



# Residential geothermal air-conditioning: inhabitants' comfort, behaviour and energy use

SPECIAL COLLECTION:  
ALTERNATIVES TO  
AIR CONDITIONING:  
POLICIES, DESIGN,  
TECHNOLOGIES,  
BEHAVIOURS

RESEARCH

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## ABSTRACT

How do occupants' behaviour and expectations influence energy use for residential geothermal air-conditioning? This detailed study of 40 homes with geothermal AC in Sydney, Australia, during the period 2019–20 covers one of hottest Australian summers and increased daytime occupancy over the winter due to working from home during Covid-19 lockdowns. Monitored data are analysed for ground source heat pump (GSHP)-AC energy, occupancy, indoor conditions, as well as a snapshot resident feedback captured during hot and cold spells. Findings indicate that the homes built to comply with 2011 energy efficiency standards maintain indoor temperatures within 10–12°C of peak summer and minimum winter temperatures, without AC. A general preference to adopt adaptive strategies such as ceiling fans and appropriate clothing before deploying AC is evident for moderately hot and cold days. A heightened dependence on AC is seen for extreme days. However, a significant number of houses adhere to a narrow range of acceptable temperatures, thereby increasing the take-up of GSHP-AC and energy consumption. The replacement of conventional AC with alternate technologies is not a one-stop solution in, and of, itself. There is a need for improved building low energy design and construction based on a better understanding of occupant behaviour and energy consequences.

## POLICY RELEVANCE

Although geothermal systems offer potential energy savings (especially in extreme conditions) and their potential for seamless technological replacement of conventional AC in homes, the findings suggest GSHP-AC is not a one-stop solution to reduce dependence on AC. The study reveals that the unconstrained use of GSHP-AC can increase energy consumption and squander energy savings achieved through its technological efficiency. The 'conditioned' expectations of inhabitants, stimulated by a lower tolerance of 'imperfect' conditions and availability of heating and cooling on standby, can lead to increased dependence and usage. In an increasing warming world, more stringent guidelines are needed for thermal performance and design to mitigate residual discomfort and transform occupant practices. These must also be supported with occupant education and engagement to ensure the design intent is realised.

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KEYWORDS:

air-conditioning; cooling;  
cooling technologies; energy  
demand; geothermal; housing;  
occupant behaviour; thermal  
comfort; Australia

TO CITE THIS ARTICLE:

Thomas, L., Woods, A., Powles,  
R., Kalali, P., & Wilkinson, S.  
(2022). Residential geothermal  
air-conditioning: inhabitants'  
comfort, behaviour and energy  
use. *Buildings and Cities*, 3(1),  
pp. 226–249. DOI: [https://doi.  
org/10.5334/bc.172](https://doi.org/10.5334/bc.172)

The design and implementation of precincts that deliver sustainability, resilience, health and wellbeing has long been one of the key aspirations for contemporary development of the built environment (Green Building Council of Australia 2014; Rinne *et al.* 2013). Against the backdrop of widespread entrenchment of conventional air-conditioning (AC) (Ürge-Vorsatz *et al.* 2015), the quest for designing and building with no AC has progressed through research (Ford *et al.* 2020; Samuel *et al.* 2013). However, the implementation and market diffusion for alternates to conventional AC, especially within large-scale housing developments, has been slow in Australia.

Geothermal AC or ground source heat pump (GSHP-AC) technology is noted for its potential to deliver energy efficiency and reduce greenhouse gas emissions (Cocchi *et al.* 2013; Lim *et al.* 2017; Omer 2008). The present research focuses on a residential development in western Sydney, New South Wales (NSW), Australia, that integrates one of the country's largest-scale installations of geothermal AC in a region of rampant urbanisation (Morrison & Van den Nouwelant 2020) which is increasingly subject to increased urban heat and extreme temperatures in summer (Khan *et al.* 2020). The development was the first in NSW to be awarded the top 6 Star Green Star Communities rating, which values liveability, innovation and environmental sustainability in addition to their governance and contribution to building economic capacity (Green Building Council of Australia n.d.).

However, as the first precinct-wide installation of an alternate mode of AC at this scale in Australia, very little is known about performance in use, its efficacy in residential settings, as well as the opportunities and barriers for occupants and outcomes for the precinct.

Previous studies have sought to research environmental performance in residential settings for different climatic contexts. These include the study of occupants' behaviour and control of the indoor environment (Saman *et al.* 2013, Daniel *et al.* 2017; de Dear *et al.* 2018; Eon *et al.* 2018; Kim *et al.* 2017), the patterns of energy consumption (Asumadu-Sakyi *et al.* 2019; Moore *et al.* 2017; Romanach *et al.* 2017), the evaluation of thermal comfort in indoor environments (Saman *et al.* 2015; Sharifi *et al.* 2020), the impact of the indoor environmental condition and thermal comfort on occupants' health and wellbeing (Asumadu-Sakyi *et al.* 2019; Bills & Soebarto 2015), and the adaptive building design standards that can be sustainable and supportive of an efficient use of energy (Hansen *et al.* 2018). Other research around health, wellbeing or sustainability (Daniel *et al.* 2019; Samet & Spengler 2003; Scott 2012) has largely occurred in isolation of the questions of the above-mentioned environmental aspects.

While it has been argued that personal control over the heating and cooling system and the indoor environmental conditions (adjusting the temperature set points, ventilation rates, *etc.*) can increase occupants' level of tolerance in extreme events (Hawkes 1982; Bae & Chun 2009; Brunsgaard *et al.* 2011; Cao *et al.* 2014), Andersen *et al.* (2009) highlight that the occupant's interactions with the control system can lead to a higher level of energy consumption, and the quest for energy efficiency in itself begets more consumption (Shove 2018). The present paper addresses the question of how resilient buildings and cities should be to a warmer world by focusing on the interrelationship between user comfort, behaviour and energy—in particular, in relation to the themes for building design, social behaviours and inhabitant agency.

The Fairwater development is subject to ongoing research through a broader living laboratory study to ascertain whether it delivers the presumed sustainability, resilience, wellbeing and commerciality benefits. In this context, this paper offers insights into occupant preferences, behaviour, and AC use during summer and winter, including extreme weather conditions and bushfires in the summer period of December 2019–March 2020 (Australian Bureau of Meteorology 2020), and the winter of 2020 with increased occupancy and work from home arising during the Covid-19 pandemic (Australian Bureau of Statistics 2021).

The Fairwater development is located within a 32 ha site that was a former golf course in the Blacktown local government area (LGA) of NSW. The climate is characterised as warm temperate with approximately 1086 heating degree-days (base of 18°C) and 133 cooling degree-days (base of 24°C). Designed and occupied from 2014 onwards, the precinct will consist of around 830 residences on completion in 2023. It consists of predominantly attached, semi-detached and detached two-storey, single residential dwelling houses. All buildings were designed and constructed by the project developer before being handed over to residents/investors.

At the time of recruitment for this study in 2019, approximately 450 dwellings were completed and occupied within the precinct. All houses follow a similar compositional and construction template, with natural ventilation to all habitable spaces. They typically adopt a two-storey arrangement with bedrooms on the upper floor and open-plan living spaces with a private outdoor space on the ground floor. The house size varies to accommodate a different number of functional spaces. Whereas the orientation of the residences varies within the precinct, there exists a prevailing east-west to north-east-south-west subdivision pattern to which the majority of the houses adhere (*Figure 1*).

Unique to the precinct is the closed-loop geothermal or GSHP-AC system installed in each property. Connected to a reverse-cycle unit within the dwelling, the GSHP system uses the ground at a relatively stable temperature as a reservoir either to reject heat in summer or to gain heat in winter. The system at each property incorporates a vertical bore 60–90 m in depth that circulates the refrigerant through the ground. In contrast to a conventional AC system, where the efficiency of the heat-exchange process with ambient air can be constrained by its temperature, especially on extreme hot or cold days, GSHP-AC systems are expected to draw less electrical power on average while achieving the same heating or cooling effect (Hackel & Pertzborn 2011).

The GSHP-AC system is typically zoned to serve either or both of two zones: living room and bedroom. According to the system contractor, it is sized:

[to] cater for the entire home for approximately 80% of the year [...] and only satisfactorily heat/cool the larger one of the zones during extreme weather.<sup>1</sup>

Occupants are able to control the zone and thermostat settings via a wall unit and remote control, and the system was promoted as being able to ‘deliver heating and cooling just like any other air-conditioning system’ but with the ‘smarts’ for saving energy, being quiet and reducing the local impact of warm air past the condenser of a conventional system (Fraser's Property Australia n.d.).

The residences are constructed with a combination of insulated brick veneer and lightweight cladding construction and single-glazed aluminium framed windows supplied as standard. A prominent cooling strategy used throughout the precinct is that of the specification of a light colour for the corrugated steel roofing to mitigate the urban heat island effect alongside a landscape regeneration programme for wetlands, parklands and open spaces. The application of performative elements such as window awnings and feature screens provide visual interest alongside their functional contributions to the shading of glazing and preservation of visual privacy between residences and the public domain.

As per the prevailing 2011 building regulations, the multi-unit development conformed to the requirement for an average rating of 5.0 Stars (out of a 10 Star scale) across all homes under the Nationwide House Energy Rating System (NatHERS) (n.d.). The ratings based on simulated/predicted heating and cooling energy demonstrate compliance with the National Construction Code (NCC) energy-efficiency requirements based on the structure, materials structure, design and materials of the home. Some variation was observed in the individual star ratings of the 40 recruited study homes described below, ranging from a 3.8 Star rating for a four-bedroom dwelling to a 7.4 Star rating for a two-bedroom dwelling. Houses relied on electricity for all end uses, with the exception of natural gas for cooktops and hot water (instantaneous).





**Figure 1:** Aerial view of the Fairwater precinct.

Source: SixMaps (<https://maps.six.nsw.gov.au>).

