy (E_{AC}) injected into the home during an SPC/H event and the change in indoor temperature which occurs due to the injection of cooling/heating energy. The change in indoor temperature is represented by the difference between T_{SP} and T_{FR}. Where T_{SP} is the indoor temperature following an SPC/H event and T_{FR} is the indoor temperature in the case where no SPC/H event occurred, or free running temperature. For ease of reference, this difference in temperature between $T_{FR} – T_{SP}$ is termed as T_d. This first relationship can be defined by equation (A1) below:

$$T_d = aE_{AC} \tag{A1}$$

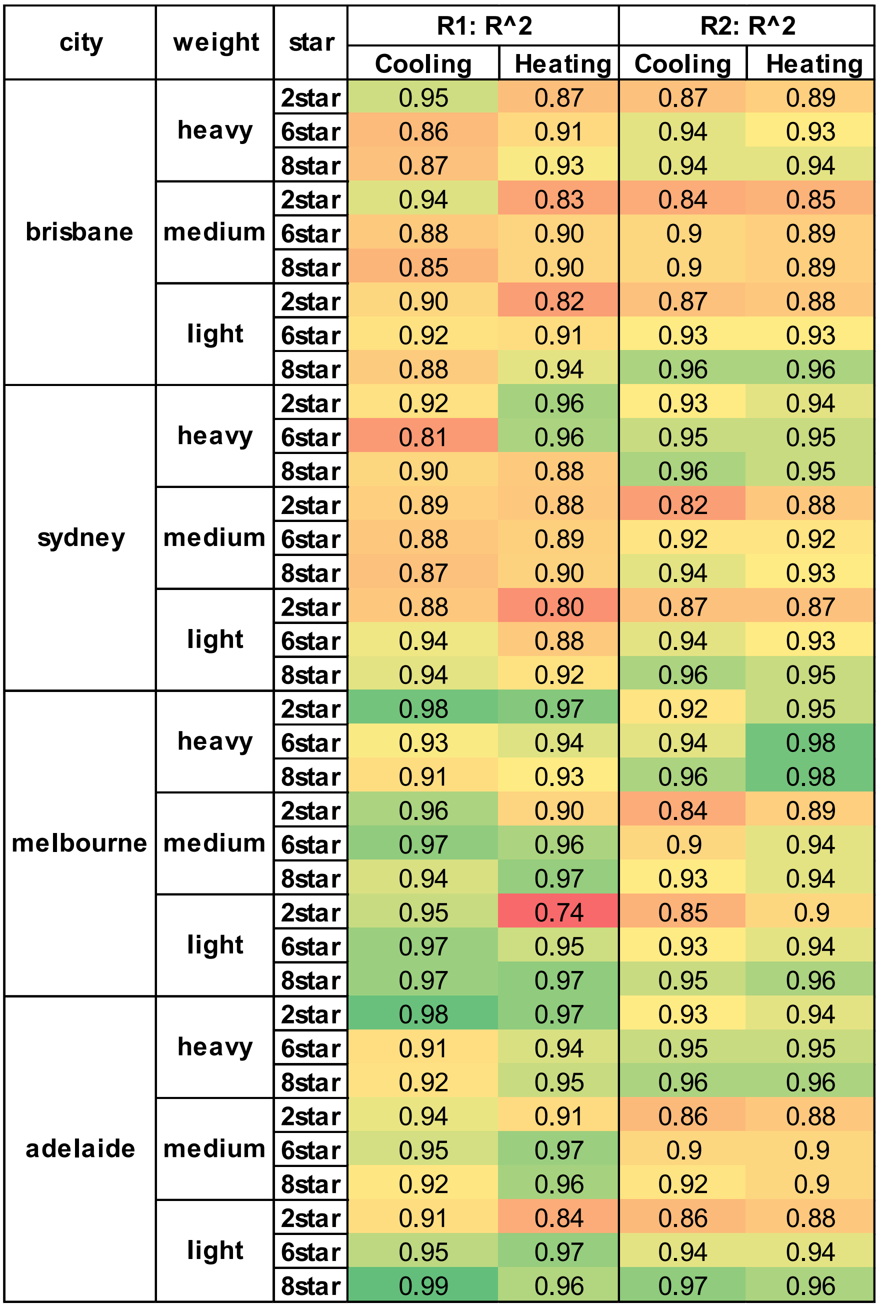
The second relationship is that the rate of convergence, or decay, between the two temperatures T_{SP} and T_{FR}, or T_d, following an SPC/H event is constant. This relationship can be written as a discrete time series:

$$T_d[h] = T_d[0]d^h \tag{A2}$$

Where h = hour and d is the decay rate. Substituting Equation A1 into Equation A2 and dividing through by a gives:

$$E_{AC}[h] = E_{AC}[0]d^h \tag{A3}$$

Where $E_{AC}[0]$ is the A-C cooling energy injected into the home, during an SPC/H event, at $h = 0$. Equation A3 can therefore be used to calculate the decay in cooling/heating energy following an SPC/H event. Table A. 1 below gives the R^2 values for the two relationships (labelled as R1 and R2). The results indicate the strength of correlation, with 0.74 the lowest recorded R^2 value.



