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New ways of measuring energy poverty: Moving beyond temperature sensor data to assess and measure cold housing

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ABSTRACT

Many people live in cold homes that are hazardous to health. In the absence of high-quality observed data, researchers have measured cold housing and assessed its prevalence using secondary proxy indicators. Proxy measures previously used in literature include self-assessed warmth of the home, perceived energy affordability, financial inability to heat the home in winter, and local climate zone. Using matched in-home temperature sensor data from 502 Australian homes, we assess the validity of these proxy measures by estimating the degree of association with measured indoor temperature. We also examine twelve correlated socio-demographic characteristics to explore promising alternative proxy measures.

Self-assessed perception of home warmth was shown to be the best existing proxy indicator of cold indoor air temperature (OR 2.5, CI 1.4 to 4.3), with climate zone (OR 2.4, CI 1.6 to 3.8) also shown to be a strong measure. Perceived energy affordability (OR 1.1, CI 0.7 to 1.9) and financial inability to adequately heat the home (OR 1.0, CI 0.6 to 1.6), were shown to be unsuitable proxy measures. Of the correlated socio-demographic characteristics, heating appliance type (electric heater OR 3.0, CI 1.4 to 6.2), household structure (living alone OR 2.5 CI 1.2 to 5.5), built date (built <1990 OR 2.11, CI 1.38 to 3.23) and flooring type (timber floor OR 1.99, CI 1.23 to 3.22) were strong indicators of cold indoor temperatures, and would make sound proxy measures. Our assessment of the reliability of existing and potential proxy measures of cold home temperature suggests a need to carefully select proxies, based on their known or established validity.

1. Introduction

Understanding the prevalence, distribution and population affected by cold housing is important [1]. Living in cold homes is a health hazard [2]; for this reason, the World Health Organization recommends 18 °C as a minimum healthy indoor temperature [3]. Understanding who is cold in their homes, and how cold, is useful to formulate policy to mitigate the health impacts of cold housing, as well as to estimate the extent of the problem, and to target assistance.

Measuring temperature inside people's homes on a meaningful scale is challenging [1,4]. Across all areas of environmental monitoring, collection of data via sampling or deployment of loggers is expensive and time-consuming, and there are additional challenges of privacy, recruitment, and trust within residential environments [4]. Therefore, a number of previous analyses have utilised more readily available data, that does not directly measure temperature but instead provides a 'proxy' identification of cold indoor conditions (Table 1). The recent paper by Mishra et al. (2023) [5], for example, created a proportional multistate lifetable (PMSLT) to estimate the health and cost impact of cold housing intervention. They used self-reported survey data of responses to the question "When it is cold, are you able to keep at least one room of the house adequately warm" as a proxy measure of cold housing, rather than less accessible temperature data. Similarly, the study by Chimed-Ochir et al. (2021) [6] examined the effects of cold indoor temperature on sleep quality, using qualitative data on the subjective 'feeling of cold', rather than observed temperature. Similarly, the study by Clair and Baker (2022) [7] used participant assessment of their ability to keep the home sufficiently warm in winter as a proxy for cold indoor temperature in modelling of the mental health impacts of cold housing. Webb et al. (2013) [8] used secondary data on fuel poverty as a conceptual proxy for cold homes in analysis of older people's risk of respiratory illness. We also note that, in the absence of in-home

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temperature data, some studies have simply used climate zone as a proxy. In Galvin's (2019) [9] study of country level inequality, climate zone data is used as a proxy for household ability to heat their homes to healthy temperatures.

Importantly, proxy measures are rarely applied without due consideration. Their application is often accompanied by an acknowledgement of the potential limitations and considerations for interpreting the results of the analysis they are used within. For example, temperature variation across homes classified as 'cold' [15], stoicism by some respondents who report to be comfortable in unhealthily cold conditions [16]; and that perception of comfort can vary between individuals at the same temperature [17]. This paper seeks to provide a baseline for interpreting the results of studies that utilise proxy measures of cold in the absence of temperature data. We base our analysis on a dataset that not only captures detailed sensor collected temperature data of 502 homes, but also links a householder survey asking common proxy questions to the same households.

The central aim of this paper is to test the validity of proxy measures of cold housing so that, in the absence of objective temperature data, households experiencing temperatures below the WHO threshold of 18 °C might still be reasonably identified using more routinely collected data. The analysis is guided by the following research questions:

1. How well do the four proxy measures of cold housing, identified in the literature, reflect measured indoor air temperature < 18 °C?
2. Are other socio-demographic or housing characteristics also useful as proxy measures for measured indoor air temperature < 18 °C?

The paper proceeds with a description of the methods, including participant recruitment, data collection and analysis. Results are then presented in terms of individual proxy measures (perception of cold, inability to heat, perceived energy unaffordability and HDD), followed by different correlated socio-demographic characteristics: household structure, household income, energy affordability (receipt of government benefits), tenure, heating appliance type, dwelling age, floor construction, and dwelling condition (building quality, presence of insulation, and presence of mould). In the Discussion, we summarise these results in a comparative assessment of their usefulness, seeking a practical answer for identification of cold homes.

Table 1
Ten example studies, where cold home temperature has been measured using a non-temperature proxy, such as 'self-reported perception of cold'.