### 3 METHODS

The paper draws on data from a cohort of 40 Fairwater study houses that were recruited for detailed monitoring and participation within a living laboratory framework in 2019. It focuses on the period 1 September 2019–31 August 2020, and monitored data collected for AC energy, occupancy in the home, indoor temperature and humidity as well as resident feedback drawn via SMS surveys administered during hot and cold spells within the study period.



- *Study houses and residents*

The opportunity to participate as a study house in the living laboratory was offered to all houses via social media and email lists. The range of recruited homes offers a good representation of the spread of houses with two to five bedrooms with occupancy ranging from one to five occupants. On average, the total built-up area was 213 m<sup>2</sup>, conditioned floor area of 144 m<sup>2</sup>, and 2.98 occupants per home. All homes were owner-occupied with only 10% reporting a household income level below the median Australian household income level of A\$94,000 per annum (Australian Bureau of Statistics 2020). All except one household had lived in the house for more than one year, with 40% having lived at Fairwater for over three years.

- *Energy monitoring*

Electricity usage in each study house was metered using a electricity monitoring device (Wattwatchers Auditor 6M). Real-time electricity consumption is captured in 30-min intervals separately for all end-use circuits in the home, including a dedicated circuit for the GSHP-AC system, and another for solar photovoltaics (PV) if in use, allowing accurate calculation of total energy consumption as well as AC usage.

- *Indoor sensors*

The indoor environmental Hux Connect sensors deployed for the project comprised two comfort motes and one air quality sensor per home. The comfort sensors placed in the living spaces and master bedroom measure relative humidity, dry bulb temperature, globe temperature, illuminance and occupancy. This paper focuses primarily on the logged dry bulb temperature (logged every 30 min) and occupancy, where the latter is measured as a number of 5-min intervals where activity is recorded over the 30-min period.

- *External sensors: weather data*

Delays meant that on-site data for external environmental conditions were not available until August 2020. Consequently, the research team had to rely on Bureau of Meteorology data for Horsley Park as well as interpolated historical time-series data for Blacktown and comparison sites sourced from Solcast. The validity and accuracy of the Solcast data are well documented (Solcast n.d.) and serve the purpose for the present analysis.

- *Occupant practices in terms of deployment of the geothermal AC for long-term data*

These practices are analysed with respect to both outdoor and indoor temperatures at times when the spaces are known to be occupied. Hourly occupancy for this analysis is based on at least one occurrence of movement being logged in a space within the hour. Deployment of AC is inferred from whether the GSHP-AC system draws energy above its standby load. Where reported, the total energy is based on the sum of all end-use energy circuits monitored and the AC energy is based on sub-metered energy for the GSHP-AC system. Although the total AC energy at any given instant is logged for the whole house, it cannot be disaggregated based on the upstairs or downstairs zones.

It should be noted that in the analyses that follow, natural ventilation (GSHP-AC off) is only logged when the system is not used across both zones in the house. Additionally, to minimise the misidentification of air-conditioned zones when AC is only directed to one zone, the data were analysed separately for day- and night-time to align with typical occupancy patterns where residents tend to occupy living room spaces during the day and bedrooms at night. The daytime plots draw their data only from the living room temperature data at times when the living space is occupied during the period from 06.00 to 22.00 hours, and the night-time plots draw their data only from the master bedroom between 22.00 and 06.00 hours where the house is known to be occupied the day prior.

Although this approach potentially excludes a vast amount of collated data, it ensures that temperatures are only reported where there is confidence that the zone is occupied. In rare instances where AC might have been directed only to the bedroom zone (but not to the living zone) during the day, it is acknowledged that the living room would be misidentified as being in the 'AC-on' mode, even though the space was not directly being heated or cooled. However,

in such cases given the fairly open-plan arrangement of the ground floor living zone, it could be somewhat argued that temperatures across the house are likely to be moderated by the AC in operation in one of the zones. Nevertheless, the above approach enables the characterisation of occupant practices for deploying AC or not in relation to outdoor temperature conditions, and also provides an insight into the indoor temperatures at which the house is maintained at these times. This provides a backdrop for understanding the SMS survey data collected, as described below.

### 3.1 OCCUPANT PRACTICES: DEPLOYING GSHP-AC WITH REAL-TIME FEEDBACK

'Extreme Weather' SMS Snapshot Surveys were conducted between January and August 2020. Intended to obtain 'right here, right now' feedback (after de Dear & Brager 1998; Manu *et al.* 2016) from study house participants, the surveys were timed to coincide with extreme cold and hot days as predicted by the Bureau of Meteorology as far as possible. The surveys sought information on occupants' locations within the house, their thermal sensation vote (Fanger 1970), and feedback on heating/cooling strategies in operation including whether geothermal AC was deployed both within the room and across the home. In addition, mean satisfaction votes were recorded on a seven-point scale, where 1 was unsatisfactory and 7 was satisfactory, in keeping with other field and post-occupancy studies to ensure neutrality is not the only criterion (Humphreys & Hancock 2007; Manu *et al.* 2016). The survey was designed to be completed in 60–90 s on a mobile phone. The winter surveys occurred during Covid-19 shutdowns that commenced in Sydney at the end of March 2020. While this meant all families were mostly housebound, it provides a better insight into usage patterns during cold winter days.

The SMS surveys were disseminated to the registered mobile numbers of study house participants. Typically administered over two to three consecutive days each month to reduce survey fatigue, and distributed between 10.00 and 15.00 hours across weekdays and weekends, surveys were able to be completed at any time on the day when occupants were at home. The SMS survey data for this paper drawn from 10 survey campaigns administered between January and March 2020 and eight campaigns during July and August 2020, yielding 311 and 294 responses for summer and winter, respectively.

The data were separately analysed for those who switched on the GSHP-AC system and for those who did not, alongside concurrent logged thermal data for their nominated room/zone. This approach mitigates the small chance of mis-identifying zones discussed above with respect to the broader data. Thermal sensation votes assigned values from +3 to -3 (hot to cold) were assessed on the basis of votes between -1 and +1 deemed to be satisfactory by ASHRAE-55 (ASHRAE 2013), alongside the satisfaction vote being above the midpoint on a seven-point scale. The study also draws on reported thermostat settings, comfort and satisfaction ratings collected via separate household surveys that were administered to all study houses.

### 3.2. BENCHMARKING PERFORMANCE

While the NatHERS Star ratings offer a way of characterising the potential thermal performance of the building envelope, it is widely recognised that a wide divergence in home occupancy and user behaviour with reference to comfort preferences and behaviours means that it is not always a predictor of actual performance (Willand *et al.* 2016). On the other hand, while there are some large-scale surveys of electrical and gas consumption in homes (Frontier Economics 2020), a major gap in Australia is the availability of adequate monitored data or benchmarks for the actual heating and cooling energy consumed in residential buildings. This is especially the case with respect to conventional reverse-cycle heat pumps AC in comparable climates.

Separate analysis emerging from this study (Thomas *et al.* 2021) will seek to establish what electrical energy savings and network benefits can be attributable to geothermal AC in this study. However, in order to offer a point of comparison, the Australian Energy Regulator NSW Electricity Benchmarks (Frontier Economics 2020) are referenced for the corresponding climate zone (climate zone 6) for Blacktown as per the Australian Building Codes Board classification. A limitation here is that while all homes at Fairwater have a gas connection, only 47% of the benchmark dataset have gas. On the other hand, given that gas usage in the benchmark homes is noted to extend to space

heating and ovens, whereas it is only used for hot water and cook tops in the Fairwater homes, it is arguable that the benchmarks remain comparable.

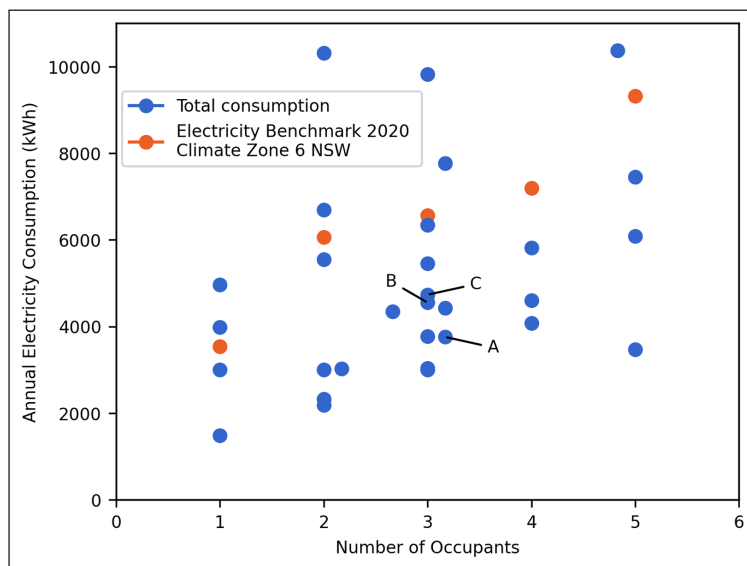
## 4 RESULTS

During the study period there were 40 days where the maximum temperature >33°C and 11 days where the maximum >39°C, with the highest recorded temperature as 46.2°C on 6 January 2020. The maximum temperature remained <18°C on 75 days and <15°C for seven days, and the lowest recorded daily maximum was 12.4°C on 7 August 2020.

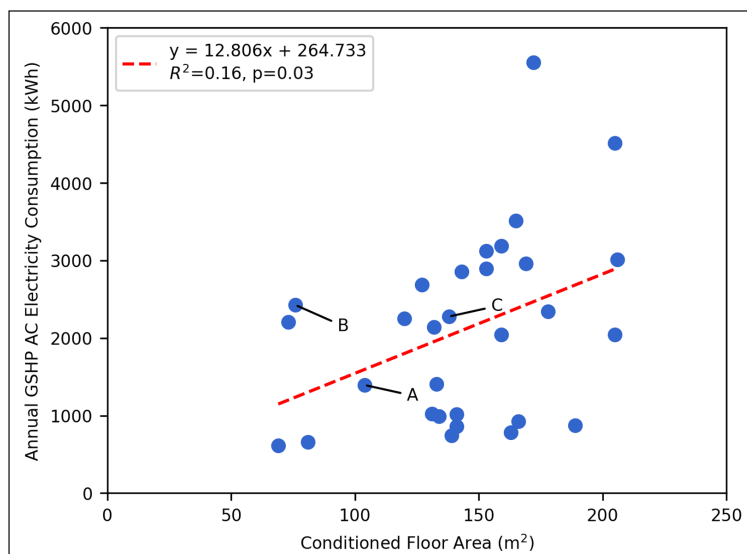
### 4.1 ENERGY OUTCOMES

**Figure 2** shows that, on average, the total electrical consumption for study houses with respect to the number of occupants per home is less than the electricity benchmark for climate zone 6 for NSW, although there are some outliers.