city	weight	star	R1: R^2		R2: R^2	
			Cooling	Heating	Cooling	Heating
brisbane	heavy	2star	0.95	0.87	0.87	0.89
		6star	0.86	0.91	0.94	0.93
		8star	0.87	0.93	0.94	0.94
	medium	2star	0.94	0.83	0.84	0.85
		6star	0.88	0.90	0.9	0.89
		8star	0.85	0.90	0.9	0.89
	light	2star	0.90	0.82	0.87	0.88
		6star	0.92	0.91	0.93	0.93
		8star	0.88	0.94	0.96	0.96
sydney	heavy	2star	0.92	0.96	0.93	0.94
		6star	0.81	0.96	0.95	0.95
		8star	0.90	0.88	0.96	0.95
	medium	2star	0.89	0.88	0.82	0.88
		6star	0.88	0.89	0.92	0.92
		8star	0.87	0.90	0.94	0.93
	light	2star	0.88	0.80	0.87	0.87
		6star	0.94	0.88	0.94	0.93
		8star	0.94	0.92	0.96	0.95
melbourne	heavy	2star	0.98	0.97	0.92	0.95
		6star	0.93	0.94	0.94	0.98
		8star	0.91	0.93	0.96	0.98
	medium	2star	0.96	0.90	0.84	0.89
		6star	0.97	0.96	0.9	0.94
		8star	0.94	0.97	0.93	0.94
	light	2star	0.95	0.74	0.85	0.9
		6star	0.97	0.95	0.93	0.94
		8star	0.97	0.97	0.95	0.96
adelaide	heavy	2star	0.98	0.97	0.93	0.94
		6star	0.91	0.94	0.95	0.95
		8star	0.92	0.95	0.96	0.96
	medium	2star	0.94	0.91	0.86	0.88
		6star	0.95	0.97	0.9	0.9
		8star	0.92	0.96	0.92	0.9
	light	2star	0.91	0.84	0.86	0.88
		6star	0.95	0.97	0.94	0.94
		8star	0.99	0.96	0.97	0.96

Table A.1. R^2 results for both relationship R1 and R2 for cooling and heating. R1 represents the correlation between cooling energy injected into a room and change in indoor temperature, T_{FR}-T_{SP}, or T_d. R2 represents the strength of correlation that the rate of convergence, or decay, between the two temperatures T_{SP} and T_{FR}, or T_d, following an SPC/H event is constant.

Figure A.1 below gives an illustration of the SPC/H process and presented to assist explanation of the above two relationships and the cooling/heating energy decay rate is derived. At hour 15, cooling energy ($aE_{AC}[0]$) is injected into the home, creating a difference in temperature between T_{SP} and T_{FR}, which were equal prior. The convergence of the two temperatures following hour 15 is traced by the two green dashed arrows. This convergence represents the decay in cooling energy injected into the home at hour 15, calculated by equation A3.

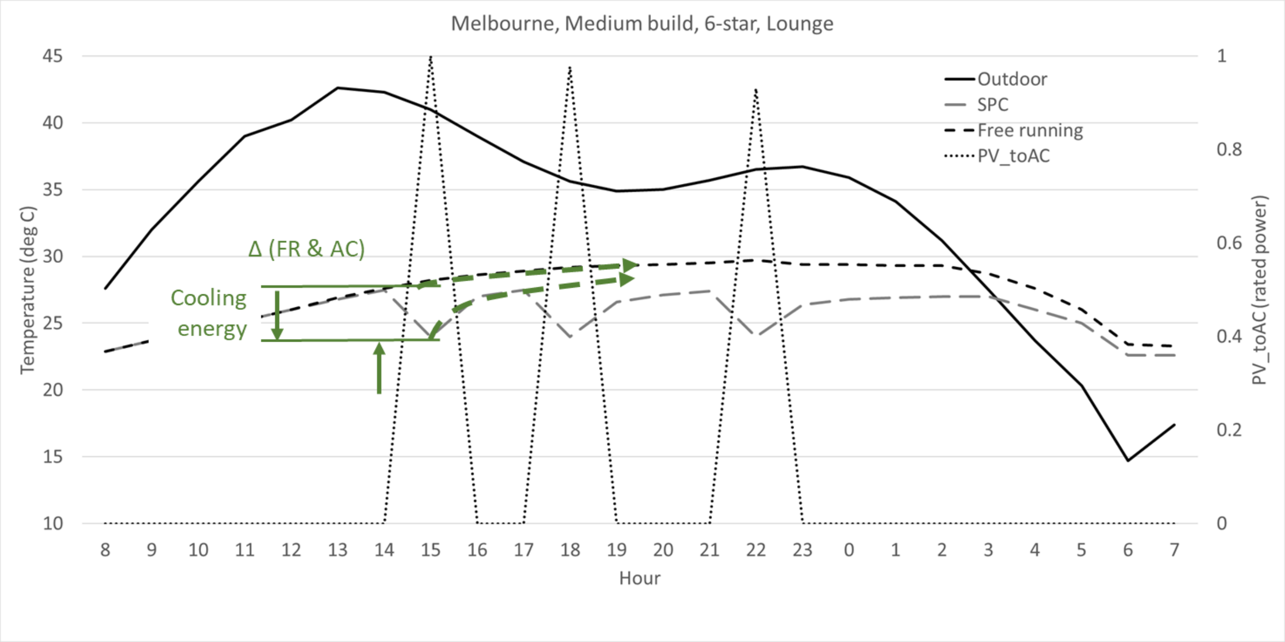


Figure A.1 Illustration of the SPC/H process and the variables involved. aEAC[0] is indicated to show where the injection of cooling energy at hour 15 (the SPC/H event) creates the difference between T_{SP} and T_{FR}. The green dashed arrows indicate the convergence between T_{SP} and T_{FR} following the SPC/H event, which represents the decay in cooling energy.