Proxy	Measure type	Variable	Use of proxy measure
Perception of warmth/cold	Self-reported, 4-point Likert scale	Experience of 'thermal problems' *Never; Sometimes; Often; Always*	In a Japanese study on sleep, feeling cold in the bedroom was used to indicate cold home temperature [6].
	Self-reported, 5-point Likert scale	How do you normally experience the temperature in your home? *Too cold; A little too cold; Just right; A little too warm; Too warm*	Occupants' thermal perception, of being too cold, in Sweden, was assumed to equate to cold temperature [10].
Ability or inability to heat the home	Self-reported	In winter, are you able to keep this accommodation warm enough? *Yes; No*	Inability to keep the home warm enough, from the UK Household Longitudinal Study, was equated with cold homes [7].
	Self-reported	Are you unable to keep at least one room adequately warm in the house when it is cold, due to a lack of money? *Yes; No*	Inability to adequately heat the home, reported in the Australian Household, Income and Labour Dynamics survey (HILDA) in Australia [11] was used to indicate cold homes in an analysis of Australian health costs [5].
	Self-reported	Are you unable to keep your home adequately warm? *Yes; No*	European Union (EU) households who cannot afford to heat their homes adequately were assumed to be cold [9], using data from [12].
	Self-reported	[In the 12 months prior to the survey] did any of the following happen to you because of a shortage of money? -Was unable to heat home *Yes; No*	Households indicating inability to adequately heat their home in the Household, Income and Labour Dynamics survey in Australia were assumed to be cold homes [13].
Energy affordability	Self-reported	Did you have difficulty paying your fuel bills? *Yes; No*	Improvements in self-reported difficulty paying fuel bills were used to indicate warmer homes in the UK 'Warm Front' program [14].
		Energy cost *>10 % net household income*	Secondary data on fuel poverty from responses of older people in the UK Household Longitudinal Study was used as a proxy for cold housing, and compared to respiratory health data [8].
Climate Zone	Measured external temperature data	Heating Degree Days (HDD) - summation of the differences between the average daily temperature and a base temperature, annually *In this example, base temperature was 18.3 °C*	Homes in climates in the EU with a higher number of heating degree days (HDD) were considered likely to be colder than others. [9]

2. Material and methods

The method of data collection is summarised in Fig. 1, moving from participant recruitment, through distribution of loggers to the matching of data. Temperature and humidity loggers were placed in homes across Australian temperate climates over winter, June–August, in 2022. Participants were recruited from five Australian states: New South Wales (NSW), South Australia (SA), Tasmania (TAS), Victoria (VIC) and Western Australia (WA) (Table 2, Fig. 2). The research was approved by the University of Adelaide Human Ethics Committee (H-2022-027).

2.1. Recruitment

Participants were contacted mainly through Australia Post's unaddressed mail service (62 %), targeted to reflect a cross-section of Australian household incomes. Additional participants were contacted via referral (16 %) and geographically targeted Facebook advertising (22 %). After completing a screening and baseline survey, pre-calibrated TZONE TEMP U 03 digital loggers were mailed to participants. The screening procedure determined if the participant lived in a temperate climate zone of interest (Table 2). Quotas were used to achieve approximately 100 representatives from each state and where possible, by income, with a natural fallout. A reasonably balanced sample was attained (Table 3), in comparison with the most recent Australian Census collected in 2021 [18].

As per Barlow et al. [19], participants were provided with written placement instructions as well as an instructional video demonstrating

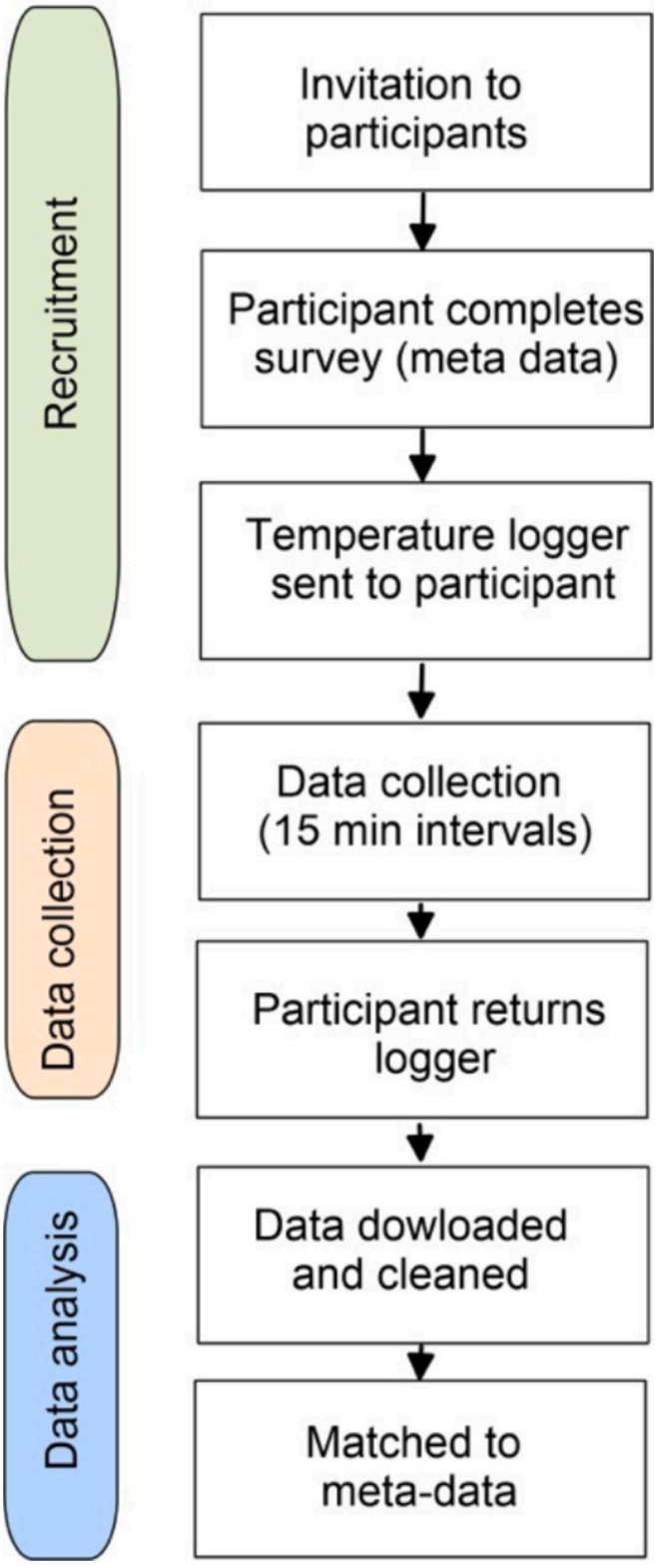


Fig. 1. Data collection method.

Table 2
Participant households by state, National Construction Code (NCC) climate zone, and rural or metro location.

State	Number of homes	NCC Climate Zone			Metro	Rural
		5: warm temperate	6: mild temperate	7: cool temperate		
NSW	107	99	2	6	86	21
SA	104	104	0	0	86	18
TAS	99	0	0	99	90	9
VIC	105	1	100	4	92	13
WA	87	79	8	0	77	10
Total	502	283	110	109	431	71

logger placement. Each logger was pre-programmed to record temperature and humidity[2] at 15-min intervals and was mounted within a stand in order that participants simply needed to place it in the living area, out of direct sunlight, away from heat sources, children and pets.