Under NatHERS, it is the heating and cooling energy intensity per unit of conditioned floor area that is used for ratings in that system. This is based on the implicit recognition that house size alters the energy consumed for this aspect. **Figure 3** shows the AC energy in relation to the conditioned floor area of each study house. While there is an overall trend where these two variables are somewhat correlated, the observable variation in the AC energy for homes once they are normalised for house size clearly indicates that other factors are at play.



**Figure 2:** Annual electricity consumption with respect to the number of occupants and NSW electricity benchmark.

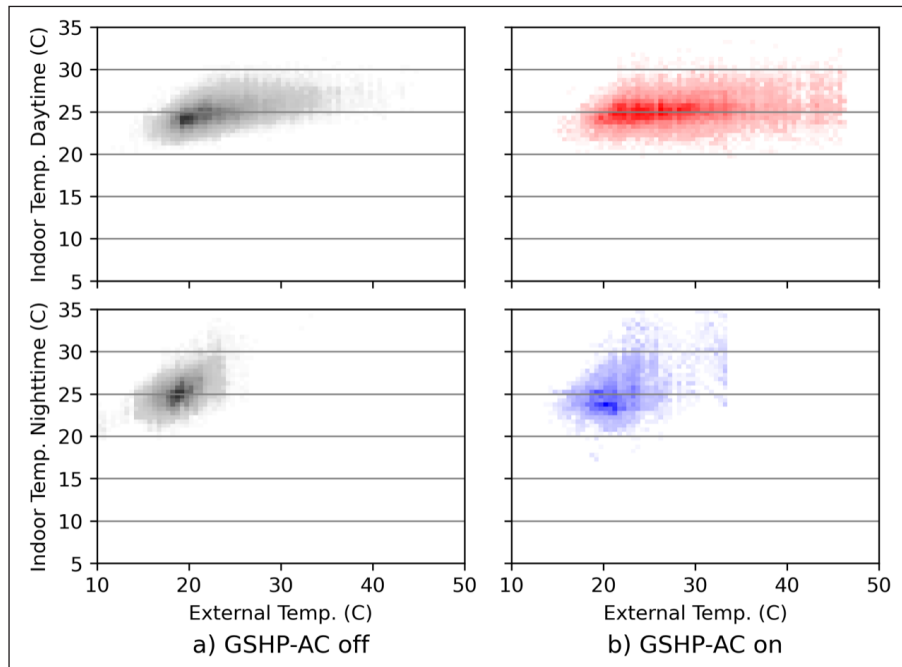


**Figure 3:** Annual air-conditioning (AC) energy with respect to conditioned floor area.

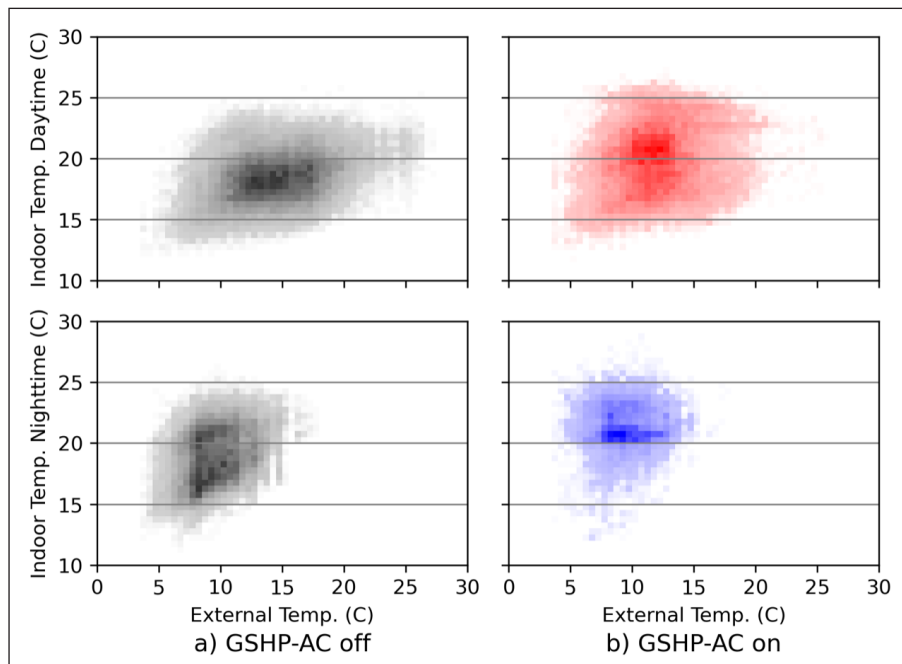
## 4.2 EXPLORATION OF INDOOR THERMAL CONDITIONS

On average the study houses were occupied for 82% of the annual hours across the year, and AC was taken up for 20% of occupied hours. The average was 24% of occupied hours in summer and 26% of occupied hours in winter. The indoor temperature conditions during occupied hours are plotted against their concurrent outdoor temperatures in summer (December–February) (**Figure 4**) and winter (June–August) (**Figure 5**). For clarity in **Figures 4** and **5**, the datapoints when the GSHP-AC is switched off are shown separately in the first set of scatterplots (a) and then datapoints when the system is switched on (b) to indicate the temperature range at which this occurs:

- Grey dots represent instances when GSHP-AC is switched off.
- Red dots represent the temperature in the living room at daytime when the GSHP-AC is switched on.
- Blue dots represent the temperature in the bedroom at night-time when the GSHP-AC is switched on.



**Figure 4:** Indoor operative temperature and concurrent outdoor temperature in summer (December–February).



**Figure 5:** Indoor operative temperature and concurrent outdoor temperature in winter (June–August).



The scatter plots show that in the absence of AC, indoor temperatures remain 10–15°C less than peak outdoor summer temperatures and around 7–12°C higher than the lowest winter temperatures in both the living room in the daytime and the bedroom at night-time.

When considering the breadth of monitored data across summer and winter, it is evident that GSHP-AC is used to moderate indoor temperatures primarily between 22 and 28°C in the living room during the day, and between 20 and 26°C in the bedroom at night. Interestingly, when heating is deployed in the bedrooms, there appears to be a tendency to maintain fairly warm conditions as high as 24°C in some homes, although others maintain conditions commencing from 16 and 18°C.

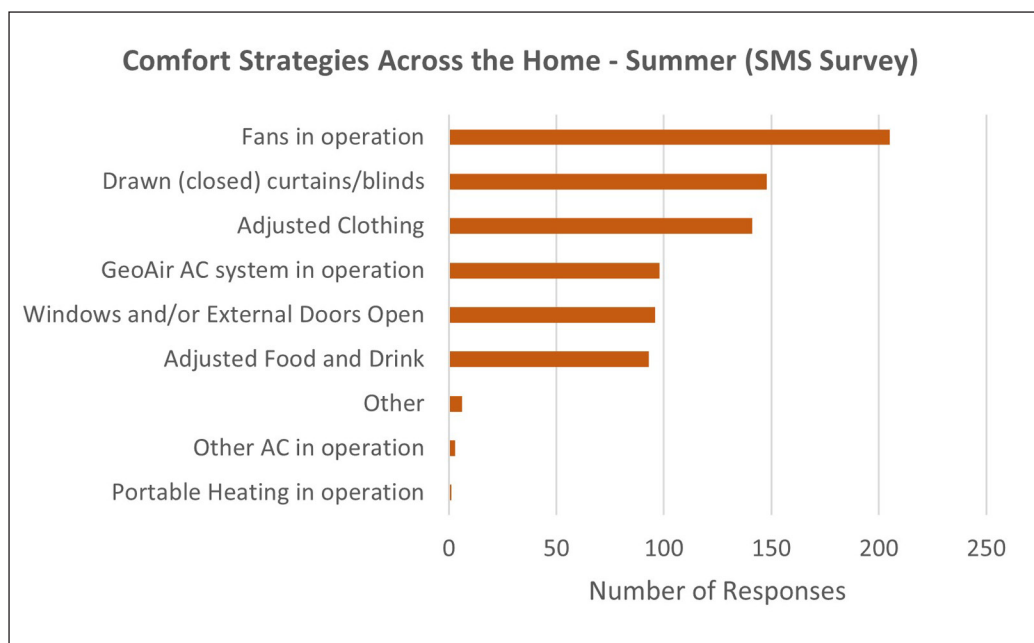
### 4.3 SNAPSHOT SURVEY FEEDBACK

A summary of survey outcomes for the summer and winter snapshot surveys are presented in *Tables 1* and *2* with respect to thermal sensation and satisfaction. The indoor thermal conditions and AC status (on or off) in the space at the time of response alongside concurrent outdoor conditions are provided for one summer (*Figure 7*) and one winter (*Figure 10*) campaign. These sample snapshots provide an insight into the extent of coverage, the variation in hourly temperatures over the surveyed days and variation in the take-up of AC between households. *Figures 6* and *9* show the frequency at which strategies for coping were nominated in response to the question, ‘Across the home how are you coping? (select all that apply)’. The variation in perception of comfort and tolerance of temperatures in the homes in summer and winter is also instructive. *Figures 8* and *11* depict the range of measured temperatures binned in 1°C increments in the two cooling and three different heating scenarios. Thermal sensation votes between +1 (slightly warm) and -1 (slightly cool) are generally deemed acceptable in most situations.