A.2 Decay rates

Decay rates are given in the Table A 1 below.

Build weight	Star rating	Decay rate % (kWh/h)							
		Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating
		Brisbane		Sydney		Melbourne		Adelaide	
heavy	**2**	13	11	7	6	8	5	7	6
	6	6	7	5	5	6	2	5	5
	8	6	6	4	5	4	2	4	4
Average		8.17		5.33		4.50		5.17	
medium	**2**	16	15	18	12	16	11	14	12
	6	10	11	8	8	10	6	10	10
	8	10	11	6	7	7	6	8	10
Average		12.17		9.83		9.33		10.67	
light	**2**	13	12	13	13	15	10	14	12
	6	7	7	6	7	7	6	6	6
	8	4	4	4	5	5	4	3	4
Average		7.83		8.00		7.83		7.50	

Table A 1. Cooling and heating decay rates for each city, build weight and star rating.

A.3 Financial viability of SPC/H

This section explains the relationship between SPC/H efficiency and tariffs, and how it determines the financial viability of SPC/H. The formula below can be used to calculate the savings from SPC/H

$$Savings = AC\_eve\_red \times t_{eve} - PV\_AC \times t_{sFiT} \tag{A1}$$

Where t_{sFiT} is the solar feed-in tariff, t_{eve} is the evening consumption tariff, AC_{red} is the reduction in evening AC consumption (kWh) and PV_{toAC} is the solar energy diverted to the A-C unit (kWh). As stated earlier, the ratio of AC_{red}/ PV_{toAC} can be interpreted as the efficiency of SPC/H. For a household to save money from participating in SPC/H, the RHS of equation (A1) needs to be greater than zero:

$$AC_{red} \times t_{eve} - PV_{toAC} \times t_{sFiT} \ > \ 0 \tag{A2}$$

Re-arranging equation (A2) gives

$$AC_{red}/PV_{toAC} > t_{sFiT}/t_{eve} \tag{A3}$$

Therefore, for a household to save money from SPC/H, AC_{red}/PV_{toAC}, *or SPC/H efficiency, must be greater than* t_{sFiT}/t_{eve}. A more generous t_{sFiT} (relative to t_{eve}) will therefore make it more difficult for SPC/H to be financially viable.

A.4 SPC/H efficiencies

Table A 2 gives SPC/H efficiency across households in each city, for each build type, and forecasting strategies F1 and F2. To help explain the relationship between t_{sFiT}/t_{eve} and SPC/H efficiency and how it impacts on household savings; for solar pre-cooling to be financially viable for a Light, 2-star home located in Brisbane with no forecasting (F1), t_{eve} needs to be ~8 (100/12.48) times larger than t_{sFiT}, but only ~3 (100/31.35) times larger with perfect forecasting (F2).

Looking at the colour coded cells from Table A 2, a key difference in SPC/H efficiency is due to the type of forecast, which indicates that for F1, the amount of solar energy diverted to the A-C unit during the day for SPC/H is often far more than is necessary, resulting in the home being cooled or heated outside of thermal comfort limits (according to historical A-C consumption measurements). Homes in Brisbane also have slightly lower SPC/H efficiencies, likely due to the higher decay rates compared to the other cities.

Forecast	Build weight	Cooling/Heating	Star rating	SPC/H efficiency (%)			
				Brisbane	Sydney	Melbourne	Adelaide
F1	light	cooling	2	12.48	18.59	17.42	17.39
			6	14.16	21.55	19.69	19.38
			8	15.64	21.93	20.39	20.12
		heating	2	17.38	26.25	30.44	26.74
			6	19.84	35.09	33.50	32.73
			8	21.83	38.61	35.15	35.15
	Average			16.29	25.18	24.15	23.51
	medium	cooling	2	11.13	16.18	17.20	17.39
			6	13.11	20.37	18.66	18.45
			8	13.11	21.55	19.69	18.94
		heating	2	15.80	27.70	29.33	26.74
			6	17.83	33.44	33.50	28.65
			8	17.83	35.09	33.50	28.65
	Average			14.36	23.83	23.41	22.08
	heavy	cooling	2	12.48	21.10	19.34	19.16
			6	14.66	21.74	20.04	19.57
			8	14.66	21.93	20.62	19.76
		heating	2	17.83	36.76	34.31	32.73
			6	19.84	38.61	37.04	33.96
			8	20.45	38.61	37.04	35.15
	Average			16.13	27.52	25.72	24.76
F2	light	cooling	2	31.35	36.90	42.19	44.05
			6	40.73	47.17	54.79	55.25
			8	45.77	51.55	59.52	59.17
		heating	2	42.55	37.88	46.08	42.46
			6	59.35	54.64	60.42	60.06
			8	72.99	62.89	68.49	67.34
	Average			45.33	46.77	53.76	53.22
	medium	cooling	2	27.36	29.50	40.65	44.05
			6	35.59	43.29	49.38	48.78
			8	35.59	47.17	54.79	52.63
		heating	2	34.19	40.00	43.38	42.46
			6	45.66	51.28	60.42	48.08
			8	45.66	54.64	60.42	48.08
	Average			36.19	42.55	50.31	47.11
	heavy	cooling	2	31.35	44.64	52.63	54.05
			6	42.28	50.00	57.31	56.50
			8	42.28	51.55	61.16	58.14
		heating	2	45.66	58.48	64.72	60.06
			6	59.35	62.89	75.47	63.29
			8	63.29	62.89	75.47	67.34
	Average			44.86	54.20	63.32	59.58