At the end of the monitoring period, loggers were returned via mail in pre-paid envelopes. A total of 538 loggers were mailed to participants, with full data returned for 502. The relatively small attrition rate (7 %) was attributed to logger delivery issues, moving house, non-reply to correspondence, and participant death.

2.2. Temperature data

Temperature data represent the main living area of each home, in a location away from direct sunlight or heat sources. Logger casings were designed to stand freely on a shelf, allowing airflow, rather than be placed against a wall. Participants received instruction for logger placement as per Barlow et al. [19]. Temperature data were collected at 15-min intervals and converted to hourly averages prior to analysis. Participants indicated via survey which hours their home was typically occupied. Data outside of these hours were removed from analysis, as were data for non-waking hours, according to Manousakis [20]. Remaining data were then converted to the following: winter averages for each home, percentage of hours below 18 °C for each home, and the winter minimum and maximum temperatures for each home, which were used in comparison of data for each proxy measure.

Participants recorded placement dates on the logger and recorded any movement of logger (within the same home or to a different address). Data were cleaned to remove any measurements collected before logger placement in homes. Data were also subject to quality analyses, including identifying any unusual (high or low) temperature measurements and determining if these were a realistic sample of temperature in homes. For homes where hourly averaged temperatures, during occupied hours, fell outside of 3 standard deviations of the mean across all homes in that state (e.g. for NSW, below 12 °C or above 22 °C), data were examined to determine if temperatures in that home followed a daily repeating pattern typical of an indoor environment, without unusual temperature events or rapid changes in temperature. All data were found to credibly reflect patterns for indoor environments [21,22]. On this basis, all samples were included in the dataset, with none being deemed to be false.

Prior to receiving loggers, participants also completed an online questionnaire. This included questions on thermal comfort, occupant perception of thermal comfort, energy affordability, heating and building conditions. Upon completing the initial questionnaire, each participant was identified by a unique participant ID. This ID was written on the logging device and used to name data files from that device. Hence

[2] Humidity data were not included in this present analysis because of the tendency for cold housing to be designated solely on the basis of temperature rather than a fuller suite of environmental factors (e.g. air movement, humidity), for example, see the WHO Housing and Health Guidelines.

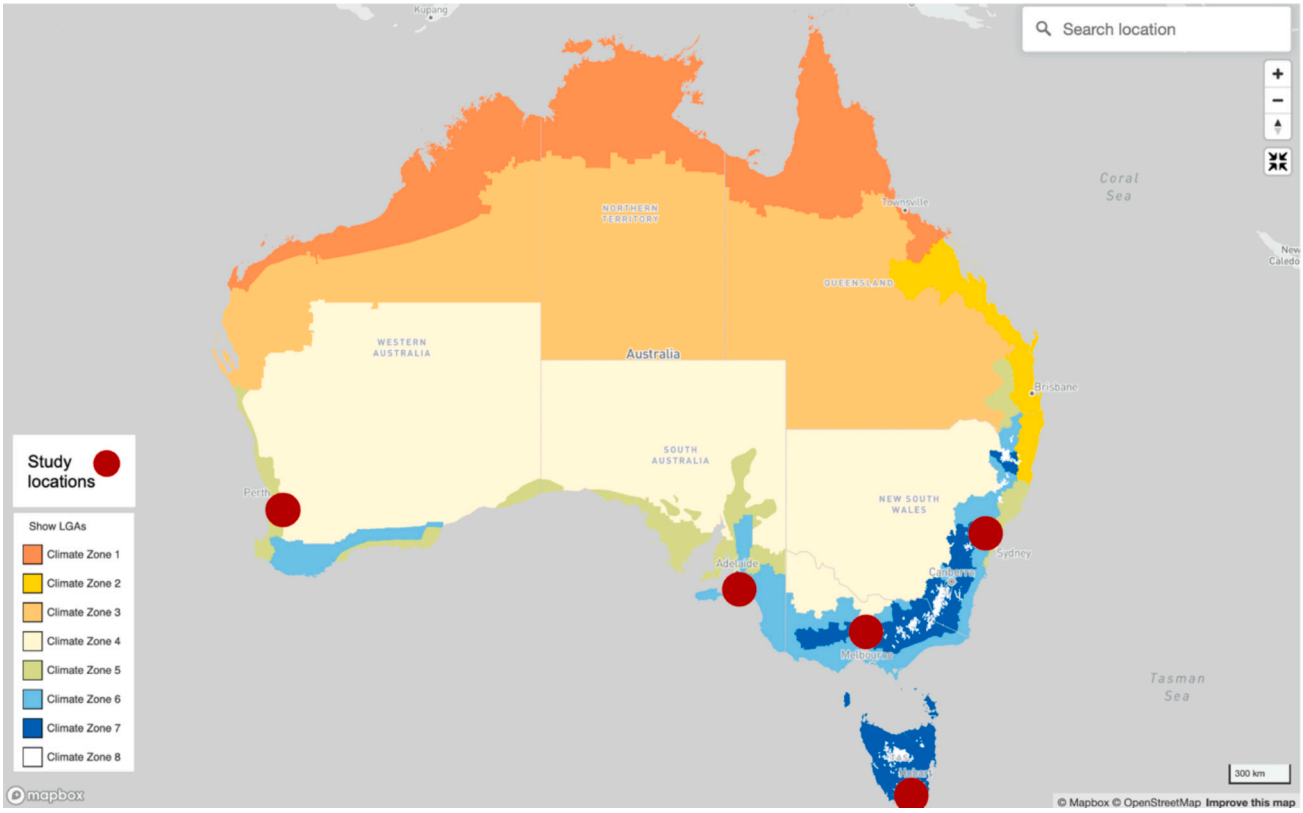


Fig. 2. Study locations and NCC climate zones (source: adapted from the Australian Building Codes Board Climate Zone Map).

temperature data were easily matched with questionnaire results.