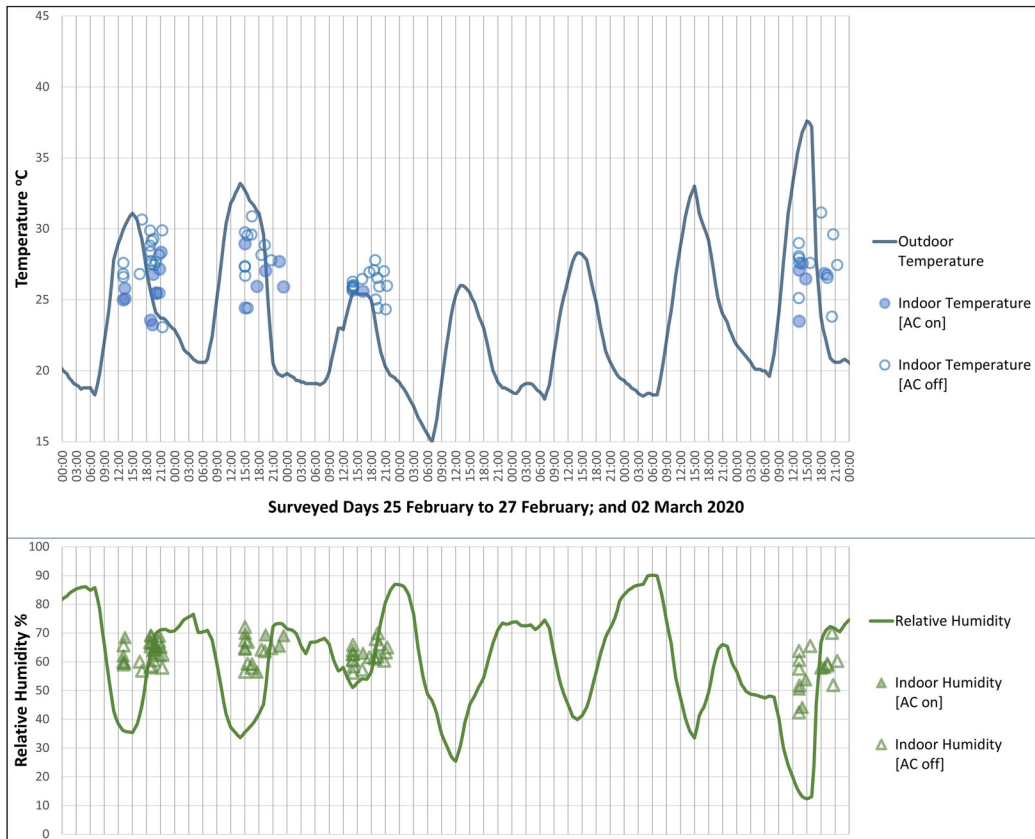
#### 4.3.1 Summer SMS Survey outcomes (January–March 2020)

The summer surveys captured extreme hot days with maximum temperature between 37.5 and 41.3°C as well as moderately hot days ranging from 30.0 to 35.6°C (*Table 1*). A total of 311 responses were received.

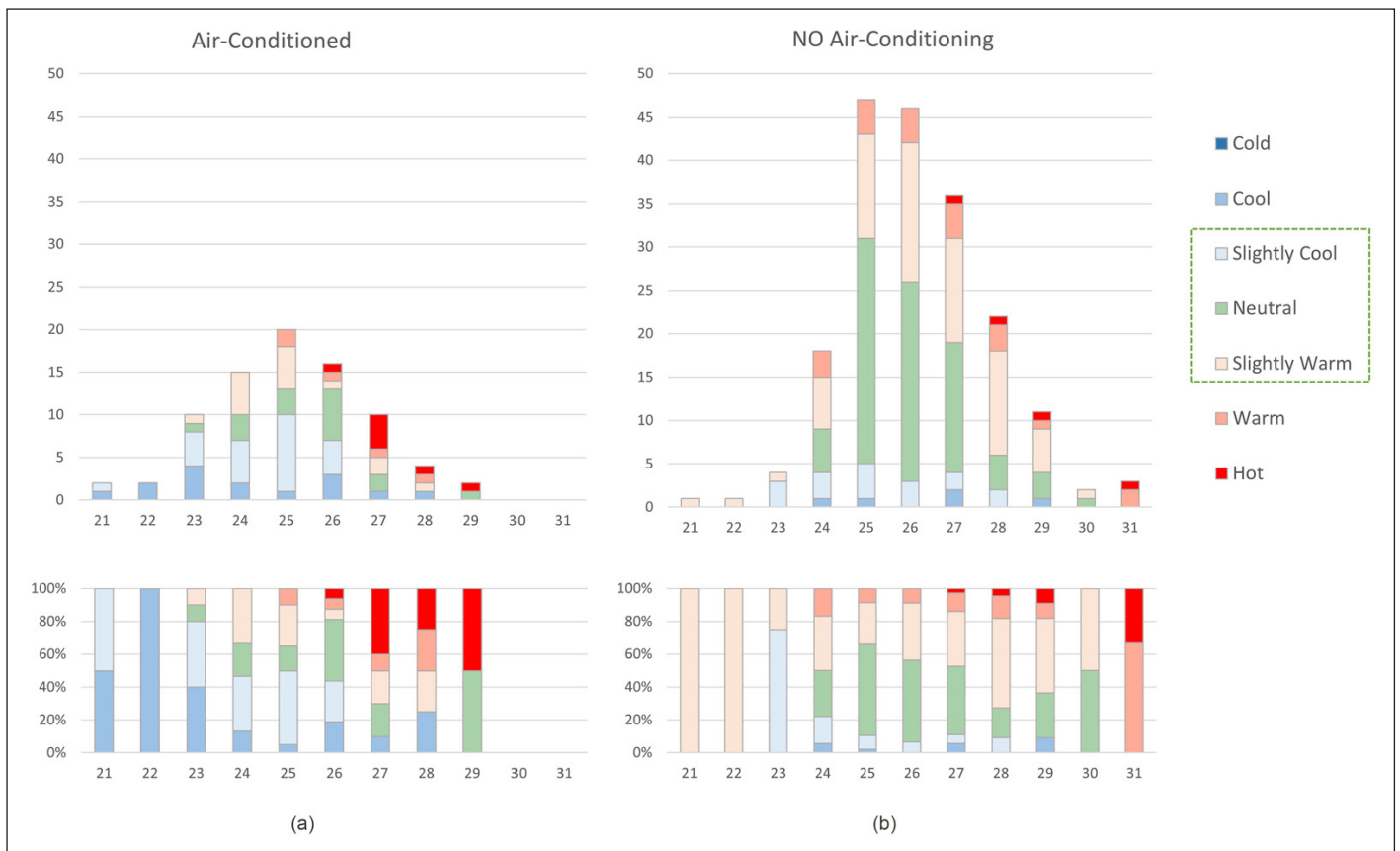
As seen in snapshot survey outcomes for the more typical summer weeks in February and March with hot but not extreme temperatures, the majority of instances were not air-conditioned (68–92%) and temperatures averaging 26.0–27.5°C were deemed satisfactory (satisfaction ratings > 5/7, and thermal sensation between 0.3 and 0.8). The divergence in the take-up of GSHP-AC on fairly warm days even at concurrent instances is evident in *Figure 7*, especially on 25 and 26 February and 2 March.



**Figure 6:** Nominated comfort strategies across the home in summer.



**Figure 7:** Snapshot survey outcomes for one summer campaign in February 2020.



**Figure 8:** Thermal sensation votes in summer.

**Table 1:** Summary of the SMS survey environmental conditions and outcomes in summer.

Notes: All responses are based on the status at the time when survey respondents completed the two-minute SMS survey.

Thermal sensation votes are recorded on a seven-point scale from +3 to -3, where +3 is hot, +2 is warm, +1 is slightly warm, 0 is neutral, -1 is slightly cool, -2 is cool and -3 is cold.

Mean satisfaction votes are recorded on a seven-point scale, where 1 is unsatisfactory and 7 is satisfactory.

With the exception of extreme days when over 65% of respondents had ground source heat pump (GSHP)-air-conditioning (AC) switched on at the time of responding to the survey, a general preference to adopt ceiling fans and other adaptive strategies is evident in **Figure 6**. Other coping measures included extending the time spent in cooler spaces including malls with AC.