Table A 2. Mean SPC/H efficiency across households in each city, for each build type, and forecasting strategies F1 and F2

A.5 Load profile changes

Table A 3 below gives the results for all three evening AC consumption metrics for all star ratings, construction types and cities. An examination of the colour coded cells gives the following insights:

- *Reduction in evening AC consumption per household (kWh).* For this metric, Adelaide demonstrates the highest reduction in evening AC consumption (1.57 kWh). Brisbane is also high for SPH. Sydney clearly has the lowest reduction for SPC (1.07 kWh) and Melbourne the lowest for SPH (0.87 kWh)
- *Reduction in evening AC consumption % per household (kWh).* Brisbane demonstrates the highest reduction in evening AC consumption % (kWh) for SPH (65%) while Melbourne (40%) and Adelaide (39%) both have high reductions for SPC. Sydney again has the lowest reduction for SPC (16%) and Melbourne the lowest for SPH (13%).
- *Reduction in peak evening AC consumption % per household (kW).* Brisbane demonstrates the highest reduction in peak evening AC consumption % (kW) for SPH (49%) while Melbourne (40%) and Adelaide (44%) both have high reductions for SPC. Sydney has the lowest reduction for SPC (19%) and Melbourne the lowest for SPH (7%).

Build weight	Cooling/ Heating	Star rating	Median reduction in evening AC consumption (kWh/household)				Reduction in evening AC consumption % (kWh)				Reduction in peak evening AC consumption % (kW)			
			Brisbane	Sydney	Melbourne	Adelaide	Brisbane	Sydney	Melbourne	Adelaide	Brisbane	Sydney	Melbourne	Adelaide
Light	Cooling	2	1.19	0.92	1.39	1.56	17	14	36	36.5	20	17	37	41.5
		6	1.44	1.09	1.55	1.73	21	17	41	40	23	20	41	46
		8	1.57	1.16	1.60	1.80	23	18	42	41.5	25	20.5	43	47
	Average		1.40	1.06	1.51	1.70	20.33	16.33	39.67	39.33	22.67	19.17	40.33	44.83
	Heating	2	1.37	0.82	0.75	1.21	60	17	11	21	43	13	6	14
		6	1.62	1.12	0.86	1.54	70	23	13	27	54	20	7	20
		8	1.73	1.24	0.92	1.67	75	25	14	29	60	22	8	22
	Average		1.58	1.06	0.84	1.47	68.17	21.67	12.67	25.50	52.17	18.17	7.00	18.67
Medium	Cooling	2	1.08	0.79	1.37	1.56	16	12	35	37	18	15	37	42
		6	1.31	1.04	1.49	1.64	19	16	40	39	22	19	40	43
		8	1.31	1.09	1.55	1.68	19	17	41	39	22	20	41	45
	Average		1.23	0.97	1.47	1.62	18.00	15.00	38.50	38.00	20.33	18.00	39.17	43.00
	Heating	2	1.25	0.87	0.72	1.21	55	18	11	21	38	15	5	14
		6	1.40	1.07	0.86	1.30	62	22	13	23	46	19	7	16
		8	1.40	1.12	0.86	1.30	62	23	13	23	46	20	7	16
	Average		1.35	1.02	0.81	1.27	59.17	21.00	12.17	22.33	42.83	17.83	6.33	15.00
Heavy	Cooling	2	1.19	1.06	1.53	1.71	17	17	41	40	20	20	40	46
		6	1.48	1.13	1.58	1.76	22	18	42	41	24	21	42	47
		8	1.48	1.16	1.61	1.78	22	18	43	41	24	21	43	47
	Average		1.39	1.12	1.57	1.75	20.00	17.50	42.00	40.33	22.67	20.33	41.67	46.33
	Heating	2	1.40	1.18	0.89	1.54	62	24	14	27	46	21	8	20
		6	1.62	1.24	0.98	1.60	70	25	15	28	54	22	9	21
		8	1.68	1.24	0.98	1.67	72	25	15	29	57	22	9	22
	Average		1.57	1.22	0.95	1.60	68	25	15	28	52	21	8	21

Table A 3. Change in load profile metrics for reduction in evening AC consumption

Table A 4 below gives the results for three metrics related to reduction in solar export. An examination of the colour coded cells gives the following insights:

- *Median reduction in solar export per household (kWh).* For this metric, Brisbane demonstrates the highest reduction in solar export (3.52 kWh) for both solar pre-cooling and heating, whereas Melbourne demonstrates the lowest reduction for both (2.39 kWh)
- *Reduction in solar export % per household (kWh).* Sydney demonstrates the highest reduction in solar export % (kWh) for SPC/H (62%). Brisbane demonstrates the lowest reduction for SPH (36%) and Melbourne (Adelaide only slightly lower) the lowest for SPC (36%).
- *Reduction in peak solar export % per household (kW).* Sydney (68.5%) demonstrates the highest reduction in peak solar export % (kW) for both SPC and SPH. Brisbane demonstrates the lowest reduction for solar pre-heating (54%) while Adelaide (Melbourne only slightly lower) the lowest for solar pre-cooling (43%)