2.3. Proxy measures

The proxy measures considered were perception of cold, inability to heat, perceived energy unaffordability and HDD, representing local climate. Correlated socio-demographic characteristics that have been associated with indoor temperature in the literature were also examined: heating appliance type, household structure, built date (comparative to introduction of Australian energy efficiency regulations), flooring type, building condition (including insulation and mould), household income, energy affordability (receipt of concession), and tenure. The rationale for each is given in Table 4.

Each variable was treated separately to increase the utility of the results to future work and application i.e., researchers and policy makers often need to rely on imperfect datasets, which may only incorporate one of the proxy measures.

2.4. Data analysis

Participants were also asked to identify what hours their home was occupied on a typical weekday. Many participants indicated that their home was occupied most of the time (78 %), others provided the hours the home is typically vacated in the morning and then re-occupied in the afternoon. Unoccupied hours were removed from this data set, as we were primarily interested in warmth of the home when occupants were present. The number of occupied hours below 18 °C (deemed 'cold hours') were also calculated for each home, based on the World Health Organization recommended minimum indoor temperature [3].[2] Additionally, maximum and minimum temperatures for each home were determined.

Temperature data were matched with participant data. Typically, participant data were discriminated by discrete groupings ('class', e.g. participants who had insulation versus no insulation). Temperatures for each home (mean, maximum, minimum) and hours below 18 °C were compared between classes, using one-way ANOVA in SPSS and $\alpha = 0.05$, to determine significant difference. Where multiple classes existed, post hoc Tukey analysis was then used, with $\alpha = 0.05$, to determine where differences existed between groups.

Odds ratios are useful to determine whether a related variable (spanning housing, socio-demographic and climatic characteristics, conceptualised as proxy measures) is associated with the main measure of interest (a home being "cold" as per the WHO definition of <18 °C), and to simply compare the degree of association [34]. Whist this does not describe the relationship between the proxy and temperature, it easily distinguishes those proxies that are useful to infer cold homes from those that are not. The information provided may also be useful for planning intervention [34]. Odds ratios were used by Sartini et al. [35] to test whether social class, financial difficulty and marital status were each associated with cold homes in the United Kingdom.

Odds ratios (ORs) were calculated to see how well each proxy or other measure predicted that people would be exposed to a cold home (below 18 °C). In each case, the 95 % confidence interval was also calculated. An OR of 1.0 mean that homes were equally likely to be cold as not cold. ORs > 1.0 mean that homes are more likely to be cold; likelihood increasing with increasing OR. A 95 % confidence interval that is entirely above 1.0 signals greater confidence in a proxy measure. If the 95 % CI for an odds ratio does not include 1.0, then the odds ratio is considered to be statistically significant at the 5 % level [36].

3. Results

Mean temperatures recorded in homes during occupied hours are summarised in Fig. 3. Mean wintertime indoor temperatures were below 18 °C for 74 % of the time, averaged across all five states in the study. In terms of state indoor winter temperature means, NSW, SA and WA homes were significantly warmer (df between groups = 4, df within groups = 494, F = 14.4, p = 4 E-11 across all groups and $\eta 2 = 0.019$)

Table 3
Demographic characteristics of survey participants compared with the 2021 Australian Census data [18].

	Wintertime temperature dataset	2021 Census
Household income [1]		
Less than $31,000	10.0 %	11.3 %
$31,000 – $59,000	10.0 %	15.8 %
$59,000 – $90,000	15.3 %	16.7 %
$90,000 – $125,000	11.4 %	13.8 %
$125,000 – $150,000	8.4 %	13.4 %
$150,000 – $175,000	10.6 %	15.9 %
$175,000 – $200,000	7.3 %	5.1 %
Over $200,000	17.3 %	14.4 %
Not stated	10.0 %	6.9 %
Age		
18–29	10.2 %	17.7 %
30–49	50.6 %	36.3 %
50–64	25.9 %	23.9 %
65+	13.3 %	22.2 %
Gender		
Male	36.3 %	49 %
Female	62.9 %	51 %
Other	0.4 %	Not reported
Not stated	0.4 %	
Tenure		
Owned outright	25.5 %	31 %
Owned with mortgage	46.8 %	35 %
Private rental	19.3 %	30 %
Public rental	3.0 %	
Other	2 %	
Not stated	3.4 %	3.4 %
Household		
Couple with children	53.8 %	35.8 %
Couple no children	23.5 %	31.8 %
One parent family	11.0 %	13.0 %
Single person	12.5 %	10.0 %
Shared living	5.0 %	4.8 %
Other	4.2 %	4.6 %
Dwelling type		
Separate dwelling	77.1 %	71.4 %
Flat <4 floors	7.8 %	7.9 %
Flat >4 floors	1.6 %	6.8 %
Semi-detached	12.2 %	6.9 %
Other	1.4 %	1.0 %
Not stated	0 %	0.3 %

[1] Income range categories in ABS 2021 data were only approximately comparable to those used in the wintertime temperature survey

than TAS ($p = 0.0002$ v NSW, $p = 7$ E-5 v SA, p = 7 E-9v WA) and VIC (p = 0.0002 v NSW, $p = 8$ E-5 v SA, $p = 2$ E-9 v WA). To summarise, the difference between state winter indoor temperature means during occupied hours was: WA (17.73 °C) > SA (17.18 °C) > NSW (17.00 °C) > VIC (15.97 °C) > TAS (15.87 °C). These results are similar to the pilot study by Barlow et al. [19]. ORs for cold homes based on proxies and other measures are shown in Fig. 4.

3.1. Performance of proxy measures

Of the existing proxy measures from literature, perception of temperature (cold some or more of the time, OR: 2.5, CI 1.4 to 4.3) and Heating Degree Days (>250, OR 2.4, CI 1.6 to 3.8) were the best predictors of cold. Self-reported inability to heat due to a shortage of money (OR 1.0, CI 0.6 to 1.6), and perceived energy unaffordability (OR 1.1, CI 0.7 to 1.9) were not deemed reliable proxy measures for cold homes.

3.1.1. Occupant perception of temperature

Based on mean winter indoor living-room temperature, participants who 'always' felt warm had homes that were 1.1 degrees warmer, at 17.8 °C, than those who 'rarely' felt warm (16.7 °C). There was a corresponding decrease in temperature 'always' (17.8 °C) > 'mostly' (16.9 °C) > 'half of the time' (16.6 °C) > 'sometimes' (16.1 °C) > 'rarely' (15.8 °C) (Fig. 5). Significant difference existed (df between groups = 4,

Table 4
Proxy measures and correlated socio-demographic characteristics assessed.