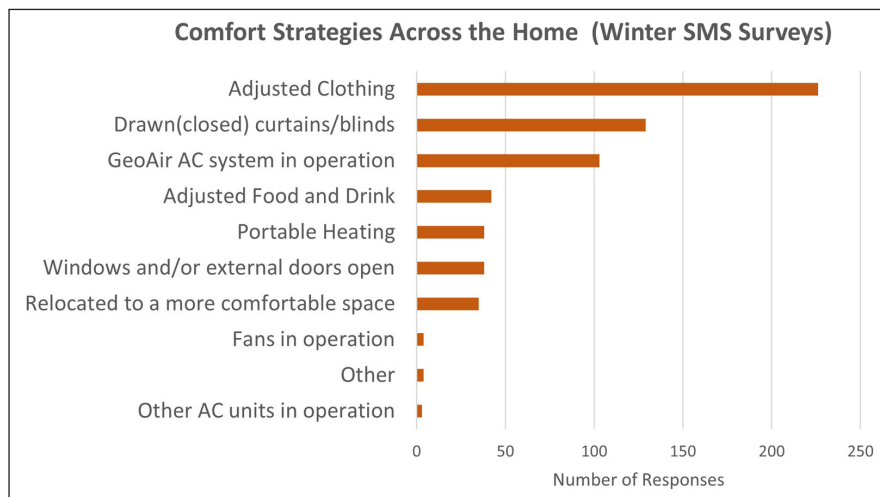
SURVEY DATES	OUTDOOR CONDITIONS					FANS				AC (GSHP) SWITCHED ON				NO AC			
	NUMBER OF RESPONDENTS	MAXIMUM TEMPERATURE (°C)	MINIMUM TEMPERATURE (°C)	AVERAGE TEMPERATURE (°C)	% WITH FANS	% WITH AC	AVERAGE INDOOR TEMPERATURE (°C)	THermal SENSATION MEAN VOTE	MEAN SATISFACTION WITH THERMAL COMFORT	% WITH NO AC	AVERAGE INDOOR TEMPERATURE (°C)	THermal SENSATION MEAN VOTE	MEAN SATISFACTION WITH THERMAL COMFORT	% WITH NO AC	AVERAGE INDOOR TEMPERATURE (°C)	THermal SENSATION MEAN VOTE	MEAN SATISFACTION WITH THERMAL COMFORT
23 January	19	41.3	20.3	30.8	84%	74%	26.1	0.4	4.9	26%	26.2	0.8	3.8				
24 January	2	30.0	21.8	25.8	100%	50%	28.9	3.0	5.0	50%	29.0	1.0	5.0				
25 January	33	31.6	22.1	25.5	67%	39%	25.4	-0.8	5.9	61%	26.1	0.4	5.1				
26 January	30	37.5	22.6	28.1	77%	67%	25.5	-0.5	5.9	33%	26.5	1.2	3.6				
25 February	41	31.1	18.3	24.0	51%	32%	25.5	0.0	5.9	68%	27.6	0.7	5.3				
26 February	28	33.2	19.6	25.6	75%	29%	26.0	0.6	5.0	71%	28.1	0.5	5.2				
27 February	37	25.5	19.0	21.5	49%	8%	25.6	0.3	5.0	92%	26.0	0.2	5.7				
2 March	27	37.6	19.6	25.2	59%	30%	26.3	-0.4	6.0	70%	27.8	0.7	4.8				
19 March	33	32.8	15.7	23.1	45%	18%	23.9	-1.0	5.7	82%	26.1	0.8	5.1				
20 March	26	35.6	19.2	26.3	62%	19%	26.0	0.6	5.4	81%	26.5	0.5	5.5				
21 March	35	26.4	16.5	20.9	63%	11%	25.7	-1.0	6.5	89%	26.0	0.3	5.5				

### 4.3.2 Winter SMS Survey outcomes (July–August 2020)

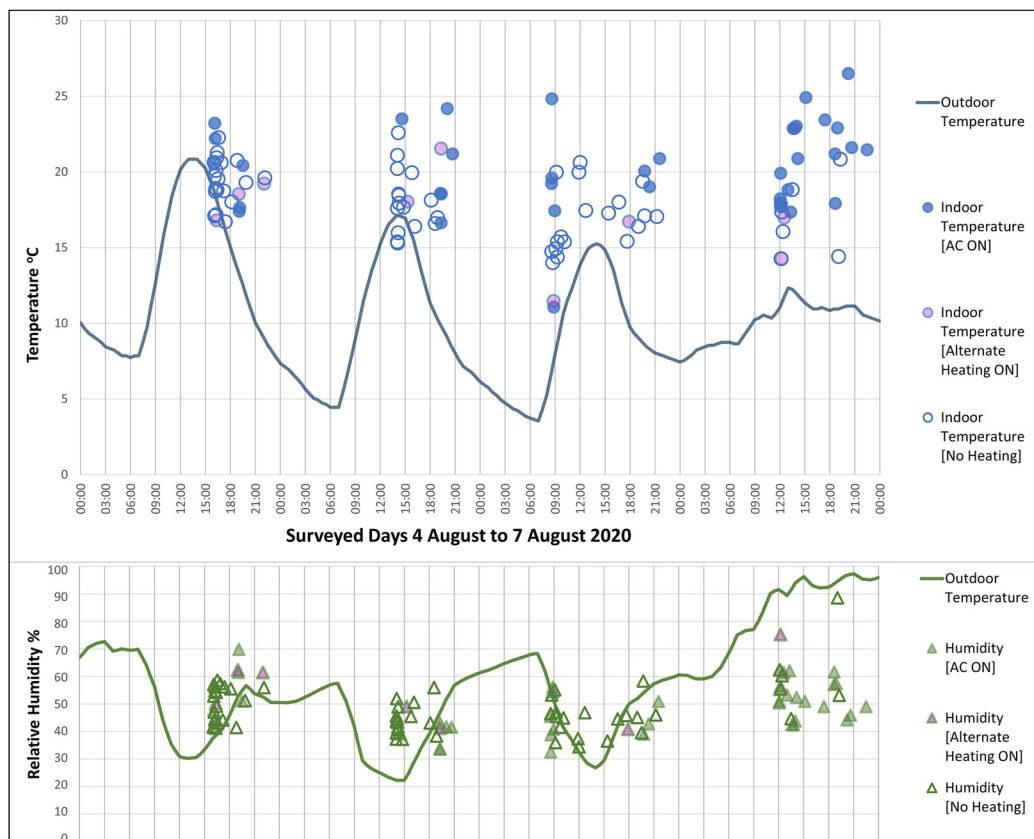
A total of 294 survey responses were received across the eight survey days. Overall, heating systems were in use for approximately 40% of surveyed instances on the cold days. Most respondents were using the GSHP-AC systems, while approximately 10% reported the use of alternate heating systems including gas and portable heaters (electric/oil column, etc.).

The take-up of heating systems during waking hours appears to be greatly influenced by low daytime temperatures (see 26 July and 7 August) rather than the lowest night temperature (see 21 July). Over 75% of respondents were using some form of heating on 7 August when the maximum temperature was only 12.4°C, in contrast to preceding days where average temperatures were lower but daytime maximums were relatively higher (**Figure 10**).

Similar to the summer SMS surveys, adaptive comfort strategies such as clothing, and shutting windows and drawing blinds and curtains closed are generally preferred over the utilisation of the GSHP-AC system or portable heating. Other coping measures included taking walks in the sun, using electric blankets, exercise or playing sport.

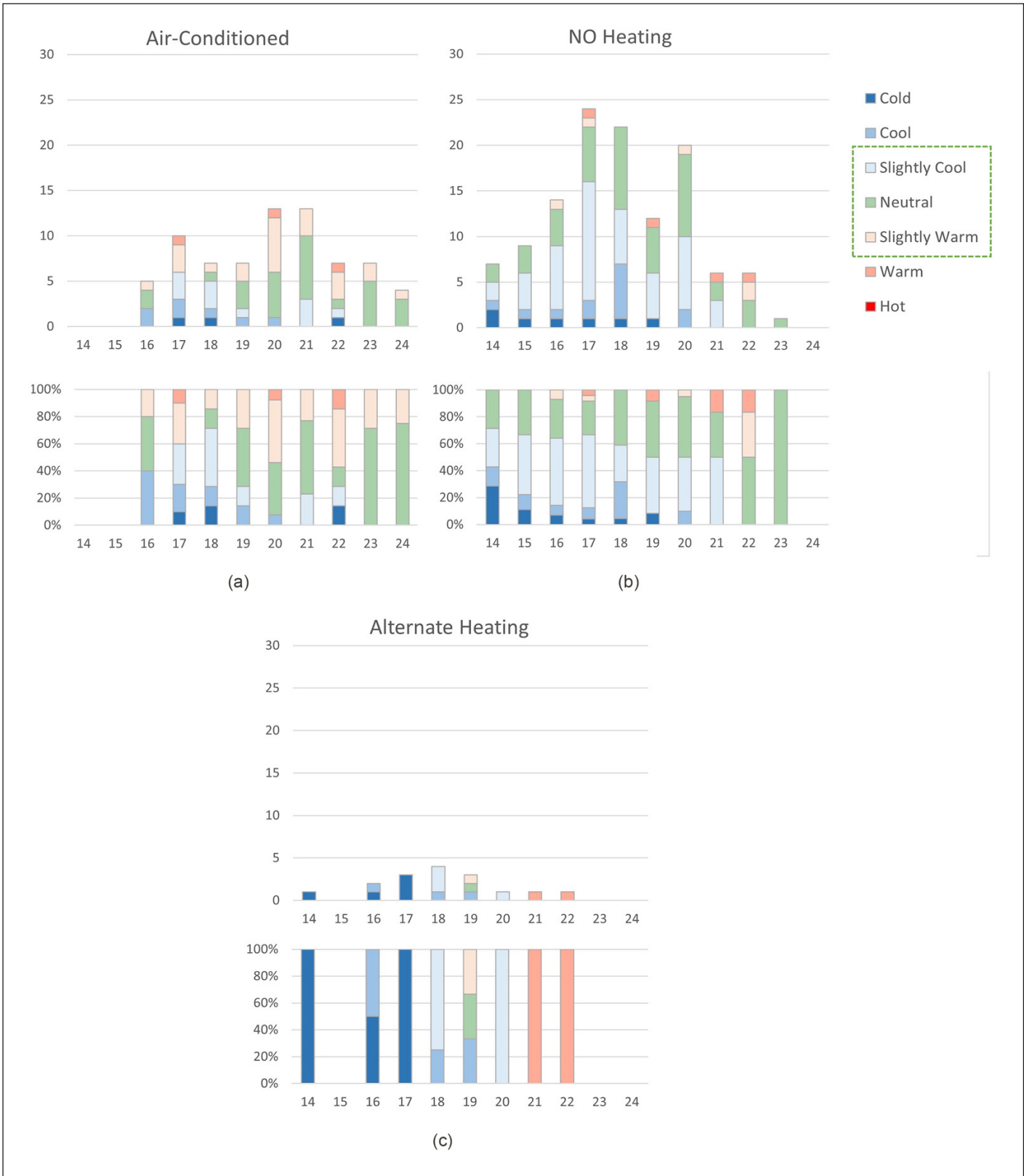


**Figure 9:** Nominated comfort strategies across the home in winter.



**Figure 10:** Snapshot survey outcomes for one winter campaign in August 2020.





**Figure 11:** Thermal sensation votes in winter.

**Table 2:** Summary of the SMS survey on environmental conditions and outcomes for winter.

Notes: All responses are based on the status at the time when survey respondents completed the two-minute SMS survey.