Build weight	Cooling/ Heating	Star rating	F2: Median reduction in solar export (kWh/household)				F2: Reduction in solar export % (kWh)				F2: Reduction in peak solar export % (kW)			
			Brisbane	Sydney	Melbourne	Adelaide	Brisbane	Sydney	Melbourne	Adelaide	Brisbane	Sydney	Melbourne	Adelaide
Light	Cooling	2	4.07	3.31	3.21	3.63	50	57	39	39.5	58	60	48.5	45
		6	3.81	3.08	2.86	3.41	47.5	53	35	37	54.5	57	45	41.5
		8	3.72	3.02	2.80	3.34	46	52	34	35.5	52	55.5	44	41
	Average		3.87	3.14	2.96	3.46	47.83	54.00	36.00	37.33	54.83	57.50	45.83	42.50
	Heating	2	3.40	2.61	1.94	3.16	38.5	75.5	67	66	57.5	84	80	73
		6	2.87	2.46	1.85	2.90	33.5	69.5	65	62	52.5	78.5	75.5	68
		8	2.57	2.39	1.81	2.82	30.5	68	63.5	60	47.5	77.5	74	66
	Average		2.95	2.48	1.87	2.96	34.17	71.00	65.17	62.67	52.50	80.00	76.50	69.00
Medium	Cooling	2	4.22	3.49	3.24	3.63	51	59	40	39.5	59	63	49.5	45
		6	3.95	3.14	2.99	3.51	49	54	37	38.5	55	58	46.5	43
		8	3.95	3.08	2.86	3.47	49	53	35	37.5	55	57	45	42
	Average		4.04	3.24	3.03	3.54	49.67	55.33	37.33	38.50	56.33	59.33	47.00	43.33
	Heating	2	3.69	2.59	1.97	3.16	42	74.5	68	66	61	83.5	81	73
		6	3.28	2.49	1.85	3.08	37.5	71	65	64	56.5	79	75.5	71
		8	3.28	2.46	1.85	3.08	37.5	69.5	65	64	56.5	78.5	75.5	71
	Average		3.42	2.51	1.89	3.11	39.00	71.67	66.00	64.67	58.00	80.33	77.33	71.67
Heavy	Cooling	2	4.07	3.12	2.91	3.44	50	54	35.5	37	58	57	46	42
		6	3.79	3.05	2.83	3.39	47	53	34	36	53.5	56	45	41
		8	3.79	3.02	2.76	3.37	47	52	33.5	35.5	53.5	55.5	44	41
	Average		3.88	3.06	2.84	3.40	48.00	53.00	34.33	36.17	55.00	56.17	45.00	41.33
	Heating	2	3.28	2.43	1.83	2.90	37.5	69	64	62	56.5	78	75	68
		6	2.87	2.39	1.75	2.86	33.5	68	62	61	52.5	77.5	73	67
		8	2.76	2.39	1.75	2.82	32.5	68	62	60	51.5	77.5	73	66
	Average		2.97	2.40	1.77	2.86	34.50	68.33	62.67	61.00	53.50	77.67	73.67	67.00

Table A 4. Change in load profile metrics for reduction in solar export for F2

A.6 Housing stock allocation tables

Year	2021	City	Brisbane			
Age	**Age % allocation**	**Weight**	**Weight % allocation**	**Star rating**	**Star rating % allocation**	**Final % allocation**
Old	72	Light	43	2	100	**31.0**
				6	0	**0.0**
				8	0	**0.0**
		Medium	48	2	100	**34.6**
				6	0	**0.0**
				8	0	**0.0**
		Heavy	9	2	100	**6.5**
				6	0	**0.0**
				8	0	**0.0**
New	28	Light	27	2	0	**0.0**
				6	91	**6.9**
				8	9	**0.7**
		Medium	73	2	0	**0.0**
				6	91	**18.6**
				8	9	**1.8**
		Heavy	0	2	0	**0.0**
				6	91	**0.0**
				8	9	**0.0**
Sum	**100**					**100**

Table A 5. Housing allocation for Brisbane for 2021, non-zero percentages highlighted in green

Year	2030 (BaU)	City	Brisbane			
Age	**Age % allocation**	**Weight**	**Weight % allocation**	**Star rating**	**Star rating % allocation**	**Final % allocation**
Old	58	Light	43	2	100	**24.9**
				6	0	**0.0**
				8	0	**0.0**
		Medium	48	2	100	**27.8**
				6	0	**0.0**
				8	0	**0.0**
		Heavy	9	2	100	**5.2**
				6	0	**0.0**
				8	0	**0.0**
New	42	Light	27	2	0	**0.0**
				6	75	**8.5**
				8	25	**2.8**
		Medium	73	2	0	**0.0**
				6	75	**23.0**
				8	25	**7.7**
		Heavy	0	2	0	**0.0**
				6	75	**0.0**
				8	25	**0.0**
Sum	**100**					**100**

Table A 6. Housing allocation for Brisbane for 2030 BaU, non-zero percentages highlighted in green