Measure	Details of measurement
Proxy Measures	
Perceived cold some or more of the time	Question: 'How often were you able to stay comfortably warm in your home during cold weather?' Included: 'warm most of the time', 'about half of the time', 'some of the time', and 'rarely' as one group. This group indicates that at some time the occupant feel cold; Versus those who felt warm 'all of the time' as a second group. (C.f. [6])
Heating degree days >250/ year	Identified by address according to the Australian Bureau of Meteorology [23]. This provides a measure of how much heating is required to attain a base temperature (18 °C) [9].
Energy affordability	Question: 'Is energy (electricity and gas) affordable?' Included: 'unaffordable', Versus: 'affordable' or 'affordable with reservations'. Odds ratios for 'Unaffordable' and 'Affordable' were also compared in Section 3.1.4. (C.f. [14,24]).
Unable to heat due to a shortage of money	Question: In the last 12 months were you unable to heat your home due to a shortage of money? (Yes/ No) (C.f. [7,25]).
Correlated socio-demographic characteristics	
Heating appliance type	Question: 'What is your main source of heating?' 'electric heater e.g. radiator, fan or dimplex type', has been contrasted against other types in the odds ratio. Other types are: 'gas ducted heating', 'gas room heater', 'wood fire', 'other central heating (e.g. electric hydronic, slab, floor)', 'other'). Most homes had one or more secondary forms of heating, here we have only considered the primary mode of heating. Inadequate heating systems are considered to be a factor in cold homes [16].
Household structure: Live alone	Question: Household structure 'single person living alone'. Living alone was given as a reason for not heating the home in Sansom [4], and would hence lead to colder temperatures.
Household structure: Single parent	Household structure 'single parent family' compared to 'two parent family'. Barnes demonstrated that UK Children in lone-parent families were twice as likely to experience persistent inadequate heating [26].
Household structure: Has person >65 years	Question: Age of occupants, containing someone >65 years. Older persons tend to live in colder homes [27], and winter mortality rates are highest in older persons [28]. Yet many older residents value a comfortable home indoor environment, and maintain warmer temperatures than others [10].
Built date (before 1990)	Question: What year was your house built? Options of '>1990' versus other years. This is based on the introduction of building energy efficiency measures in Australia, beginning in the 1990s.
Flooring type (Timber floor)	Question: What is the base structure of your home? 'stumps and wooden flooring', compared to 'concrete slab'. The high thermal mass of concrete slab flooring compared to thinner timber floors, with air movement underneath, is likely to lead to a warmer indoor environment [29].
Building condition: 'Poor' building quality	Question: Physical quality of home: 'poor' (or 'very poor') versus 'average', 'good', or 'excellent'. Housing conditions, particularly poor maintenance, are a factor in cold homes [30].
Building condition: Not insulated	Yes/No, results for 'unsure' were removed. Insulation impacts on energy efficiency and indoor temperature [31].
Building condition: Mould present	Question: In the last 12 months have you had mould or mildew on surfaces in your home, other than on food. Yes/No. Mould has been associated with cold homes [32].
Household income (<$90,000)	Question: Gross household income 2020–2021 (choice of 5 income brackets). Australian median income was approximately $90,000 [18] hence we compare indoor temperature for those above and below this median.

(continued on next page)

Table 4 (*continued*)

Measure	Details of measurement
Energy affordability: Concession received	Yes/No. Those receiving an energy concession may be better able to afford to heat their homes, leading to warmer temperatures [33].
Tenure: Rental v Owned/ mortgaged	Question: tenure 'renting from a government housing authority' and 'renting from a real estate agent' compared to other tenures. As renters have less control over their housing, they may have more difficulty heating their homes [4].

df within groups = 494, F = 8.797, $p < 0.001$ and η2 = 0.066) across all groups and between classes as follows:

- 'Always' with all other classes ($p = 0.03$ v 'mostly', $p = 0.003$ v 'half of the time', $p < 0.001$ v 'sometimes' and $p < 0.001$ v 'rarely');
- 'Mostly' with all ($p = 0.024$ v 'sometimes', $p = 0.008$ v 'rarely'), except 'half of the time' ($p = 0.6$);
- 'Half of the time' only with 'Always' ($p = 0.003$); and
- 'Sometimes' with 'Always' ($p < 0.001$) and 'Mostly' ($p = 0.008$).

Results for the proportion of hours <18 °C followed a similar pattern, with significant difference across all groups (df between groups = 4, df within groups = 494, F = 8.144, $p < 0.001$ and η2 = 0.062) between most classes ('always' v 'mostly' $p = 0.01$, 'always' v 'half the time', 'sometimes' and 'rarely', $p < 0.001$; no significant difference 'mostly' v half the time, ($p = 0.7$) and 'rarely' ($p = 0.1$), yet significant difference v 'sometimes" (0.03)). There was no significant difference between those who 'sometimes' and 'rarely' felt warm, both with 76 % cold hours and $p = 1.0$. Cold hours decreased, however, for those who felt warm 'half of the time' (70 %), 'mostly (66 %) and 'always' (53 %).

3.1.2. Heating degree days (HDD)

Homes located in climate zones with <250 HDD ($n = 267$) were significantly warmer in terms of mean winter indoor temperature (17.3 °C, $p < 0.001$) compared with those experiencing >250 HDD ($n = 218$, mean 16.0 °C). The same applied for the number of cold hours, with zones having <250 HDD experiencing significantly less cold hours (63 %, $p < 0.001$) compared with >250 HDD (74 %).

3.1.3. Perceived inability to heat due to a shortage of money

Participants were asked if they had been unable to adequately heat their home due to shortage of money over the last 12 months. People who answered 'yes' to this question (25 %, $n = 124$) were significantly colder, in terms of mean temperature, by 0.6 °C, than those who answered 'no' (df between groups = 1, df within groups = 484, F = 5.43, p = 0.02, η2 = 0.004). They also experienced minimum temperatures that were 1.5 °C colder, on average. However, they did not experience significantly more cold hours than those who had not been impacted by a shortage of money. This did not perform well as a proxy measure, using this dataset, as determined by OR (OR 1.0, CI 0.6 to 1.6).