Thermal sensation votes are recorded on seven-point scale from +3 to -3, where +3 is hot, +2 is warm, +1 is slightly warm, 0 is neutral -1 is slightly cool, -2 is cool and -3 is cold. Mean satisfaction votes are recorded on a seven-point scale, where 1 is unsatisfactory and 7 is satisfactory.

AC = air-conditioning; GSHP = ground source heat pump.

SURVEY DETAILS	OUTDOOR CONDITIONS				AC (GSHP) SWITCHED ON				ALTERNATE HEATING SWITCHED ON				NO HEATING IN USE				
	SURVEY DATES	NUMBER OF RE- SPOND- ENTS	MAXIMUM TEMPER- ATURE (°C)	MINIMUM TEMPER- ATURE (°C)	AVERAGE TEMPER- ATURE (°C)	% WITH AC	AVERAGE INDOOR TEMPER- ATURE (°C)	MEAN SATS- FACTION WITH THERMAL COMFORT	% WITH ALTERNATE HEATING (GAS OR PORTABLE HEATERS)	AVERAGE INDOOR TEMPER- ATURE (°C)	MEAN SATS- FACTION WITH THERMAL COMFORT	% WITH NO HEAT- ING	AVER- AGE INDOOR TEMPER- ATURE (°C)	MEAN SATS- FACTION WITH THERMAL COMFORT	THERMAL SENSA- TION MEAN VOTE	THERMAL SENSA- TION MEAN VOTE	
19 July	28	20.0	6.7	12.6	20.4	21%	20.4	-0.5	7%	19.5	0.0	71%	19.3	6.5	6.5	-0.6	5.8
21 July	36	15.8	5.4	10.1	19.6	36%	19.6	-0.1	6%	17.9	-2.0	58%	19.4	3.0	3.0	-0.5	5.9
23 July	37	17.9	6.5	11.3	21.3	24%	21.3	0.3	8%	19.2	-1.3	68%	18.6	4.0	4.0	-0.4	5.9
26 July	42	14.5	12.5	13.2	20.9	33%	20.9	-0.2	14%	19.7	-0.8	55%	18.0	4.8	4.8	-1.1	5.6
4 August	42	20.9	7.8	13.0	20.3	24%	20.3	-0.2	10%	18.2	-1.0	67%	19.5	4.8	4.8	-0.3	6.0
5 August	32	17.2	4.5	9.7	20.5	22%	20.5	-0.3	16%	19.8	0.0	66%	18.1	5.8	5.8	-0.6	5.8
6 August	40	15.3	3.6	8.7	19.1	33%	19.1	-0.4	8%	14.2	-3.0	63%	16.9	4.0	4.0	-1.1	5.5
7 August	37	12.4	7.5	10.1	21.0	65%	21.0	-0.3	14%	15.7	-2.3	27%	17.0	4.0	4.0	-2.1	4.9

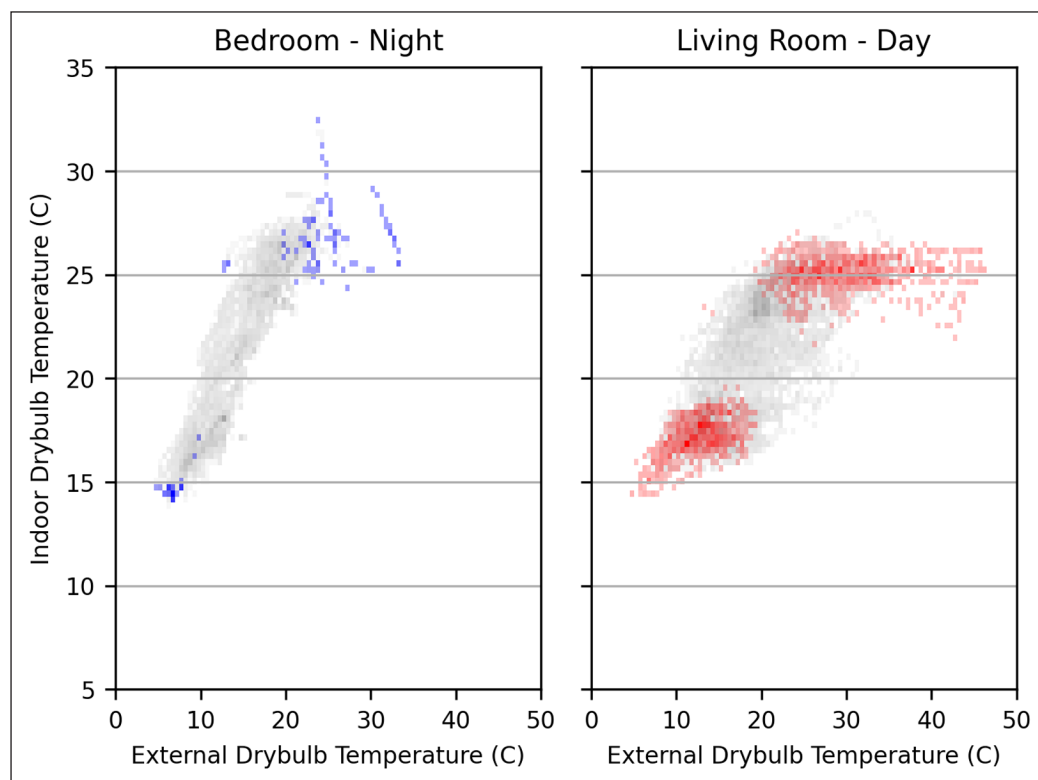
#### 4.4 EXPLORATION OF ANNUAL AND SEASONAL ENERGY IN THREE CASES

Three households with similar level of overall electricity consumption (between 10.3 and 12.9 kWh/day), each with three occupants, have been selected as case studies to explore the variation in occupant behaviour. Including night-time, these homes were occupied for between 87% and 91% of the total hours of the year. Notwithstanding these similarities, the three houses offer a rich narrative and interesting insight into varied patterns of reliance on GSHP-AC for heating and cooling seen amongst the study houses and discussed below. They are highlighted as cases A–C in the scatter plots in *Figures 2* and *3*. *Table 3* shows total electricity usage and geothermal AC energy across the year, as well as GSHP-AC energy intensity per unit floor area for each case. Scatterplots (*Figures 12–14*) of indoor temperatures for the living room (day) and bedroom (night) in each case and concurrent outdoor temperatures follow the same format and colour codes explained for *Figures 4* and *5*. They enable a clear visual interpretation of the take-up of AC as well as the temperatures at which conditions are maintained across the whole year.

**Table 3:** Summary of the annual and seasonal energy used in the three cases.

Note: AC = air-conditioning;  
GSHP = ground source heat pump.

CASE	ANNUAL ELECTRICITY (kWh)	ANNUAL GSHP-AC ENERGY (kWh)	TOTAL FLOOR AREA (m <sup>2</sup> )	CONDITIONED FLOOR AREA (m <sup>2</sup> )	GEOTHERMAL AC (GSHP-AC) ENERGY NORMALISED FOR CONDITIONED FLOOR AREA (kWh/m <sup>2</sup> )				
					SPRING, 91 DAYS	SUMMER, 91 DAYS	AUTUMN, 92 DAYS	WINTER, 92 DAYS	ANNUAL, 366 DAYS
A	3759	1393	173	104	1.47	6.00	1.47	4.45	13.39
B	4551	2425	111	76	4.49	6.46	6.61	14.34	31.90
C	4735	2277	189	138	1.84	4.63	3.39	6.64	16.50



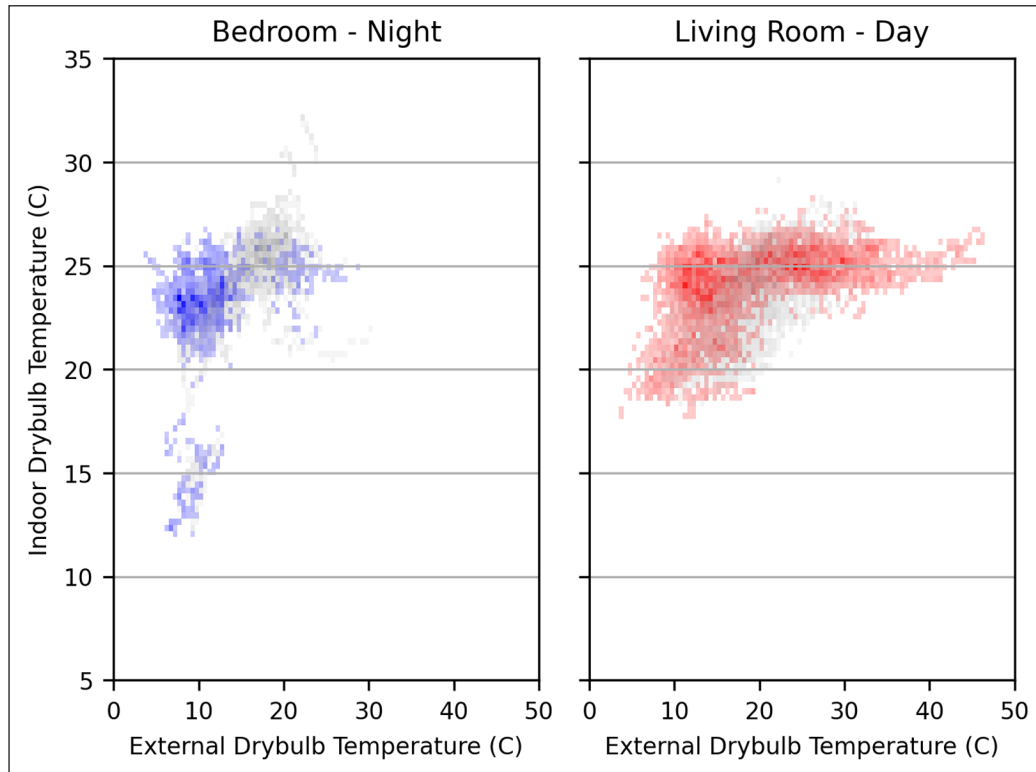
**Figure 12:** Indoor and concurrent outdoor temperatures during occupied hours: case A.