Year	2021	City	Sydney			
Age	**Age % allocation**	**Weight**	**Weight % allocation**	**Star rating**	**Star rating % allocation**	**Final % allocation**
Old	72	Light	38	2	100	**27.4**
				6	0	**0.0**
				8	0	**0.0**
		Medium	43	2	100	**31.0**
				6	0	**0.0**
				8	0	**0.0**
		Heavy	19	2	100	**13.7**
				6	0	**0.0**
				8	0	**0.0**
New	28	Light	18	2	0	**0.0**
				6	91	**4.6**
				8	9	**0.5**
		Medium	78	2	0	**0.0**
				6	91	**19.9**
				8	9	**2.0**
		Heavy	4	2	0	**0.0**
				6	91	**1.0**
				8	9	**0.1**
Sum	**100**					**100**

Table A 7. Housing allocation for Sydney for 2021, non-zero percentages highlighted in green

Year	2030 (BaU)	City	Sydney			
Age	**Age % allocation**	**Weight**	**Weight % allocation**	**Star rating**	**Star rating % allocation**	**Final % allocation**
Old	58	Light	38	2	100	**22.0**
				6	0	**0.0**
				8	0	**0.0**
		Medium	43	2	100	**24.9**
				6	0	**0.0**
				8	0	**0.0**
		Heavy	19	2	100	**11.0**
				6	0	**0.0**
				8	0	**0.0**
New	42	Light	18	2	0	**0.0**
				6	91	**6.9**
				8	9	**0.7**
		Medium	78	2	0	**0.0**
				6	91	**29.8**
				8	9	**2.9**
		Heavy	4	2	0	**0.0**
				6	91	**1.5**
				8	9	**0.2**
Sum	**100**					**100**

Table A 8. Housing allocation for Sydney for 2030 BaU, non-zero percentages highlighted in green

Year	2021	City	Melbourne			
Age	Age % allocation	Weight	Weight % allocation	Star rating	Star rating % allocation	Final % allocation
Old	72	Light	19	2	100	13.7
				6	0	0.0
				8	0	0.0
		Medium	78	2	100	56.2
				6	0	0.0
				8	0	0.0
		Heavy	3	2	100	2.2
				6	0	0.0
				8	0	0.0
New	28	Light	5	2	0	0.0
				6	96	1.3
				8	4	0.1
		Medium	95	2	0	0.0
				6	96	25.5
				8	4	1.1
		Heavy	0	2	0	0.0
				6	96	0.0
				8	4	0.0
Sum	100					100

Table A 9. Housing allocation for Melbourne for 2021, non-zero percentages highlighted in green

Year	2030 (BaU)	City	Melbourne			
Age	Age % allocation	Weight	Weight % allocation	Star rating	Star rating % allocation	Final % allocation
Old	58	Light	19	2	100	11.0
				6	0	0.0
				8	0	0.0
		Medium	78	2	100	45.2
				6	0	0.0
				8	0	0.0
		Heavy	3	2	100	1.7
				6	0	0.0
				8	0	0.0
New	42	Light	5	2	0	0.0
				6	96	2.0
				8	4	0.1
		Medium	95	2	0	0.0
				6	96	38.3
				8	4	1.6
		Heavy	0	2	0	0.0
				6	96	0.0
				8	4	0.0
Sum	100					100

Table A 10. Housing allocation for Melbourne for 2030 BaU, non-zero percentages highlighted in green

Year	**2021**	**City**	**Adelaide**			
Age	**Age % allocation**	**Weight**	**Weight % allocation**	**Star rating**	**Star rating % allocation**	**Final % allocation**
Old	72	Light	14	2	100	**10.1**
				6	0	**0.0**
				8	0	**0.0**
		Medium	66	2	100	**47.5**
				6	0	**0.0**
				8	0	**0.0**
		Heavy	20	2	100	**14.4**
				6	0	**0.0**
				8	0	**0.0**
New	28	Light	8	2	0	**0.0**
				6	94	**2.1**
				8	6	**0.1**
		Medium	92	2	0	**0.0**
				6	94	**24.2**
				8	6	**1.5**
		Heavy	0	2	0	**0.0**
				6	94	**0.0**
				8	6	**0.0**
Sum	**100**					**100**

Table A 11. Housing allocation for Adelaide for 2021, non-zero percentages highlighted in green

Year	**2030 (BaU)**	**City**	**Adelaide**			
Age	**Age % allocation**	**Weight**	**Weight % allocation**	**Star rating**	**Star rating % allocation**	**Final % allocation**
Old	58	Light	14	2	100	**8.1**
				6	0	**0.0**
				8	0	**0.0**
		Medium	66	2	100	**38.3**
				6	0	**0.0**
				8	0	**0.0**
		Heavy	20	2	100	**11.6**
				6	0	**0.0**
				8	0	**0.0**
New	42	Light	8	2	0	**0.0**
				6	94	**3.2**
				8	6	**0.2**
		Medium	92	2	0	**0.0**
				6	94	**36.3**
				8	6	**2.3**
		Heavy	0	2	0	**0.0**
				6	94	**0.0**
				8	6	**0.0**
Sum	**100**					**100**

Table A 12. Housing allocation for Adelaide for 2030 BaU, non-zero percentages highlighted in green

Appendix B Development of future scenarios

B.1 Total dwellings

The number of total dwellings in Australia can be found from previous censuses as shown in Table B 1 (https://profile.id.com.au/australia/population).