3.1.4. Perceived energy unaffordability

Likewise, perceived energy affordability proved to be a poor proxy, using this dataset (OR 1.1, CI 0.7 to 1.9). The perception of energy unaffordability is widespread (Fig. 6), with 28 % considering energy unaffordable and 52 % having reservations about its affordability; leaving only 20 % considering energy to be affordable. As per Table 4, the OR in Fig. 6 was calculated by comparing the 'unaffordable' class to the 'affordable' and 'affordable with reservations' classes. Alternately, comparing only 'unaffordable' and 'affordable' classes yields OR of 0.37 (CI 0.18 to 0.77). It must be kept in mind here that there was no significant difference in indoor winter temperature between these three classes (df between groups = 2, df within groups = 494, F = 0.675, $p = 0.5$, η2 = 0.003[2]).

3.2. Performance of other measures

In terms of correlated socio-demographic characteristics, heating type was the best predictor of living in a cold home (Fig. 4), with reliance on an electric heater returning an OR of 3.0, (CI 1.4 to 6.2). Indeed, it was a stronger predictor than any of the existing proxy measures from literature. Household structure was also a good predictor of cold, with living alone (OR 2.5 CI 1.2 to 5.5) as strong as the best proxy (perception of cold). Built date (built <1990, OR 2.1, CI 1.4 to 3.2) and flooring type (timber floor, OR 2.0, CI 1.2 to 3.2) were also significant proxy measures. All other measures investigated were stronger predictors of living in a cold home than the remaining proxies from literature of being unable to heat due to a shortage of money or perceived energy

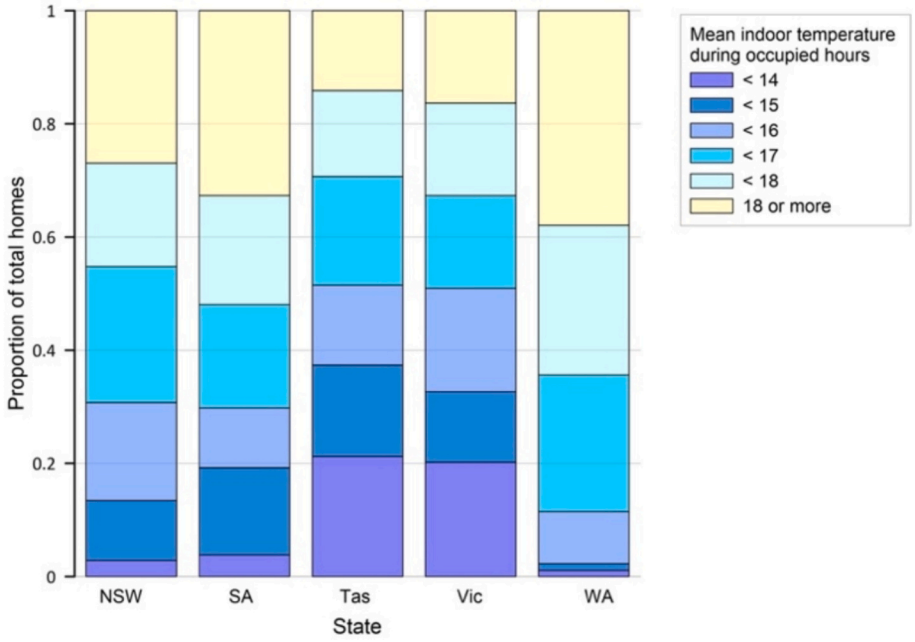


Fig. 3. Indoor wintertime temperatures during occupied hours for 502 Australian homes.

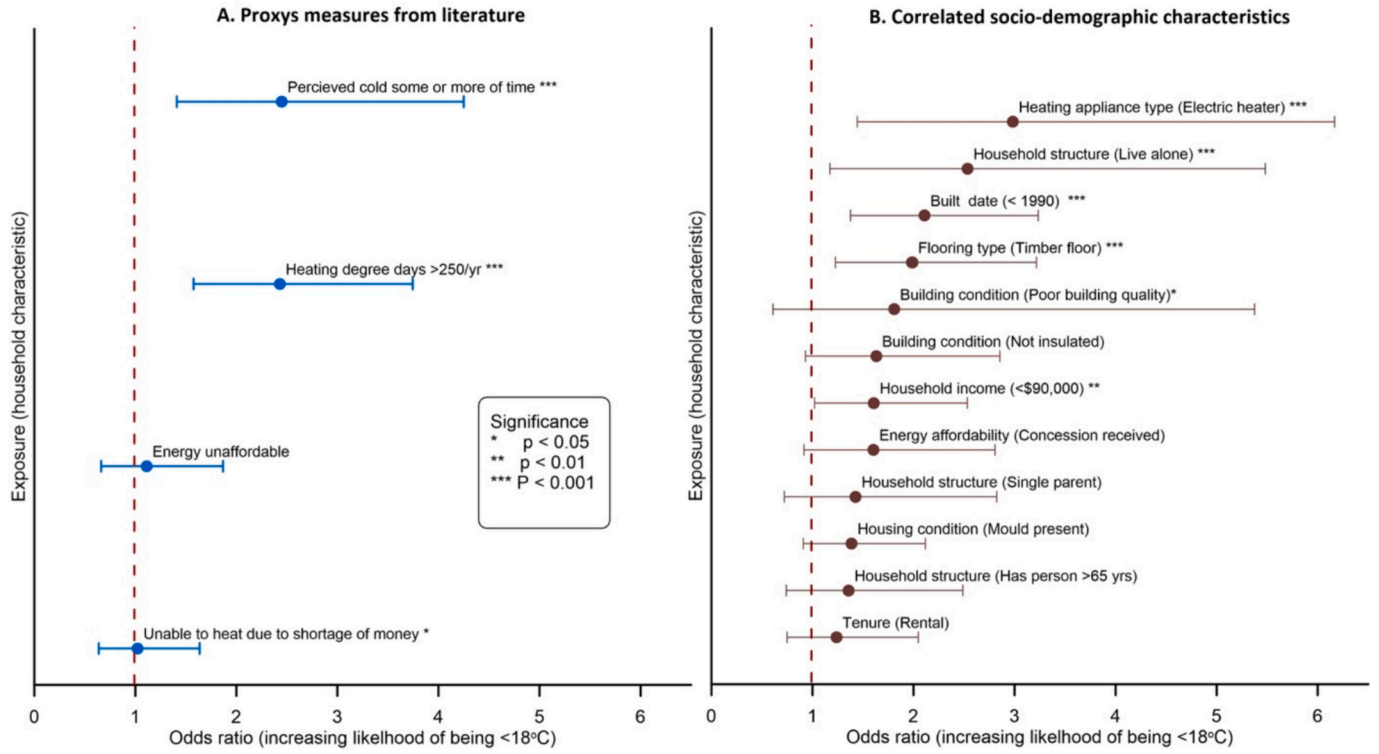


Fig. 4. Odds ratios of living in a cold home based on A. Proxy measures from literature and B. correlated socio-demographic characteristics. Error bars show 95 % confidence interval.