Case A is a 5.0 Star NatHERS-rated two-bedroom house with three occupants. The living room is oriented east, and the daily average across the year is 10.3kWh.

During the household survey the residents stated they resorted to GSHP-AC only after adjusting clothing, drawing blinds, switching on ceiling fans in summer, and adjusting food and drink. Occupants rated the home well for its comfort in summer in the absence of active heating and cooling. On the other hand, the house was rated to be too cold some of the time, with hot or cold

surfaces and not enough sunlight. The take-up of GSHP-AC across the year was 13% of occupied hours, concentrated over summer and winter at 23% for both these periods.

An adaptive approach where AC is only deployed to remedy uncomfortable temperatures is evident in **Figure 12** with indoor temperatures ranging between 16 and 20°C in winter and between 24 and 28°C in summer. These are corroborated by reported thermostat settings of 18 and 26°C for extreme weather days; right-now, right-here satisfaction between 5 and 6 (out of 7) for comfort; and concurrent thermal sensation ratings between -1 and 0.5.

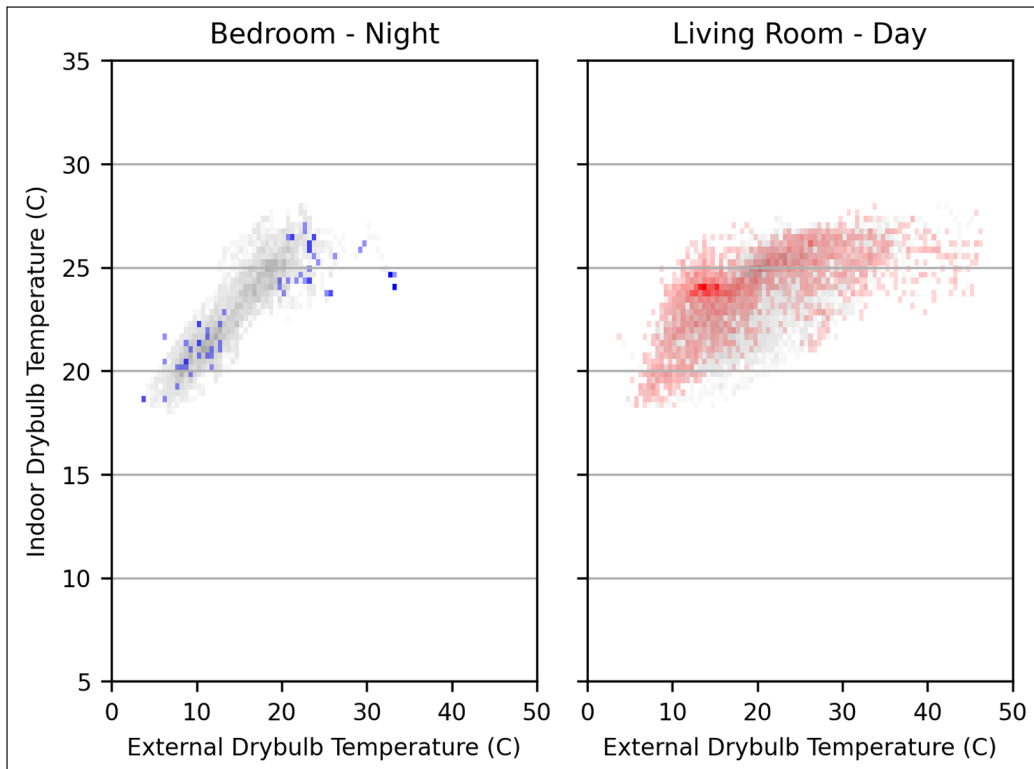


**Figure 13:** Indoor and concurrent outdoor temperatures during occupied hours: case B.

Case B is a two-bedroom home with three occupants, with a NatHERS rating of 4.8 Stars. The living room is oriented east, and the daily average across the year is 12.4 kWh. Occupants had installed a 6 kW PV system before the commencement of the study and reported they did this to reduce their electricity bill and environmental impact. The household survey feedback indicates high satisfaction with thermal comfort without GSHP-AC during the summer, autumn and spring, but a low level of satisfaction with thermal comfort for the same during the winter. The household reported opening windows at night, frequent use of fans on their own and in combination with GSHP-AC during warmer months, and nominated AC as the fourth option resorted to – after other adaptive measures.

Despite these reported adjustments, take-up of AC across the year was 38% of occupied hours spread across the year, with increased concentration over summer and winter at 40% and 62% for these respective periods. Additionally, residents reported using a thermostat set point between 25 and 26°C during the summer and higher than average set point of 24°C during the winter. These practices alongside a comparatively higher usage over night-time (**Figure 13**) contribute to the house having one of the highest AC energy intensities (31.9 kWh/m<sup>2</sup>) across the year when normalised for house size (**Figure 3**). As shown in **Table 3**, half the load is attributable to winter, with substantial loads in summer and autumn. A limited number of SMS survey responses were received for this house, and the temperature averaging 23°C for winter and 26°C for summer were rated as comfortable with ratings of 5 and 6 out of 7, respectively.





**Figure 14:** Indoor and concurrent outdoor temperatures during occupied hours: case C.

Case C is a three-bedroom 5.8 Star NatHERS home with three adult occupants, where the living room is oriented west and the daily electricity average across the year was 12.9 kWh.

While the house was rated well for its comfort in summer when no active cooling systems were in use, it was rated moderately for autumn and winter. The latter assessment is borne out in the higher AC energy intensity over these seasons. In terms of adaptive practices, the household ranked the take-up of the GSHP-AC system only after other measures such as appropriate clothing and ceiling fans. The occupants reported the use of portable fans, simultaneous operation of ceiling fans and the AC system, but were reluctant to open windows at night on account of insects.

The take-up of AC in the house was 15% across the year and for summer, and 26% of occupied hours in winter. While this is lower than cases A and B, energy consumption and intensity in case C is impacted by a preference for fairly stable conditions when AC was deployed. Thermostat set points were reported to be 24–25°C all year round, and the outcomes of this mode of operation can be seen in the fairly narrow band of temperatures when AC is in use (*Figure 14*).

On extremely cold and hot days, concurrent temperatures averaged between 21 and 24°C in winter and between 25 and 27°C in summer. According to the SMS surveys, these temperature were deemed to be comfortable by occupants, and were achieved about half the time through GSHP-AC.

## 5 DISCUSSION

### 5.1 IMPACT OF BUILDING DESIGN

A key element towards the success of integrating alternate AC systems in practice is that the building fabric must first be designed to mitigate overheating and overcooling. The buildings, as designed in 2014, conformed to the 2011 energy standards (section J) in the National Construction Code (NCC) of Australia. The thermal performance of the fabric is best understood by reviewing observable indoor temperature data at times when the GSHP-AC system is not deployed and the house is occupied.

As seen in the results for annual temperatures (*Figures 4a* and *5a*), the homes remain within 10–12°C of peak summer and minimum winter temperatures, without heating and cooling.

Furthermore, the instances with no AC captured via the SMS surveys indicate that this experience remains consistent even on extreme days where temperatures  $>37^{\circ}\text{C}$  in summer or consistently remain  $<12^{\circ}\text{C}$  all day. These results suggest that the code-compliant housing, with relatively compact built form can largely serve as an environmental modifier.

On the other hand, data captured in occupied homes where cooling was not deployed at night-time (*Figure 4*) highlight the challenge of warm temperatures  $>30^{\circ}\text{C}$  indoors at night-time while outdoor temperature lie between 26 and  $30^{\circ}\text{C}$  in summer on warm nights that typically follow extremely hot days. Moreover, the high take-up of AC on extreme days indicates that the building fabric as designed is in itself unable to deliver comfort at all times, and points to areas for potential improvement. In light of climate change, instances of warmer days and nights are expected to rise, and this becomes more relevant, especially as discomfort and expectations influence the take-up of heating and cooling, a point discussed below.

## 5.2 TEMPERATURE PREFERENCES WITHOUT AC IN USE

With the provision of the GSHP-AC system as a standard inclusion in the home, occupants are free to deploy AC at any time. Based on the premise that if occupants were uncomfortable, they had the freedom to turn on the AC, it is arguable that documented conditions while the AC was not in use were largely acceptable to occupants. *Figures 4* and *5* show that most of these temperatures would fall within the limits of the ASHRAE-55 (ASHRAE 2013) comfort limits for adaptive comfort (predominantly between  $18$  and  $28^{\circ}\text{C}$ ), which asserts that preferred temperatures are a function of ambient temperature conditions rather than a fixed set point (de Dear & Brager 1998). The analysis for the living rooms and bedrooms shows greater instances of temperatures  $<18^{\circ}\text{C}$ , with no take-up of heating despite its availability. This points to some tolerance of colder conditions in the living room during the day, although it is possible some of these occupied instances occur where there is transient rather than continued occupation.

The greater drift of temperatures to the warmer (*Figure 4*) and cooler (*Figure 5*) ends of the mean outdoor temperatures seen in the bedroom points to a confirmed situation on-site that indoor thermal conditions are more stable in the ground floor living spaces compared with the upper bedroom spaces. Nevertheless, the tolerance of lower temperatures at night in the bedrooms may also be due to the general practice of using blankets and quilts, and therefore not requiring further measures to redress the situation. Further evidence of occupant preferences for comfort and AC-related behaviour is discussed below.

## 5.3 OCCUPANT EXPECTATIONS FOR COMFORT IN EXTREME WEATHER AND AIR-CONDITIONED SETTINGS

The SMS survey data across both summer and winter yield several interesting insights. Unsurprisingly, there was a substantial take-up of GSHP for cooling the extreme hot days (for Sydney's climate) when maximum temperatures are  $>37^{\circ}\text{C}$  (67–74%) at the time of completing the survey, and for heating on a consistently cold survey day ( $>65\%$ ).