Table B 1. Number of total dwellings in Australia from previous censuses

	Census 2001	Census 2006	Census 2011	Census 2016
Total No. of Dwellings	7790065	8426560	9139293	9924992

B.2 Projection of total households

The projection of total number of households in Australia from 2016 up to 2041 is available in: https://quickstats.censusdata.abs.gov.au/census_services/getproduct/census/2016/quickstat/1GSYD?opendocument. The total number of households for 2016 was based on Census 2016. Table B 2 shows the medium projection of the total number of households from the website.

The increase in the number of households is essentially linear. A projection up to 2050 can thus be obtained as in the following table. It is noted that the total number of households is less than the total dwelling number as some of the dwellings is non-occupied. If we assume that this ratio between household and dwelling number keeps approximately the same, the total dwelling number for future years can be estimated. Unfortunately, projections for capital cities are not available in this webpage. For this study, we assume that this change in the household number is uniform across Australia which is a rough approximation.

Table B 2. Projected number of household and total number of dwellings in Australia

Year	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Household number	9204635	9345350	9495177	9648665	9802786	9955106	10114968	10273045	10429975
Dwellings Number	9924992	10076719	10238272	10403772	10569954	10734195	10906568	11077016	11246227
Year	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**
Household number	10585423	10739561	10896268	11051907	11205601	11358657	11511088	11666868	11822310
Dwellings Number	11413841	11580042	11749013	11916832	12082554	12247588	12411949	12579920	12747527
Year	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**
Household number	11975396	12127722	12279823	12428012	12577293	12724763	12871726	13018657	13195702
Dwellings Number	12912593	13076841	13240845	13400631	13561595	13720606	13879070	14037500	14228401
Year	**2043**	**2044**	**2045**	**2046**	**2047**	**2048**	**2049**	**2050**	
Household number	13349485	13503267	13657049	13810832	13964614	14118396	14272179	14425961	
Dwellings Number	14394219	14560036	14725853	14891671	15057488	15223305	15389123	15554940	

Note: household numbers from 2042 are extrapolated in this study.

B.3 Housing growth

According to ABS (https://www.abs.gov.au/statistics/industry/building-and-construction/building-approvals-australia/latest-release), the monthly dwelling approvals are available from March 2006 to April 2021. In average, the number of dwelling approvals is around 2% of the residential building stock in Australia since 2006. We assume that this trend will continue in the future and also assume that it is uniform across the four cities (this is a rough approximate).

B.4 Dwelling types

According to ABS 2016 Census, the number of occupied private dwellings for different dwelling types are available for the four city areas as shown in Table B 3.

It is noted that the total number of occupied private dwellings is less than the total number of dwellings as there are non-occupied as well as public dwellings. If we assume that the ratios between the number of occupied private dwellings and the total number of dwellings is the same across different types of dwellings, then, an estimate of different dwelling types can be made as in Table B 4.

Table B 3. Occupied private dwelling numbers in 2016 (2016 Census data)

	2016	**2016**	**2016**	**2016**	**2016**	**2016**
	Total no. of Dwellings	**Occupied Private Separate house**	**Occupied Private Semi-detached, row or terrace house, townhouse etc**	**Occupied Private Flat or apartment**	**Others**	**Total occupied Private Dwellings**
Greater Sydney	**1855734**	924,225	227,235	456,231	9,132	**1,616,823**
Greater Melbourne	**1832043**	1,067,637	264,404	231,297	6,400	**1,569,738**
Greater Brisbane	**901797**	602947	79228	99679	4659	**786,513**
Greater Adelaide	**562147**	368244	82994	38309	1379	**490,926**

Table B 4. Estimated dwelling number distributions among different types in 2016

	2016	**2016**	**2016**	**2016**	**2016**	**2016**
	Total no. of Dwellings	**Separate house**	**Semi-detached, row or terrace house, townhouse etc**	**Flat or apartment**	**Others**	**Total occupied Private Dwellings**
Greater Sydney	**1855734**	1,060,794	260,813	523,646	10,481	**1,616,823**
Greater Melbourne	**1832043**	1,246,040	308,586	269,947	7,469	**1,569,738**
Greater Brisbane	**901797**	691,325	90,841	114,290	5,342	**786,513**
Greater Adelaide	**562147**	421,667	95,034	43,867	1,579	**490,926**

Considering the addition of 2% new dwelling each year and that NatHERS rating was introduced in building code since 2006, new dwellings are approximately 20% of the 2016 building stock. Consequently, we have approximate old and new house number in Table B 5.

Table B 5. Estimated new and old dwelling number distributions among different types in 2016.

New Houses	2016	2016	2016	2016
	Separate house	Semi-detached, row or terrace house, townhouse etc	Flat or apartment	Others
Greater Sydney	212,159	52,163	104,729	2,096
Greater Melbourne	249,208	61,717	53,989	1,494
Greater Brisbane	138,265	18,168	22,858	1,068
Greater Adelaide	84,333	19,007	8,773	316
Old Houses	**2016**	**2016**	**2016**	**2016**
	Separate house	**Semi-detached, row or terrace house, townhouse etc**	**Flat or apartment**	**Others**
Greater Sydney	848,635	208,650	418,917	8,385
Greater Melbourne	996,832	246,869	215,958	5,976
Greater Brisbane	553,060	72,673	91,432	4,274
Greater Adelaide	337,334	76,027	35,093	1,263

B.5 Percentage of Class 1

Based on Australian Housing Data, the percentage of Class 1 dwellings which include separate house and semidetached dwellings for new dwellings since 2016 are listed in Table B 6 for the four states in consideration (currently the data is only available to the state scale).