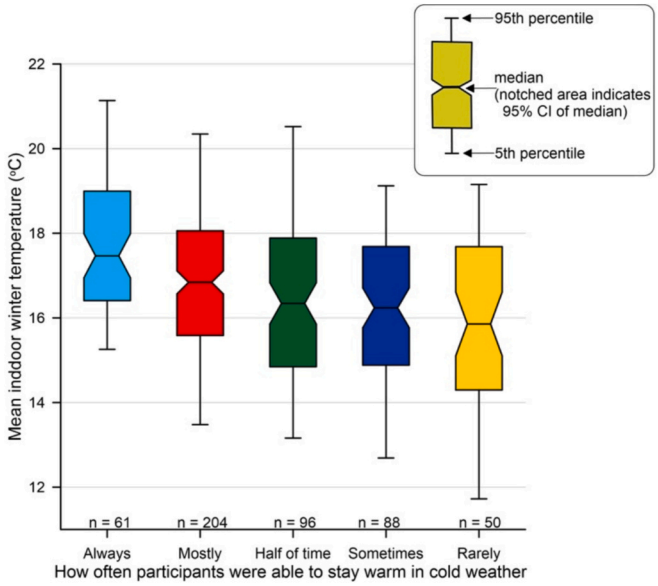


Fig. 5. Participant perception of warmth versus measured indoor winter temperature.

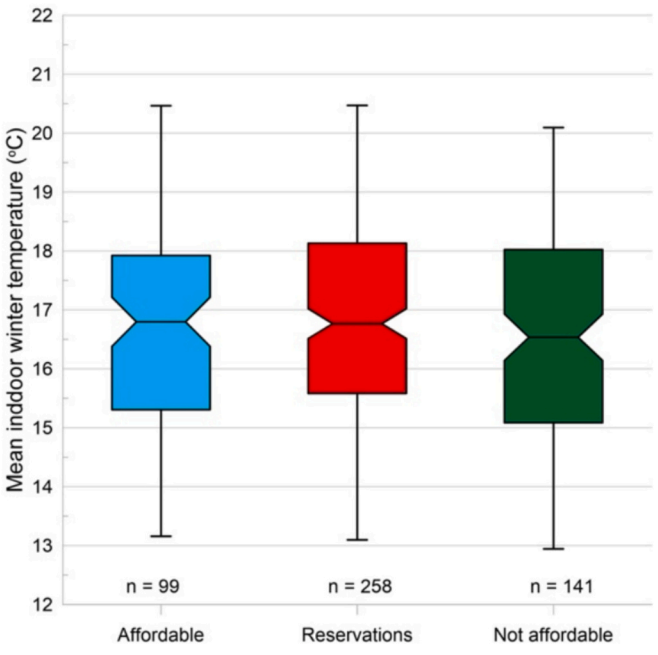


Fig. 6. Perceived energy affordability versus indoor winter temperature energy.

unaffordability.

Choice, or availability, of heating, made the most significant difference to indoor temperatures (df between groups = 6, df within groups = 492, F = 4.073, $p < 0.001$ across all groups and $\eta 2 = 0.066$). Those with primarily electric heating (e.g. electric radiator or fan heating) were coldest, with a mean of 15.9 °C and 81 % of occupied hours below 18 °C. Those with gas room heating and reverse cycle air conditioning (both 17.1 °C mean and 63 % cold hours) were significantly warmer ($p < 0.001$ v reverse cycle air conditioning, $p = 0.009$ v gas room heating). These classes also had significantly higher maximum temperatures (gas room heating 23.5 °C and $p = 0.033$ and reverse-cycle air conditioning 23.1 °C and $p = 0.048$) compared with homes using electric heating (21.8 °C). There were no significant differences in minimum temperature.

4. Discussion

Our analysis confirms the reliability of two existing proxy measures for cold housing, self-perception of cold, climate (in this case defined by HDD), and suggests four additional, highly-correlated proxy measures: heating appliance type, household structure, built date and flooring type. The performance of the different proxy measures in reflecting indoor temperature are summarised in Fig. 4. Perception of temperature was a very strong indicator of measured indoor temperature. Those who identified as being the coldest were indeed the coldest, and similarly for those who identified as warmest. In general, mean temperature decreased stepwise with perception of warmth (Fig. 5). This is an important finding as it is much easier, and less costly, to collect data on perceived temperature than to measure temperature in homes. Perception of warmth is therefore a very useful tool in identifying households and individuals at risk from living in cold homes. It is interesting to note that even those who perceived themselves as 'always warm' had a mean winter temperature (during occupied hours) of only 17.8 °C, which is just below the WHO recommendation of 18 °C [3]. The number of HDD is also a strong proxy and is perhaps the most useful of all proxies, in that no personal data needs to be collected to determine HDD. It is simply based on location. Surprisingly, perceived inability to heat due to a shortage of money performed poorly as a proxy. Many Australians (36 %) perceived household energy costs to be high, as far back as 2013 [37], since which time energy costs have risen by over 150 % [38]. Manturuk [39] concludes that households experiencing similar levels of financial difficulty perceive it differently based on other factors such as home ownership. This finding is important as the measure has been one of the most readily available proxy measures to researchers to-date (e.g. [5,11,13,14,24]).