A pertinent finding of this study is that while practices and preferences for heating and cooling vary between households, there is a tolerance of a wider range of temperatures and take-up of adaptive opportunities especially during moderately hot and cold conditions across the year. Whilst the 'non air-conditioned' cohort on such days outnumbered (approximately 70%) those with AC, it is interesting to note their higher tolerance of warmer temperatures. The bulk of binned temperatures even at  $26$ – $28^{\circ}\text{C}$  were deemed to be comfortable by this cohort (ratings between slightly cool (-1) and slightly warm (+1)) (*Figure 8b*). Conversely, as soon as GSHP-AC is deployed, there is a greater tendency to assess temperatures  $>25^{\circ}\text{C}$  as warm and temperatures  $<24^{\circ}\text{C}$  as cool amongst the 'air-conditioned' cohort (*Figure 8a*). The SMS winter survey results (*Table 2* and *Figure 11*) point to a tolerance of lower temperatures such as  $16$ – $19^{\circ}\text{C}$  amongst a sizeable number of respondents both in 'air-conditioned' and 'no heating' situations. There also appears to be a marginal shift in perception of warmth, whereby similar temperatures are rated slightly warmer in the air-conditioned spaces than in the unheated spaces. These findings suggest that maintaining

and designing for adaptive thermal comfort in residences remains viable but needs to be better understood in relation to occupant practices.

## 5.4 OCCUPANT PRACTICES AND THEIR ENERGY IMPLICATIONS

The seamless integration of the GSHP-AC system has meant heating and cooling can be resorted to on the flick of a switch in much the same way as conventional AC. An in-depth view of the case studies shows how three homes seemingly not very different in terms of the number of occupants and total energy use have divergent patterns of AC usage.

Despite a similar occupancy level, and only a single-star band separating the three homes (4.8, 5.0 and 5.8 Stars), discreet patterns of the take-up of AC are observable in the study houses presented above. Case A represents the 'ideal' case where the take-up AC is mainly limited to uncomfortable periods in winter and summer, aligning with assumptions of how passive buildings must be operated. Coupled with climate-responsive heating and cooling set points of 19 and 25°C, the house returns the lowest AC intensity of the three cases at 13.3 kWh/m<sup>2</sup>/year. Although case C had the lowest take-up of AC at 15% of occupied hours, the household preference for a much narrower band of temperatures in the 24–25°C range, especially in winter, means the AC intensity 16.5 kWh/m<sup>2</sup>/year is higher than for case A.

Alternately, although apparently lower than other homes at 12.93 kWh/day, case B has the highest AC intensity of 31.9 kWh/m<sup>2</sup>/year of the selected case studies. As one of nearly half the houses with AC intensity higher than the other two cases discussed (*Figure 3*), case B is also illustrative of the tendency to deploy AC 'on tap'. Although this home also reports AC as the fourth option in summer, the occupants' tendency to maintain temperatures around the reported thermostat settings of 24–25°C, plus a seemingly conditioned preference for these temperatures all year (*Figure 13*), has meant that the take-up of AC in this home is as high as 40% and 62% of occupied hours in summer and winter, respectively. Another finding for case B is that this home has installed PV and is a net exporter to the grid. Admittedly the occupants' stated motivation to save energy and reduce environmental impact has probably resulted in a rebound effect (Qiu et al. 2019; Herring 2006) with a more indiscriminate take-up of GSHP-AC.

## 5.5 ADAPTIVE AND SUSTAINABLE PRACTICES TOWARDS LOW ENERGY OUTCOMES

The case study examples reinforce the broader study results for the study houses that occupants can and do exercise their agency to deploy AC as desired. As discussed above, occupant practices and behaviour via changing set points and varying preferences for summer and winter conditioning play a major role in determining the energy used for heating and cooling.

Although there was no training with respect to home usage, across the study homes occupants demonstrated a general awareness to adopt ceiling fans and other adaptive strategies before resorting to AC. Practices of adjusting clothing, drawing blinds to manage solar ingress or heat loss based on the season, as well as not opening windows when conditions were already uncomfortable outdoors indicate that home occupants are cognisant of several basic strategies to mitigate discomfort. On the other hand, a greater reluctance to open windows at night citing dust, noise, insects and a preference for the cleaner, swifter option of AC suggest the very thin line between the 'passive building/active occupant' frame (Cole et al. 2008) or indeed an active building/passive occupant frame observed in many other contexts (Thomas 2017).

The occupants may also adapt the building to provide and support their comfort requirements. In the latter case, their actions will depend on the design of the building, their personal knowledge of adjustment strategies, and their social and cultural contexts (Palmer et al. 2014). The study's finding that residents were aware of, and more likely to use, adaptive comfort strategies or coping mechanisms rather than be completely reliant on ducted AC during periods of moderate conditions suggests residential development is perhaps the last bastion for maintaining and designing for adaptive opportunities for residences. A recent direction of the Fairwater Living Laboratory has been to provide reports of usage patterns and infographics of usage and take-up of AC in ways

that communicate the energy consequence of practices. Further, meaningful engagement with occupants has been greatly hampered due to Covid-19 lockdowns in 2020 and 2021. While not within the funding regime of the project, an important next step would be to educate occupants and develop ways of providing real-time meaningful feedback to them to invite changes in behaviour.

## 5.6 IMPLICATIONS FOR DESIGN, POLICY AND REGULATION

The results of building performance show the value of existing regulations to reduce the use of AC. Given that most residences are built just to comply with the minimum performance requirements (Moore et al. 2019), higher stringencies are clearly required to drive thermal efficiency. Under proposed changes to the NCC for 2022 (Australian Building Codes Board 2021), it anticipated that the minimum star requirement will be raised to the 7 Stars NatHERS level. This increased stringency required to be met without offsets from any on-site renewable energy could help to encourage industry to improve the thermal performance of the building fabric.

Furthermore, the proposed introduction of the whole-of-home approach with an energy budget for regulated equipment in the home (*i.e.* space conditioning, heated water, lighting, and swimming pool and spa pumps) is likely to include stipulations for a 4.5 Star heat pump for heating and cooling. While these moves align with the shift towards efficient all-electric AC, as seen at Fairwater, the study findings in relation to the indiscriminate take-up of AC highlight the extra attention that must be paid to ensuring the energy efficiency does not lead to increased consumption via the rebound effect.

Proactive occupant education and engagement is needed to ensure the design of homes includes tangible ways of encouraging adaptive and sustainable practices. From a regulatory perspective these will include continued emphasis on creating naturally ventilated homes with minimal discomfort in the absence of active heating and cooling. In addition, designs would need to include adaptive opportunities such as secure openable windows, ceiling fans as well as indoor–outdoor living opportunities to acclimatise occupants to a wider range of temperatures, integration of trees to reduce the urban heat island effect, and creation of cool outdoors and social spaces through shaded pathways and parks.

The robust data capture and analysis of the occupants for 40 homes over a 24-month period is also expected to provide a crucial dataset towards characterising different types of user patterns and preferences that will be useful inputs for better modelling real energy use in favour of deterministic simulation methods traditionally used in building energy simulation for rating purposes (Marschall & Burry 2019).

## 6 CONCLUSIONS

Notwithstanding their energy-saving potential, the study suggests that the replacement of conventional air-conditioning (AC) with alternate technologies is not a one-stop solution in, and of, itself. Geothermal AC has been widely presented as a viable alternative to conventional AC, especially in its efficiency during extreme weather. While a step-up in the energy efficiency and sustainability stakes, the integration of ground source heat pump (GSHP)-AC as a piece of inconspicuous infrastructure seemingly no different to the conventional AC has its benefits and challenges. From a market point of view, the take-up is seamless, air-conditioned comfort is a selling point and the scale of the installation across a precinct has the potential for economic viable energy savings. On the flip side, much of the savings that could be realised may be squandered by the very notion of its efficiency, coupled with increased utilisation prompted by the availability of heating and cooling on standby. The approach to further offset the excessive utilisation using photovoltaic (PV) systems again has the potential to correct matters towards a net zero direction. However, this trade-off occurs at the cost of realising the full potential for greenhouse gas mitigation.



Moving forward, it is important to recognise that efficiently designed housing with adequate adaptive opportunities offers one of the best opportunities to break the cycle of dependence on conventional AC. Findings from this study point to both the opportunity for adaptive occupation of homes to deliver low energy outcomes as well as the potential for entrenching a cycle of expectation for AC alongside a lower tolerance of 'imperfect' conditions. An increasing number of warm days also brings the discussion squarely to the question of thermal comfort, expectations and preferences, and the manner in which inevitable residual hours of discomfort are designed for and managed. In focusing on the nexus between comfort, occupant behaviour and energy, the findings highlight implications for energy dependence and time of use, and the value of detailed understanding the opportunities and barriers towards designing for resilient and low-energy homes, ensuring the design intent is realised in practice, and transforming the social and sustainable practices of occupants.

## NOTE

1 Email correspondence with Alinta representatives, 2020.

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## COMPETING INTERESTS

The authors have no competing interests to declare.

## ETHICAL CONSENT

This study was approved by the University of Technology Sydney Human Research Ethics Committee (UTS HREC reference number ETH18-2752).

## FUNDING

The paper drew on findings from the Fairwater Living Laboratory, an ongoing research project undertaken at the University of Technology Sydney in association with Climate KIC Australia and Curtin University. The project was also funded by the Australian Renewable Energy Agency (ARENA), the Department of Planning and Environment, the New South Wales government (formerly the NSW Office of Environment and Heritage), and Frasers Property Australia.

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TO CITE THIS ARTICLE:

Thomas, L., Woods, A., Powles, R., Kalali, P., & Wilkinson, S. (2022). Residential geothermal air-conditioning: inhabitants' comfort, behaviour and energy use. *Buildings and Cities*, 3(1), pp. 226–249. DOI: <https://doi.org/10.5334/bc.172>

Submitted: 18 September 2021

Accepted: 15 March 2022

Published: 06 April 2022

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