Table B 6. Percentage of Class 1 dwellings for new dwellings after 2016.

State	Percentage of Class 1 dwellings
NSW	49.10%
VIC	84.60%
QLD	84.80%
SA	94%

B.6 Forecast changes in dwelling types

With the 2% annual new dwelling approval rate, the total number of national dwelling forecast (Section 2) to be uniformly applied to the four cities and the percentage of Class 1 dwellings in Section 5. The number of old and new dwellings in the four cities are estimated as in Tables B 7-9 for 2021, 2030 and 2050 respectively.

Table B 7. Estimated new and old dwelling number distributions among different types in 2021

New Houses	2021	2021	2021	2021
	Separate house	Semi-detached, row or terrace house, townhouse etc	Flat or apartment	Others
Greater Sydney	220,985	54,333	279,810	5,601
Greater Melbourne	375,360	92,959	82,954	2,295
Greater Brisbane	204,232	26,836	39,569	1,849
Greater Adelaide	130,300	29,367	9,837	354

Old Houses	2021	2021	2021	2021
	Separate house	Semi-detached, row or terrace house, townhouse etc	Flat or apartment	Others
Greater Sydney	569,995	140,142	721,725	14,446
Greater Melbourne	968,182	239,774	213,967	5,920
Greater Brisbane	526,785	69,220	102,061	4,770
Greater Adelaide	336,088	75,747	25,374	913

Table B 8. Estimated new and old dwelling number distributions among different types in 2030

New Houses	2030	2030	2030	2030
	Separate house	Semi-detached, row or terrace house, townhouse etc	Flat or apartment	Others
Greater Sydney	374,579	92,096	474,290	9,493
Greater Melbourne	636,253	157,570	140,611	3,891
Greater Brisbane	346,183	45,489	67,070	3,135
Greater Adelaide	220,864	49,778	16,675	600
Old Houses	**2030**	**2030**	**2030**	**2030**
	Separate house	**Semi-detached, row or terrace house, townhouse etc**	**Flat or apartment**	**Others**
Greater Sydney	527,919	129,797	668,448	13,380
Greater Melbourne	896,713	222,074	198,173	5,483
Greater Brisbane	487,898	64,110	94,527	4,418
Greater Adelaide	311,279	70,155	23,501	846

Table B 9. Estimated new and old dwelling number distributions among different types in 2050

New Houses	2050	2050	2050	2050
	Separate house	Semi-detached, row or terrace house, townhouse etc	Flat or apartment	Others
Greater Sydney	786,633	193,406	996,030	19,937
Greater Melbourne	1,336,159	330,904	295,290	8,171
Greater Brisbane	726,999	95,529	140,851	6,583
Greater Adelaide	463,825	104,536	35,018	1,261
Old Houses	**2030**	**2030**	**2030**	**2030**
	Separate house	**Semi-detached, row or terrace house, townhouse etc**	**Flat or apartment**	**Others**
Greater Sydney	359,577	88,408	455,295	9,113
Greater Melbourne	610,770	151,259	134,980	3,735
Greater Brisbane	332,318	43,667	64,384	3,009
Greater Adelaide	212,018	47,784	16,007	576

B.7 Distribution of star ratings

According to Australian Housing Data, the average star ratings for existing and new houses are 2.2 stars and 6.2 stars respectively. Table B 10 shows the ratio of the distribution of 2 star, 6 star and 8 star houses for old and new houses in the four cities based on Australian Housing Data. For business as usual scenario, we assume that these distributions will be the same from now to 2050.

Table B 10. Percentage of houses with different star ratings for old and new houses

New Houses	**2 stars**	**6 stars**	**8 stars**
Greater Sydney	0%	90.65%	9.35%
Greater Melbourne	0%	96.45%	3.55%
Greater Brisbane	0%	74.19%	25.81%
Greater Adelaide	0%	93.68%	6.32%
Old Houses	**2 stars**	**6 stars**	**8 stars**
Greater Sydney	100%	0%	0%
Greater Melbourne	100%	0%	0%
Greater Brisbane	100%	0%	0%
Greater Adelaide	100%	0%	0%

B.8 Distribution of construction types

The distribution of building construction types requires the combined information of the types of external walls and floors. In this study, an approximate approach was used by just using the external wall types.

For new dwellings, insulation is normally used in external walls. Only cavity brick wall construction is considered as heavy-weight construction. For old houses, insulation is generally not used in external walls. Consequently, both cavity brick wall and concrete wall are considered to be heavy-weight construction. EPS, Fibre-cement, Metal Clad, Timber clad are all accounted as light-weight constructions and the rest of the external constructions are included in the medium constructions. Table B 11 shows the estimated distributions of constructions for old and new houses.

Table B 11. Percentage of house constructions for old and new houses

New Houses	**Light**	**Medium**	**Heavy**
Greater Sydney	18%	77.85%	4.62%
Greater Melbourne	5%	95.17%	0.05%
Greater Brisbane	27%	72.64%	0.05%
Greater Adelaide	8%	91.29%	0.35%
Old Houses	**Light**	**Medium**	**Heavy**
Greater Sydney	38.1%	42.9%	19.1%
Greater Melbourne	18.8%	78.2%	3.0%
Greater Brisbane	42.9%	48.6%	8.6%
Greater Adelaide	13.6%	65.9%	20.5%

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