The ability to predict cold homes from other measures, particularly from heating type, occupancy, built date and flooring type is promising. Homes with electric heating were almost three times as likely to be cold compared to homes with other heating types, such as gas or reverse-cycle air conditioning. In Australia, central heating is uncommon, and many houses are sold or let without fixed heating systems. Primary reliance on electric heaters indicates that the housing lacks necessary infrastructure to adequately heat the occupants, or, that the occupants cannot afford more expensive built-in appliances. The association between cold temperature and electric heating may be indicative of other unobserved factors, for example, it is a very inexpensive appliance to purchase, though expensive to run [4]. Therefore, electric heaters are often used in instances where people are unable to make changes to the property. For example, renters, or social housing, or cannot afford more expensive built-in appliances, such as reverse-cycle split systems or gas central heating, which are both common in the Australian context [4]. This further exacerbates the effects of fuel poverty for those already in vulnerable situations. Electric heaters may also be more prevalent in the lower cost housing market where fixed appliances are less common and, therefore, potentially indicative of poorer overall quality and thermal performance of the dwelling itself.

The conceptual relationship between cold indoor temperature and sole occupancy is less clear, however previous research has found that people living alone are less likely to turn heating on whether due to stoicism or financial concerns [4]. It has also been found that people are more likely to use alternate methods of staying warm if alone, such as blankets and heavy clothing, but are disinclined to do so when others were present who may think them odd [28]. These groups may need additional support to keep their homes warm. Our results showed that people aged over 65 years were not necessarily colder in their homes. Likewise, Hitchings and Day [28] found the idea that older people do not heat their homes to be an outdated stereotype, with many older people now being relatively wealthy.

Built date is easily obtainable from cadastre; and flooring type can be broadly assumed by type of development. Hence these measures are able to be utilised for prediction of cold housing without the need for occupant surveys or temperature measurement. Whilst perceived building condition and base structure were both useful as proxy measures, surprisingly, no association was found between temperature and insulation. This may be due to a lack of householder knowledge on the location (e.g. roof, walls) of insulation, or its condition. Other studies have found insulation to be significantly associated with warmer homes, as well as improved health [40,41]. Homes built since 1990 were warmer, but only marginally so, with a difference of only 1 °C between age categories. There was significant difference in mean indoor temperature only between homes built post 1990 (17.4 °C) compared to those built prior to 1930 (16.3 °C) or in the 1960's (16.2 °C). The National House Energy Rating Scheme (NatHERS) was initiated in 1993 [42]. It was gradually adopted by Australian State and Territory governments, with minimum four-star ratings required for new homes in the Australian Capital Territory by 1995 [42]. Australian building efficiency codes followed, introduced in 2004 [43], affecting new buildings, with the older housing stock remaining cold.

In the application of these new proxy measures, each of these variables have different degrees of uncertainty and utility. The strongest odds of cold indoor temperature are indicated by the use of electric heating (OR 3.0), though this measure has the greatest uncertainty (CI 1.4–6.2). Perception of cold and sole occupancy both demonstrate the same odds (OR 2.5) of cold indoor temperature, though perception of cold would appear to be more reliable, based on the 95 % confidence intervals (CI 1.4–4.3 for perception of cold and CI 1.2–5.5 for sole occupancy). Climate (indicated by HDD) has an odds ratio of 2.4, but has lower uncertainty (CI 1.6–3.8) than both perception of cold and sole occupancy. Finally, build date (OR 2.1) and flooring type (2.0) have relatively lower odds of indicating cold indoor conditions when compared with the other proxy measures; but have the lowest uncertainty (CI 1.4–3.2 and 1.2–3.3 respectively).

When we consider these results in conjunction with the ease of data collection, climate would appear to give us the most widely applicable indicator of cold indoor temperature. Weather data, climate zones and summary indicators such as HDD, are readily available in most countries either freely or at low cost from meteorological services. Application of three of the other measures (perception of cold, use of an electric heater and sole occupancy) require data to be collected from the individual, most likely via questionnaire survey. Data on household structure (indicative of sole occupancy) is likely to be collected in a wide range of surveys as a matter of form (e.g. in Australia routine surveys such as the Census and the General Social Survey collect this information), while data perception of cold and heating type are generally only collected in surveys specific to housing conditions and energy use. Therefore, sole occupancy may be the best proxy measure to use when relying on population level secondary data, however if designing and administering a tailored survey, both perception of cold and heating type would be the most appropriate measures to include.

These three proxy measures (perception of cold, use of an electric heater and sole occupancy) also have the benefit of enabling identification of potentially cold houses at a unit record level, rather than at the spatial level of a particular climate zone. Both build date and flooring type may be picked up in household surveys such as those mentioned above, but are also likely represented in cadastre records and are relatively unchanged over time (apart from where major renovations occured). In measuring cold housing environments using proxy variables, it would seem prudent to use a combination of the measures above that each shed light on a different contributor to cold housing: the local climate, physical dwelling characteristics and conditions (including heating appliances), and the socio-demographic profile of the occupants.

5. Conclusion

This study has highlighted the need to benchmark proxy measures against observed temperature data. Our analysis has shown that the selection of which proxy measure is used in research and policy makes a

very significant difference to the estimation of the extent of the problem of cold housing. Necessarily, the estimation of how many households and who is affected, drives research concern, but also public policy, interventions, and budget decisions. Some common proxies (such as the inability to heat the home due to a shortage of money) were shown in this analysis to actually provide very poor approximation of cold housing, and it is hoped that this finding will influence the design of future work and policy. Two of the existing proxy measures from the literature – occupant perception of warmth and heating degree days – performed well. These are valuable; they are reliable proxy measures, but they also potentially enable the prevalence and depth of the problem of cold housing to be assessed and monitored cheaply, quickly, and using data that often already exists. Our analysis suggests that the perceived inability to heat home due to a shortage of money, and perceived unaffordability of energy were not reliable proxies. Indeed, each of the correlated socio-demographic characteristics studied were better predictors of cold homes than these two previously used proxies form the literature. The correlated socio-demographic characteristics: reliance on electric heaters, living alone, timber flooring and homes built before 1990 were of particular value as indicators of cold homes and future work should be undertaken to explore and standardise their potential use. This research provides guidance and greater confidence to researchers and policymakers alike in the use of routinely collected data to identify cold houses.

CRediT authorship contribution statement

Cynthia Faye Barlow: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lyrian Daniel:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Emma Baker:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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